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Non-structural measures for water management problems

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Preface

Non-structural measures are an attractive alternative and addition to structural measures that may reduce the loss of life and property caused by water-related problems. The main objective of the workshop was to identify the role of non-structural measures in sustained set of actions that improve society's capacity to, anticipate, mitigate, withstand and recover from water-related problems.

Recent water resources management is emphasizing a more integrated approach including measures such as insurance, forecasting, warning and land use planning. The advent of non-structural measures can be viewed within the wider context of the need for the development of more hazard effective and sustainable relationships with the environment in an era of integrated water resources management.

Debate still continues about the relative merits of structural measures, although there is a growing realization that they may be inappropriate for long-term development given the relative lack of financial resources coupled with concerns about environment degradation. Experience shared during the workshop is clearly indicating overwhelming support for a mix of structural and non-structural measures. Therefore, there is a need for interdisciplinary work and communication.

Papers presented during the workshop and printed in the Proceedings are organized to provide the coverage of different issues related to the use of non-structural measures in water resources management. Kundzewicz (Poland), Porto and Porto (Brazil) and Takeuchi (Japan) are dealing with general issues related to water resources management and the role of non-structural options within the context of their respective countries. Contribution by Bourget (USA), Simonovic (Canada), Mujumdar (India) and Stancalie et al (Romania) are focusing more on the importance of data and computer-based methodologies for water resources management. Great examples are provided in the papers by Cheng et al (China), Li and Weatherbe (Canada) and Prowse et al (Canada). Issues related to forecasting are addressed by McBean (Canada), Nguyen (Canada), Kuchment and Gelfan (Russia), and Xia (China). Very insightfull discussion of economic issues is included in the papaers by Kulshreshtha (Canada), Crichton (UK), Savenije and der Zaag (Netherlands) and Kovacs (Canada). Interesting example of social considerations related to the role of non-structural measures is addressed at the end by Rasid and Heider (Canada)

This set of Proceedings is intended to serve as a key source of reference for water researchers in academia and professionals, including practitioners and policy makers in agencies, consultancy and government departments. But I hope that it will also appeal to everyone who is concerned about comprehensive water resources management and who wishes to increase their understanding of the role that non-structural measures can play in the future.

I would like to extend my gratitude to organizations that provided financial resources for the Workshop: UNESCO IHP Program; Canadian Commission for UNESCO; Environment Canada; National Water Research Institute; and The University of Western Ontario. Support of the Canadian Society for Civil Engineering; Upper Thames River Conservation Authority; and the International Association for Hydrological Sciences is also acknowledged. I wish also to thank all participants and colleagues who have provided their interest, time and expertise and contributed to the success of the Workshop. Mrs. Sandra Doyle prepared the text for publication and Dr. Veerakcuddy Rajasekaram prepared the post-workshop web site (http://www.engga.uwo.ca/research/iclr/Post-ws/default.htm). For any failings and mistakes that remain, I take full responsibility.

Slobodan P. Simonovic
London, January 2002

A Landmark Workshop on Non-Structural Measures for Water Managament Problems

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Introduction

Humankind has to live with hazards, be they natural, or of human origin, and means have to be invented how to cope with them: to reduce their incidence, to resist better when they occur, and repair efficiently the damages when they are over. In water management, these actions turn into sets of structural and non-structural measures.

Till some fifty years ago, the water profession was dominated by the doctrine of "harnessing nature", and the response to flood hazards took the form engineering structures, of increasing size, scale, and importance: levees, dikes, river channel works, dams and storage reservoirs, etc. All these structures managed to reduce the frequency of flooding of protected land, but much less to moderate the damages caused by them. Humankind has to accept that engineering structures, however expensive they be, must be combined with other, non-structural measures, to better adjust and live with inevitable hazards.

The importance of non-structural measures in water resources management has fully been recognized in the Fifth Phase of the International Hydrological Programme (1996-2001). The topic has found its place within *Theme 4 - Strategies for water resources management in emergency and conflicting situations*, and within that theme, it was explicitly addressed through *Project 4.3,* entitled *"Non-structural measures for water management problems"*. The objectives of the project were to identify the possibilities of non-structural measures in water-related emergency, including risks such as floods, accidental pollution of surface and groundwater, dam-breaks, inappropriate operation of reservoirs, exceptional draughts, etc. The Project outline indicates that the non-structural measures were seen as complementary to the essentially structural answers to water problems, be they connected to water uses, or to defense against water related hazards.

One of the main products of IHP-V Project 4.3 was the Workshop under the same title, organized by the Institute for Catastrophic Loss Reduction (ICLR), London, Ontario (Canada). The results of the Workshop entirely responded to the expectations, and thus efficiently concluded the Project, close to the end of IHP-V. However, the analysis of the proceedings of the Workshop will show, that the achieved results extend beyond the original objectives, defining non-structural measures not just as complementary measures to structural water resources systems, but as the very substance of integrated water resources management. In that sense, the London Ontario Workshop can be considered as a landmark in the appreciation of non-structural measures, applied to all aspects of water resources management.

Objectives and Participation

Organized by the Institute for Catastrophic Loss Reduction (The University of Western Ontario, London, Canada), the Workshop was geared towards identifying the role of non-structural measures for the reduction of water-related economic and societal hazards. The meeting was attended by some 50 participants, composed of experts from different disciplines of natural, health and social sciences, water management practitioners, representatives of policy- and decision makers.

During the three days (18-20 October 2001), fourteen papers were presented in five plenary sessions (in general, three papers per session). After each session, discussion was organized in three separate rooms, with 15-18 participants in each group, randomly selected from the participants. The arrangement secured that each participant could express his/her opinions about the whole agenda; the discussions were then summarized by the moderators of each group, and presented at the plenary closing session. The success of the Workshop was greatly due to the excellent organization - the sessions, group discussions, and social events.

These proceedings contain all the papers presented in the workshop. Selected papers will be published after review in the special issue (March 2002) of the *Water International Journal* published by the International Water Resources Association.

Accents and Results

The concept of non-structural measures was some 50 years ago first used in the context of flood control, as a means to reduce the ever increasing damages, without unduly expanding the costly infrastructure. In that sense, NSM were perceived rather as complementary additions to the essentially structural solutions to flood control, in order to reduce costs and enhance efficiency. The Workshop marks an important shift in these perceptions: it has become obvious, that the approach to flood damage reduction is increasingly non-structural: structural, engineering solutions appear as indispensable complements to the essentially non-structural, integrated water resources management, of which flood damage reduction is but an integral part.

Typically, most of the papers presented at the Workshop, concerned flood damage reduction; though, besides the well-established, traditional non-structural measures, such as zoning, flood proofing, early warning, emergency planning, flood insurance, etc., the Workshop reflected a much broader context, embracing activities such as planning, systems approach to decision making, networking, etc., all made possible through advances in computer sciences and communications.

Several papers dealt with aspects of water resources management other than flood damage reduction, and the ensuing discussion endorsed the broad perception of non-structural measures. Measures so far qualified as non-structural, could well be called the software of water resources management. Even far reaching societal actions, such as population control, and reducing water demand for excessive consumption, might in a way be considered as non-structural aspects of sustainable water resources management, in the broadest sense.

Time will only show the real impact of the Workshop on the water profession; yet, to the participants at least, the London/Ontario Workshop appears as a landmark in the perception of non-structural measures: from now on, the traditional non-structural measures must be seen only as an aspect of integrated water resources management, an inter-disciplinary activity, where natural, engineering and social sciences meet, supporting societal decisions, and interacting with political governance.

Closing note: Expected follow-up within the IHP

The IHP begins this year its Sixth Phase (2002-2007), with the general theme dedicated to *water interactions, systems at risks, and social challenges*. At the transition from the Fifth into the Sixth Phase, the London Ontario Workshop may have a direct influence on certain aspects of how the new phase will develop. The Workshop's proceedings and results fit well into the general theme, and also cut across all the planned activities. In particular, they are relevant to Theme 4 that *"focuses on the complex relationships between people and their water resources."* The main activities within the Theme cluster around five focal areas, and it is easy to see, that all of them strongly correlate with the Workshop. It suffices to quote here their titles:

Theme 4: Water and Society

Focal areas:

4.1 Water, civilization and ethics
4.2 Value of water
4.3 Water conflicts - prevention and resolution
4.4 Human security in water-related disasters and degrading environments
4.5 Public awareness raising on water interactions

The participants of the Workshop, as well as readers of the proceedings, will immediately realize how the papers and discussions at the Workshop are relevant to all the above topics. It is to be expected that all those who will work on the IHP-VI, will find inspiration and motivation in the articles that follow.

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Non-structural Flood Protection and Sustainability

By

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Abstract: Flood protection is considered in the sustainability context. On the one hand, floods destroy human heritage and jeopardize sustainable development, whose one definition refers to "non-decreasing quality of life". On the other hand, following the most common interpretation of sustainable development, one should not choose flood protection policies, which could be rated by future generations as inappropriate options of flood defence. This is how several large structural flood defences are often looked upon. A category of non-structural measures agree better with the spirit of sustainable development, being more reversible, commonly acceptable and environment-friendly. Among such sustainable measures are: source control (watershed / landscape structure management), laws and regulations, zoning, economic instruments, efficient flood forecast-warning system, system of flood risk assessment, flood-related data bases, etc. As a flood safety cannot be reached in most vulnerable areas with structural means, further flood risk reduction via non-structural measures is usually indispensable, so a site-specific mix of structural and non-structural measures seems to be a proper solution. Since sustainability concern requires thinking about the future generations, the climate change issue comes into picture. Non-structural measures lend themselves well to application in climate change adaptation strategies. As uncertainty in assessment of impacts of climate change is high, flexibility of adaptation strategies is particularly advantageous.

Key words: flood protection, non-structural measures, sustainable development, sustainability criteria, risk management

Introduction

Since the dawn of civilisation, destructive floods have jeopardised settlements located in river valleys and plains. Despite developments in technology and extensive investments in flood control works, flood occurrences and accompanying hardship and material damages are not decreasing. Just the opposite! Now, the global flood losses have grown worldwide to the level of billions of US dollars per year. According to the Red Cross, floods in 1971-1995 affected more than 1.5 billion people worldwide, including 318 thousand killed and over 81 million homeless (IFRCRCS, 1997).

Based on the data presented by Berz (2001), one could state that the number of great flood disasters (understood as those where the ability of the region to help itself is distinctly overtaxed) has grown considerably worldwide (cf. Fig. 1). The number of great flood disasters in the nine years, 1990-1998 was higher than in the three-and-half decades 1950-1985.

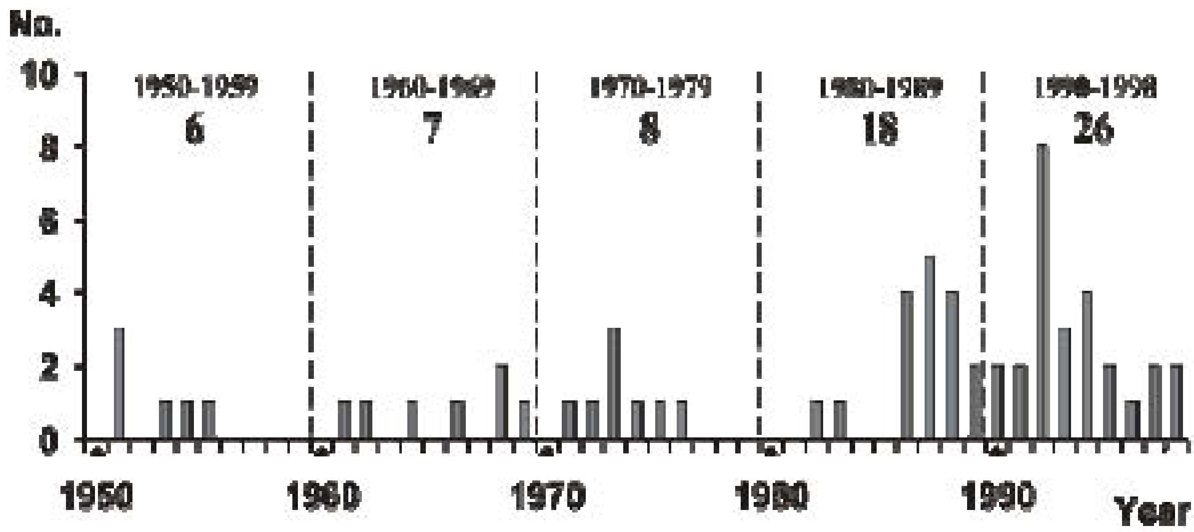

Figure 1. Number of great floods worldwide in the time period 1950-1999

In the 1990s, there were two dozens flood disasters in each of which either the material losses exceeded one billion US dollars or the number of fatalities was greater than one thousand, or both (Kundzewicz & Takeuchi, 1999). In a storm surge flood in Bangladesh in April 1991, 140 thousand people lost their lives, while material losses, of the order of 30 and 26.5 billion US dollars, were recorded in China in the 1996 and 1998 floods, respectively.

Vulnerability of societies grows as they become wealthier and more exposed - technology helps populate more “difficult” areas. Vulnerability to floods can be regarded as a function of exposure and adaptive capacity (cf. IPCC, 2001a). All three have been increasing (and are likely to continue to rise). However, since exposure grows faster than adaptive capacity, the vulnerability growth is not slowing down. The rise in exposure has largely been caused by human activity, e g. elimination of storage: wetlands and natural vegetation; and encroachment of infrastructure in floodplains. According to Newson (1997), one sixth of all urban land in the USA lies within the 100-year flood area. The 1998 flood inundated over two-thirds of the area of Bangladesh. Around ten per cent of population of such countries as the USA and UK live within the 100-year flood area, while in Bangladesh, this portion is very much higher.

On the top of direct human impacts, also climate change is likely to contribute to the increase in flood risk.

Floods are natural events and will continue to occur in the future - one can never achieve complete safety. Yet, the flood risk can be seriously restricted, if an appropriate preparedness system is built, meeting the constraints of sustainable development - the principle guiding development policies in many countries.

Structural and non-structural flood protection measures

There exists a roster of strategies for reducing flood losses by flood protection and management shown in Box 1, together with examples of particular activities.

BOX 1. Strategies for flood protection and management

(1) modify susceptibility to flood damage (actions taken before flood)

legislation, land-use planning and management, zoning - delineation of areas where certain land uses are restricted or prohibited, development control of flood hazard areas leaving floodplains with low-value infrastructure, e. g. riparian forests which are subject to frequent flooding, buy-out of land and property located in floodplains – stimulating relocation, flood proofing **(by elevation, barriers, or sealing i. e. water-proofing of parts of buildings or individual appliances)**, disaster contingency planning, flood forecasting and warning systems, flood insurance schemes, awareness raising: improving information and education on floods and on actions to take in a flood emergency, community self-protection teams

(2) modify flood waters

flood defence infrastructure: dams and flood control reservoirs, flood dikes, diversions, floodways, improvement of channel capacity to convey a flood wave, enhancing source control via watershed management, enhancing storage - floodplains and wetlands, polders and washlands, enhancing infiltration – permeable pathways and parking lots, etc., vegetation management (afforestation, cropping pattern avoiding bare soil during precipitation season), terracing and contour ploughing.

(3) modify impact of flooding (during and after flood)

detection of the likelihood of a flood forming, forecasting of future river stage / flow conditions, warning issued to the appropriate authorities and the public on the extent, severity and timing of the flood, dissemination of warning, response by the public and the authorities, evacuation, financial aid (insurance claims, loans, tax deduction, debt reduction), relief for those affected by the disaster, reconstruction of damaged buildings, infrastructure and flood defences, post-flood recovery and regeneration of the environment and the economic activities in the flooded area, review of the flood management activities to improve the process and planning for future events (links to (1) and (2))

In bold: lumped, large-scale structural measures

It is common to assume that flood protection measures can be structural („hard") or non-structural („soft"). Structural defences have a very old tradition, as dams and dikes have been built since at least four thousand years. Nearly all floodplain areas in Hungary (about a quarter of the country) are protected by river dikes. Constructing reservoirs where the excess water can be stored allows a regulated temporal distribution of streamflow and helps alleviate the flood problem by flattening destructive flood peaks.

However, it is quite a common interpretation that the term "structural" refers to large-scale defences, such as dikes, dams and flood control reservoirs, diversions, floodways, etc and channelisation improving channel conveyance capacity (widening, deepening, realignment, bank protection, etc). Then, distributed, small-scale, structural approaches, such as flood proofing, are also regarded as soft approaches, which could be rigorously labelled as a category of "non-structural and small-scale structural measures".

An efficient flood preparedness system should embrace solutions to a plethora of problems, which may happen. One should anticipate problems to avoid failure at emergency. Elements of concern embrace a myriad of issues, ranging from additional capacity for mobile, cellular phones, which fail to work satisfactorily subject to a massive use in a flood situation; to appreciation that married Muslim women, if alone at home, may not react to a flood warning.

Flood forecasting and warning

This is a very important non-structural flood protection measure. Thanks to flood forecasting and warning systems, it is possible to save lives. Forecasting, based on mathematical modelling, allows experts to convert the information on the past-to-present rainfall, status of moisture and snow cover into a river flow forecast (discharge, stage, and inundated area for a future time horizon). For small catchments and flash floods, there is a very short time lag between an intense precipitation and the flood peak. Therefore deployment of radar and quantitative precipitation forecast is necessary. Routing a flood wave in a large river may take several weeks, allowing for ample time for response to flood forecast. There are many attempts to improve the forecast accuracy and to extend the time horizon for a meaningful forecast. One of challenging avenues is to make use of atmospheric-oceanic-hydrological links.

Watershed management

An important flood protection measure, modifying formation of floodwater, is the source control. This concept belongs to a broader category of watershed management including land use and soil conservation to minimize surface runoff, erosion and sediment transport, e. g. by terracing and contour ploughing, vegetation cover management and afforestation. The idea of "catching water where it falls" is implemented by such measures as enhancing infiltration, reducing impermeable area, enhancing storage, e. g. by ponds, artificial storages (cf. Kundzewicz & Takeuchi, 1999). Enhancing retention counteracts such adverse effects of urbanisation as drop in storage potential, growth of flood peak, drop in time-to-peak of a hydrograph. Watershed management should also include increase of storage in the river system (floodplains, polders, washlands).

Insurance, aid and post-flood recovery

Existence of appropriate schemes of insurance, that is distribution of risks and losses over a high number of people and long time; and aid, that is capacity to compensate burning losses not covered by insurance, are important components of flood preparedness. These mechanisms are needed in order to help flood victims recover after losses and regain livelihood.

Post-flood recovery is an important element of the flood preparedness system; often less spectacular, as prime minister left the natural catastrophe area and media are not interested. Yet, the life must go on, despite the trauma and destruction. Disaster aid, based on voluntary solidarity contribution, national assistance, and international help, is essential to restore livelihood and employment of survivors.

Several measures of flood preparedness, such as structural means: levees, dams, but also insurance and post-flood aid can induce a counterproductive effect. One of common misconceptions is the following: if a costly flood defence infrastructure is in place, the flood protection problem is solved for now and forever, unless the defence is not adequately maintained and hydrological variables are not monitored appropriately. Structural means raise a false feeling of safety and weaken preparedness and vigilance. Existence of insurance at a flat rate (with no franchise) and aid mechanism may result in weakening protective activities during a flood (e. g. placing valuable mobilities in higher, safer places). Risk taker should bear real financial responsibility. Compulsory insurance of all households, without differentiating a flood hazard, at flat premium rate is unfair to no-risk-owners. Existence of generous government aid or insurance schemes may enhance settlement in hazardous zones, encouraging the affected individuals to remain in vulnerable areas. Otherwise they may consider leaving, especially if there is an incentive, such as a programme of buying land and property in floodplains (e. g., for re-establishment of wetlands).

Relocation

A saying goes that if people build in a floodplain, there is no solution. Definitely, precautionary measures, such as zoning and regulation of floodplain development, are advantageous. However, if endangered locations have already been developed, a remedy is that humans, and infrastructure, move out of harm's way. After the Great Flood of 1993, the US Interagency Floodplain Management Review Committee (cf., IFMRC, 1994,. Galloway, 1999) recommended that the administration should fund acquisition of land and structures at risk from willing sellers in the floodplain. The number of families relocated from the vulnerable floodplain locations in the Mississippi Basin is of the order of 20,000 (Galloway, 1999), and further growing.

However, despite the encouraging example from the USA, mentioned above, permanent evacuation of floodplains is unthinkable in Bangladesh - a densely populated (an average farm size is below 1 ha) and low-lying country, virtually the most flood-prone country of the globe. The nation of Bangladesh indeed has to live with damaging floods. Most of the country area is constituted by floodplains whose soil fertility depends on flood visits. New flood embankments, even if they were affordable, would take much of this, highly demanded, land. Thus, reinforcing of the existing structutal defences and enhancing non-structural measures, such as forecast-warning system, and awareness raising seem worthwhile.

In the global scale, an essential self-sustaining measure is benign population growth management, attainable by the family planning and fertility reduction through improving living standards. If there were less demographic pressure, floodplain settlement would be more constrained.

Sustainable developments – notions and interpretation

Although the notion of "sustainable development" has been broadly used nowadays, there is no common understanding of this term and the concept may still mean different things to different people. The term serves a variety of targets, being used and abused as a convenient argument to justify, to support, or to criticize actions (or lack of actions), decisions, etc. Because of ambiguity, it is not possible, to delineate the borders between "sustainable" and "non-sustainable" in a unique way, though one can demonstrate examples, which can be rated as clearly sustainable or clearly non-sustainable.

In fact, the idea behind "sustainable development" is quite old, having been used in management of renewable natural resources to ensure that the rate of harvesting a resource is smaller than the rate of its renewal.

Sustainable development embraces a blend of objectives, being economically feasible, socially acceptable and environmentally sound (Takeuchi *et al.*, 1998). A sample of specific objectives read: in the economy area - growth, efficiency, equity-fairness, in the social area - participation, empowerment, culture, tradition, institutional development, and in the environmental area - ecosystem health and integrity, conservation of nature, respecting the carrying capacity, biodiversity. In all these areas, the notion contains resilience to surprise or shock, therein to climate variability and change, and to violent abundance of destructive floodwater.

There exist a number of alternative definitions of sustainable development, sample of which are presented in Box 2.

BOX 2. A sample of definitions of sustainable development

assuring that the development meets the needs of the present generation without compromising the ability of future generations to assuring their own needs (WCED, 1987);

living on the "interests" from the Earth "capital" without depleting the possessions inherited from former generations (cf. Kundzewicz *et al.*, 1987);

improving the quality of human life (attaining non-decreasing human welfare over time) within the carrying capacity of supporting ecosystems (IUCN, 1991);

keeping dynamic equilibrium of the Earth system over a long (theoretically - infinite) time;

property of the system whose essential features remain within satisfactory domain over a long time;

discounted present value of the cost of curing the consequences of present actions being less than the extra cost of taking preventive actions in the present;

development minimizing probability of future regret for decisions taken today.

In order to monitor the progress towards sustainable development one needs a set of suitable criteria and indicators assisting one to steer action, to make decisions and to increase focus on sustainable development. Yet, despite numerous proposals, there exists no commonly accepted set of criteria and indicators.

Flood protection in sustainability context

It is worthwhile to view flood hazard mitigation in a broader context, as a part of a general sustainable development strategy.
A common interpretation of sustainable development is that civilisation, wealth (human and natural capital) and environment (built and natural) should be relayed to future generations in a non-depleted shape. That is, civilisation and wealth should be protected, *inter alia*, from devastating floods, which destroy cultural landscapes and undermine sustainable development by breaking continuity.

Another aspect of the definition of sustainable development is that, while flood protection is necessary for the present generation to attain a fair degree of freedom from disastrous events, it must be done in such a way that future generations are not adversely affected. Brooks (1992) stated that a minimum requirement for general sustainability is that "one does not paint oneself into a corner from which retreat is either impossible or unaffordable". According to the UK Environment Agency (1998, p. 9), sustainable flood defence schemes should "avoid as far as possible committing future generations to inappropriate options for defence". Many objects of flood protection infrastructure have been criticised in the context of sustainable development as solutions closing options for future generations and introducing unacceptable disturbances in ecosystems (cf. Takeuchi *et al.,* 1998).

Soft measures, which do not involve large structural components, can be rated as more sustainable than hard measures, yet the latter may be indispensable in particular circumstances.

However, soft, non-structural measures alone cannot provide a satisfactory solution in flood-vulnerable countries. Structural defences are needed in Bangladesh and in Japan. Strategy for major cities along large rivers in Japan, where absolutely no embankment collapse is allowed, includes protection by large-cost structural measures, “super levees”, which are high and 300-500 m wide (cf. Kundzewicz & Takeuchi, 1999). They protect considerable wealth accumulated in urban areas of Japan. On the other hand, distributed, small-scale, structural measures, such as source control, flood proofing, building codes, extending permeable areas etc, are regarded as sustainable.

One could consider which indicators lend themselves to assess sustainability of a flood protection scheme.

One can take recourse to a general proposal of four conceptual criteria for evaluation of sustainability, that is: reversibility, fairness, risk and consensus, recommended by Simonovic (see Takeuchi *et al.,* 1998), which are all relevant in the context of flood defences.

Reversibility is not a strong feature of large, structural flood defences. Yet, there have been several examples of decommissioning of dams and of intentional removal of dikes (renaturalisation of rivers). The cost of transformation of an engineered system to the original unengineered state can be predicted.

Fairness or equity means that flood protection should be extended to all members of the society. Difference in vulnerability to floods between neighbouring households can be high, especially in less developed countries. Wealthy households may receive flood warning on the radio and can escape by their vehicle, whereas poor families, deprived of the warning, may remain on the site and suffer death and total destruction of their houses and belongings.

Risk is typically understood as a product of (low) exposure (alternatively – probability of failure), and (high) consequences. The concept of risk can be illustrated in the context of structural flood defences. Dikes may provide excellent protection against more frequent small-to-medium floods, yet their existence creates a false feeling of absolute safety and may trigger intensive development of low-lying areas. If a dike breaks, this defence does not act as a protection, but rather as an amplifier of damage; flood losses without a dike would have been lower.

Consensus means that stakeholders - involved and affected parties should agree as to the programme of flood protection and management. Yet, striving for absolute consensus can suffocate decision-making.

One could add to these criteria a measure of efficiency and synergism; e.g. a multi-purpose reservoir may also have a number of functions related to sustainability: flood protection, water supply, waterpower, navigation, etc.

Takeuchi *et al.* (1998) devised a sustainability checklist for reservoirs evaluating four aspects: efficiency in use of existing reservoirs; the magnitude of marginal environmental impact; the degree of democratic decision making; and the mitigation measures, to minimize the negative environmental effects and ensure the quickest recovery of the damaged ecological system. The checklist refers to all stages of development, that is planning and design; construction; and operation and maintenance of a storage reservoir. There are broad subject areas to check: conservation of nature; inter-; and intra-generational equity; efficiency; and integrated water resources management. A checklist proposed by Takeuchi *et al.* (1998) in the reservoirs context, can be also used to examine other structural means of flood protection.

A least marginal environmental impact rule, as advocated in Takeuchi *et al.* (1998), suggests that the option selected, while yielding the same level of satisfaction of the principal objective, should have minimum adverse environmental effect as compared to alternative options.

Another checklist has been devised by the Delft Hydraulic Laboratory (see Loucks, 1995). It embraced five main criteria, which are subsequently divided into four sub-criteria each. The main criteria, which can be used to evaluate flood protection systems, read:

- socio-economic aspects and impacts on growth, resilience and stability;
- use of natural and environmental resources including raw materials and discharge of wastes within the carrying capacity of natural systems;
- enhancement and conservation of natural and environmental resources;
- public health, safety and well being;
- flexibility and sustainability of infrastructural works, management opportunities for multi-functional use, and opportunities to adapt to changing circumstances.

Gardiner (1995) compared options of flood defence and assessed their performance from the sustainability viewpoint. He suggested using four groups of criteria, which related to global environment (resilience to climate change, energy efficiency, biodiversity), inter-generational equity (retention of strategic adaptability / future options), natural resources (quantity and quality of surface water and groundwater, wildlife habitat) and local environment quality (morphological stability, landscape and open land, recreation and amenity and enhancement of river environment). In his rating, source control received very good marks in all categories, while channelised river was found bad to very bad according to all criteria. He also noted that, among the many advantages of source control, it conserves resources, buffers systems from possible climate change impacts, conserves energy through increasing retention “at source”, promotes biodiversity by retaining water, improves self-sufficiency and recharges groundwater.

Criteria, indicators and checklists could be used to compare options for flood protection. Usually, there exist a spectrum of means to achieve a development target of concern, with differing values of quality criteria. Each alternative may have its advantages and disadvantages. One has to evaluate the alternative means and weight their pros and contras (not only short-term benefits but also long-terms impacts and side effects) in a possibly objective way. The viable alternatives should be revealed, made transparent to the stakeholders, subject to public discussion and, finally, the decision as to how to solve the problem should gain support of the society.

Examples of quality indices which could be used for comparing flood protection measures may relate to socio-economic and financial feasibility, related investment and operational costs; degree of intervention in the natural regime, stress to ecosystems and humans, use of energy and raw materials, and safety, risk and reliability issues, and opportunities for reversibility (flexibility) and rehabilitation (Kundzewicz, 1999). Table 1 shows a roster of components of flood preparedness system and the author’s rough assessment of their compliance with the spirit of sustainable development.

Table 1. Compliance of components of pre-flood preparedness with the spirit of sustainability.

Flood preparedness measures	Compliance with sustainability
Construction of large physical flood defence infrastructure	L to M
Zoning, development control within the floodplains	M to H
Source control, land-use planning and watershed management	M to H
Flood forecasting and warning system	H
Flood proofing	L to H
Disaster contingency planning and maintenance of preparedness of community self-protection activities	H
Installation of insurance scheme	L to H
Capacity building, improving flood awareness, understanding and preparedness	H

Notation: H – high, M – medium, L – low.

Information for sustainable development

Information about flood(s) is a very important, non-structural, element of the flood protection system. Examples of such projects for which hydrological information is indispensable comprise flood protection infrastructure (dikes, dams, reservoirs, spillways, floodways, canals, etc.), as well as non-structural approaches such as zoning, insurance, legislation, etc.

The water storage reservoir is the basic component of water management. It serves multiple purposes, flood protection being one of them. Hydroclimatic information plays a significant role in both reservoir design and operation. In the design phase, estimating of the necessary reservoir capacity and the size of spillway has to be done based on the available hydrological data. Long time series of records are necessary to detect slow (e. g. caused by climate change or land use change) tendencies that can significantly influence flood protection. Finally, during flood, a need for real-time information arises for flood forecasting and warning.

In order to minimize the chances of non-satisfactory design, construction or operation of water systems, an adequate level of basic data collection is required. The basic hydrological network should therefore provide a level of hydrological information that would preclude gross mistakes in decision-making related to freshwater. Therefore, hydrological observations should be recognized as an essential component of sustainable development and management of water resources (Kundzewicz, 1997, 2001).

The numbers of hydrological stations in operation, as reported by the WMO Member countries, are high and impressive. According to WMO (1995), there are nearly 200,000 precipitation gauges operating worldwide. At over 64,000 stations discharge is being observed and at nearly 38,000 - the water level. However, these comforting global totals are misleading – the hydrological observation networks are not uniformly distributed, with acute lack of data in some regions. Furthermore, due to financial stringencies in many countries, hydrological services and data collection networks are shrinking and are not able to provide the information needed for flood protection.

Given that important decisions nowadays need to be made under vast uncertainty, it is rational to try and reduce this uncertainty, by collecting observational data characterizing the natural, and man-influenced, processes and the state of the environment. Acquisition of data and information undoubtedly belong to sustainable measures. They help increase understanding and awareness of floods, and enhance capacity building for better preparedness in the future.

Awareness raising

Improving information about floods is badly needed for awareness raising and enhancing the consultative process, which leads to a flood protection strategy. Only informed stakeholders can make rational decisions about strategies of flood protection, making otimal choice in cost-benefit framework; with the account of sustainability issues.

Yet, misconceptions and myths about floods and flood protection are deeply rooted in the society – not only general public, but also politicians and decision-makers. It is of utmost importance to dispell and to rectify misconceptions, such as those collected in Box 3. Apart from misconceptions, there are unfortunate “principles”, valid throughout political and social systems. Klemes’s rule of hydro-illogical cycle is a point in case – flood occurrence triggers high expenditures on flood protection. Yet; memory fades and after some time without flood, the willingness to pay drastically decreases. How to communicate this truth to electorate and decision-makers with a short term of office?

Efficient actions aimed at awareness raising are of vast importance for a flood preparedness system. Among over 50 fatalities of the 1997 flood in Poland, many could have been avoided, were the awareness better. Most flood fatalities in the US are related to vehicles whose drivers underestimate the danger.

A difficult, yet much needed thing in the dialogue of experts and the public is the communication of uncertainty.

Role of media in awareness raising and information is worthy of interest. Not always the freedom of press matches responsibility. A particularly bad example is embedding flood mitigation into a political campaign.

Apart from collecting data and building flood-related databases, information can be generated by modelling. Mathematical models do not only serve forecast systems. They are indispensable for improving general understanding – simulation of events, analysing efficiency of policies and measures, what-if studies, etc. Flood risk mapping, typically in a GIS framework, conveys valuable spatial messages. Yet, in a number of cases, flood risk maps, solicited by authorities, have not been disseminated – the consequences would be unbearable for the ruling powers.

Looking into the past – sustainability perspective

Flood losses worldwide have been increasing with time. It has been so for a number of reasons, such as myriads plethora of locational decisions related to settlements and economic development of flood-prone areas (floodplains, coast). Floodplains indeed attract development due to their flatness, high soil fertility, proximity to water and availability of construction materials. Human pressure and shortage of land cause the tendency of encroaching into floodplains, and investing in infrastructure there. In such a way, much of natural flood storage volume is lost, ecosystems are devastated and riparian wetlands destroyed.

BOX 3. A sample of common misconceptions about floods and flood protection.

Flood protection systems, which are in place, warrant absolute safety. If levees and dams cost that much money, they must withstand great floods!

Floods occur at semi-regular intervals. This misconception results from a common layman's interpretation of the notion of "100-year flood". In consequence, many naively believe that once a 100-year flood has occurred recently, the next deluge will not come in a human lifetime. (A separate misconception is a deep belief that one can reliably estimate what will be a 100-year flood.)

Stationary world: geophysical processes in the future will be similar to those in the past. Having lived in a place for a while one can get a feeling of what can be expected. Some find it hard to appreciate that a flood wave may have dimension considerably exceeding all events on record.

Floods do not happen at all rivers. They happen frequently in "wet" areas, such as Bangladesh, etc. It is less appreciated that destructive floods occur also in arid and semi-arid zones, where the population is unprepared.

Urbanization has adversely influenced flood hazard in many watersheds. Increase in the portion of impervious area (roofs, yards, roads, pavements, parking lots, etc), deforestation and regulation of watercourses result in faster and higher peaks of runoff responses to intensive precipitation. In mountainous areas, development extends to hilly slopes, which are endangered with landslide and debris flows. High vulnerability to flooding is a feature of mushrooming urban squatting.

Important discussion of strategy of flood protection dates back to the mid-XIXth century USA (cf. Williams, 1994), when the US Congress looked into the problem of the Mississippi floods. One expert recommended that large areas of the Mississippi floodplains be used as flood storage and overflow areas, but the US Congress heeded another expert who recommended embanking the Mississippi river in a single channel isolated from its floodplain. This decision has largely influenced flood protection policy in the USA and was followed worldwide for more than a century, leading to transformation of rivers and reduction of wetlands. Thomas (1995) noted that 54% of the wetlands area in the USA have been drained, primarily for agricultural use. In 1936, the US federal government assumed primary responsibility for flood damage reduction across the nation and over the next 40 years embarked on a multi-billion programme of structural defences (Galloway, 1999).

In the absence of well agreed upon quantitative criteria and indicators measuring sustainability, a retrospective view is useful. What heritage of the past is not liked by our generation? What elements of flood protection systems are being criticized? Which acts of past generations does our generation regret?

Definitely, changes leading to aggravating flood risk are perceived as negative. In some locations, the present generation regrets that past generations built levees and developed low-lying areas. Now, the issue of river renaturalization may come about. Some large reservoir, whose construction required inundation of large areas and/or displacement of high number of people, do not match the principles of sustainable development. Studies on decomissioning reservoirs are being made and in a few cases indeed decommissioning has taken place (cf. Takeuchi *et al*., 1998).

When looking back into past developments, one often finds one-sided arguments supporting a decision, with important aspects neglected. This was, on the one hand, due to lack of knowledge and understanding and, on the other hand, since value judgment changed in time.

Looking into the past, one can identify a monument-building syndrome accompanying some large-scale flood defences under several totalitarian regimes. Wittfogel (1975) studied total power and concluded that designations “hydraulic society” and “hydraulic civilization” can be used, due to the role of large-scale water-related infrastructure. A distinct feature of such civilization is the existence of large-scale flood protection to safeguard lives and crops from destructive inundations. As noted by Wittfogel (1975), in major hydraulic civilizations, large irrigation schemes are supplemented by and interlocked with protective works for the purpose of flood control. „Hydraulic” societies had to provide labour for „hydraulic” service - construction and maintenance of embankments, flood watch and fight. The resulting regime was decisively shaped by the leadership and social control required by „hydraulic” (i. e. irrigated) agriculture. Wittfogel (1975) expressed the opinion that disciplinary measures involved in flood protection did much to strengthen the power of a government.

Climate impact assessment

The process of river flow has been heavily influenced by direct changes caused by man, discussed earlier.
Other changes may have been caused by man in an indirect way, e.g. through enhanced emissions of greenhouse gases resulting in the global warming and the related effects.

The possibility of climate variability and change may add another dimension to sustainability notion. As sustainable development considerations refer to the future (prospects of future generations), climate changes, which are slow at present but may accelerate later, are of substantial concern. There are a number of cases when the recent behaviour of time series of hydrological variables largely differed from the historical patterns. Many scientists attribute a part of these changes to the anthropogenic impact on the natural climatic system; the growing greenhouse effect and the corresponding climate change. Increasing severity of extreme events has been detected recently in a number of locations and some experts have reported considerable local shortening of recurrence intervals of a given flood magnitude. Insurance industry is being concerned with the increase of compensations following natural water-related disasters. If the climate change goes on, existing infrastructure may not guarantee the adequate level of protection.

However, it is difficult to find a gradual change (e. g., related to climatic impacts) in the behaviour of the extremes of river flow, amidst strong natural variability. Global temperature rise generally enhances accelerating the hydrological cycle. Runoff is a difference between precipitation and evapotranspiration (whose annual means have been increasing, and are projected to continue to increase over most areas), so the net effect on their difference is not intuitively clear. In order to detect a weak, if any, climate change component, it is necessary to eliminate other influences, using data from baseline river basins.

Apart from the inherent complexity of the issue of detecting a greenhouse component in flow records, there are serious problems with the data with which to work, and also with the methodology to detect changes (cf. Radziejewski *et al.*, 2000).

But, even if the data are perfect, it is worthwhile to re-state a tautology: extreme (hence rare) events are rare. They do not happen frequently, so even having a very long time series of instrumental records one deals with a small sample of truly extreme floods, of most destructive power (Kundzewicz & Robson, 2000).

What have observed data been telling us?

It is a well-established fact that the effects of human pressure have aggravated flood risk. Development of low-lying areas at risk has continued and the storage capacity of catchments has decreased. As noted by Bronstert (1996), urbanization is particularly influencing small or middle size floods – the urbanized area in West Germany more than doubled from 6% in 1950 to approximately 13% in 1995.

Is there a climate change signature in flood data? Existing prognostications anounce increasing frequency and severity of floods in the future warmer world with accelerated hydrological cycle. A question can be posed: how do these prognostications fare in the context of the evidence provided by the already observed data?

According to IPCC (2001), instrumental records of land surface precipitation continue to show an increase over much of mid- and high latitudes of the Northern Hemisphere. Furthermore (IPCC, 2001), it is very likely that in regions where the total precipitation has increased, there have been even more pronounced increases in heavy and extreme precipitation events. The converse is also true. Moreover, increases in heavy and extreme precipitation have also been documented even in the regions where the total precipitation has decreased or remained constant (number of days with precipitation decreasing stronger than the total precipitation volume).

Increases in heavy precipitation events can arise from a number of causes, e. g. changes in atmospheric moisture, thunderstorm activity and large-scale storm activity. Observations confirm that atmospheric moisture is increasing in many places. For example, growth at a rate of about 5% per decade was observed in the USA (Trenberth, 1998). Increased atmospheric moisture contents favours more intensive precipitation events thus increasing the risk of flooding.

Trends in precipitation in the 20th century show indeed marked increase of precipitation, especially in winter, in much of Europe, in particular North and Northeast. There are numerous studies restricted to a single drainage basin or a country, corroborating these findings. For instance, there is evidence that the frequency of extreme rainfall has increased in the UK (IPCC, 2001a) and a greater proportion of precipitation is currently falling in large events than in earlier decades (Osborn *et al.*, 2000). Karl *et al.* (1995) noted that within the United States, the proportion of total precipitation contributed by extreme one-day events has increased significantly during the 20th century. The incidence of intensive precipitation events has steadily increased at the expense of moderate events.

As far as the river runoff is concerned, there have been a plethora of studies of time series at a single stream gauge, reported in the literature. Several reports of significant changes detected in flow records at a single gauge encouraged researchers to extend the analysis into a spatial domain, to check whether or not a pattern observed at a single gauge has been reproduced in the neighbouring locations. Yet, it would be a gross oversimplification to say that, in general, floods have exhibited growing trends worldwide. Only some series show a significant trend and out of those only some (yet, typically more than half) feature a growing trend. It is not uncommon that neighbouring gauges behave in a different way. The time series of flood data show a complex response (due to other, non-climatic factors), not necessarily in tune with gross climate-related prognostications.

A sample of findings obtained in analysis of long time series of data is presented in Table 2. After IPCC (2001a), the costs of extreme weather events have exhibited a rapid upward trend in recent decades and yearly economic (inflation-adjusted) losses from large events have increased ten-fold between 1950s and 1990s. The insured portion of these losses has grown even stronger. Demographic and socio-economic trends are increasing society's exposure to floods and part of the observed upward trend in weather disaster losses is linked to socio-economic factors, such as increase in population, wealth, and developing settlements in vulnerable areas, but these factors alone cannot explain the observed growth in losses.

As stated in IPCC (2001a, Chapter 8), a part of losses is linked to climatic factors, such as the observed changes in precipitation and flooding events. Even if precise attribution is complex, the growth in losses caused by non-weather-related natural disasters has been far lower than of weather-related extreme events.

Table 2 A sample of findings on trends in existing flow data reported in literature.

Source	**Location**	**Time interval**	**Finding**
Engel (1997)	Rhine at Cologne	1890 to 2000	Positive trend in annual maxima.
Nobilis & Lorenz (1997)	Austrian rivers	1952-1991 and shorter periods	Only in a portion of cases (from 4.3% to 31.5 %), a significant trend was detected, therein more examples of positive trend (64.3%) than of negative trend (35.7%).
Gilvear & Black (1999)	River Tay in Scotland	1988/9 *versus* 1996/7	Growth of flood-induced embankment failures.
Mansell (1997)	Four catchments in Scotland	Last 30 years	General increase in river flow, significantly stronger than the increase in rainfall over the same period.
Robson & Reed (1996)	Ca. 600 stream gauges in the UK	Long data series (from 15 to over 100 years)	Some regional features visible in the results. More incidences of increased flooding than decreased flooding, particularly in Scotland and in South East of England.
Olsen *et al.* (1999)	Rivers: Upper Mississippi, Lower Missouri and Illinois	Long series (up to nearly 120 years)	In many gauges, large and statistically significant upward trends were detected.
Lins & Slack (1999)	Ca 400 stream gauges in the conterminous U. S.	30-, 40-, 50-, 60-, 70-, and 80-year periods, all ending in 1993	For all, but the highest quantiles, streamflow has increased across broad areas of the US. These results were summarized as ”getting wetter, but less extreme”.

Pielke & Downton (2000) studied the rates of change in flood characteristics and socio-economic indicators in the USA in the time period from 1932 to 1997. They found that the total annual flood damage, adjusted for inflation, has grown in the average with the rate of 2.92% per year, that is more strongly than population (+1.26%) and tangible, inflation-adjusted, wealth per capita (+1.85%).

An important change observed in flow data refers to seasonal characteristics. River flow regimes, i. e. temporal distributions of flow, have considerably changed. It was reported from much of Europe that high flows come earlier in the year due to earlier snowmelt (sometimes in winter rather than spring) and lower snow cover may reduce the spring snowmelt floods. Milder winters lead generally to thinner ice cover, so ice-jam floods are not a major problem anymore in much of Europe.

Search for links of hydrological extremes with climatic variability is a challenging study area (e. g. oscillations in the oceanic-atmosphere system, such as El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Arctic Oscillations (AO)). The frequency and intensity of ENSO have been unusual since the mid 1970s, as compared with the previous 100 years, in the context of the instrumental record. Warm phase of ENSO episodes has become more persistent and intense (IPCC, 2001). In some regions, intensive precipitation (causing floods) occurs more frequently in the El Niño phase than in the La Niña phase, while in other locations, it is the other way round. There may exist a link between extreme flood events and the SOI anomalies.

The global average sea level rose by 10-20 cm during the 20th century, partly due to the thermal expansion of ocean water (steric rise) and the widespread loss of land ice associated with the 20th century warming. The average rate of the sea level rise in the 20th century was by order of magnitude larger than the average rate over the last 3000 years (IPCC, 2001). Rise of the mean state of the sea level clearly impacts on extremes. Increased frequency of flooding in Venice accompanied 30 cm relative sea level rise in the 20th century (IPCC, 2001a). After Cecconi *et al.* (1999), this relative sea level rise (approximately half due to subsidence, half due to an absolute sea level rise) has led to an increase in the number of floods (defined by threshold of 80 cm): from a few to ten occurrences per year in the early 1920s to over 30 in 1990s with the maximum exceeding 100 in 1996.

Storm surge data obtained from hourly tide gauge records in the US Atlantic coast show considerable increase over the 20th century in the number of hours of anomalous high water level (surges greater than two standard deviations) per year at Atlantic City, N. J. (Zhang Keqi *et al.*, 1997). Yet, no discernible secular trend was found in storm activity or severity.

Extreme events – projections for the changing climate

A significant portion of the increase of flood hazard has been caused by direct human pressure, which drivers will continue to be active in the future.

However, there are also several climate change related mechanisms, which may significantly influence flood characteristics. Characteristics of extreme climatic phenomena related to floods, can change in the future climate, in the light of scenario analyses (cf. IPCC, 2001 and 2001a). Among foreseen climate-related impacts relevant to floods are: increased magnitude of precipitation events of high intensity in many locations, more frequent wet spells in mid / high latitude winters, more intense mid-latitude storms, and more El Niño-like mean state of ENSO. Some models show increase of mean and peak intensity of precipitation and peak wind intensity of tropical cyclones (IPCC, 2001).

As stated by Cubasch & Kasang (2001), in regions with increasing precipitation, heavy precipitation will increase as well. The reason being that atmosphere´s capacity to absorb moisture, and thus its absolute water content, increases with temperature. Based on global model simulations and for a wide range of scenarios, global average water vapour concentration and precipitation are projected to increase during the 21st century. Hence, the potential for intensive precipitation, and likewise floods, will increase.

Precipitation extremes are projected to increase more than the mean. The frequency of extreme precipitation events is projected to increase over many areas (IPCC, 2001).
Arnell (1999) compared projected changes in precipitation across the world land areas. In all six scenarios considered, precipitation is expected to increase, globally, depending on the scenario; from 0. 6 to 3.4% in the 2020s, and from 2.1 to 7.5% in the 2080s, as compared to the climatological standard normals, 1961-1990. Arnell (1999) also noted an amplification effect in change in annual runoff, versus annual rainfall. He showed that many regions will feature considerable changes in 10-year return period maximum monthly runoff, noting increases in such areas as the northwest north America and in the east Asia.

Regional precipitation scenarios for winter developed under the ACACIA project (Parry, 2000), for the ACACIA A2-high scenario, show increases across most of Europe, while the median of annual precipitation grows in particular grids by up to 14% in 2020s, through up to 35% in 2050s and up to 53% in 2080s. Wetter winters are predicted throughout the continent, with two regions of highest increase: the Northeast and northwest Mediterranean coast, including northern Italy.

Climate change is likely to increase the risk of river flooding, and loss and damage generally in Europe. As stated in Chapter 13 of IPCC (2001): “[i]n more continental and upland areas, where snowfall makes up a large proportion of winter precipitation, a rise in temperature would mean that more precipitation falls as rain and therefore that winter runoff increases and spring snowmelt decreases. The timing of streamflow therefore alters significantly.” “In some areas the time of greatest risk would move from spring to winter.” In particular, winter flood hazard is likely to rise for many catchments under many scenarios. However, global warming may not generally reduce snowmelt flooding. Winter precipitation is going to increase, but in the areas where the temperature will still be below 0°C, the snow cover may increase. After IPCC (2001a, Chapter 15), “[p]ossible changes in runoff patterns, coupled with apparent recent trends in societal vulnerability to floods in parts of North America suggest that flood risks may increase as a result of anthropogenic climate change. Seasonal changes in flow are also expected, caused by changes in snowmelt accumulation and timing of snowmelt.” “Canadian rivers in northern areas may begin to experience winter ice break-ups and regional flooding.”

Sea level rise

Perhaps the sea level rise is the most important single climatic factor, which contributes to increasing (coastal) flood risk. A change in the mean level may exert significant impacts on the extremes and higher peak wind intensities may contribute to increasing severity of coastal flooding. Needless to say, that sea level rise itself is already a dangerous occurrence, which may lead to permanent inundations (including disappearance of whole small and flat islands) and the need of massive relocation.

Estimates of flood exposure and incidence for Mediterranean coasts in 1990s – 2080s, given in IPCC (2001), foresee a sea-level-rise driven increase of the average number of people experiencing flooding by 260 to 120 000 per cent, under assumption of no adaptation.

Conclusion: living with floods

Since a flood protection system guaranteeing absolute safety is an illusion, a change of paradigm is needed. It is necessary to live with the awareness of the possibility of floods and to accommodate them, rather than to try, in vain, to eradicate them. Kundzewicz & Takeuchi (1999) give examples of past implementation of the notion "living with floods" in the South-East Asia and Japan.

Important is building out flood and risk consciousness among the public. No matter how high a design („safe"?) flood is, there is always a possibility of having a greater flood, inducing losses. Should dikes be designed to withstand a 100-year flood or perhaps a 500-year flood? The latter solution would give a better protection, being far more costly. Yet, it may still turn out to be insufficient if a 1000-year flood arrives.

Such principles of sustainable development as "source control rather than end-of-pipe", "participatory approach", "subsidiarity principle", "precautionary principle", "working with nature rather than against nature" are of universal validity also for flood preparedness. One more flood-specific principle could be formulated as "risk taker pays" resulting from the fact that "living with floods" means taking risks consciously.

Despite criticism of structural flood protection mesures like dams and levees, they are absolutely needed to safeguard existing developments, in particular in urban areas. In developed countries, costly protection facilities can be in place, designed (say overdesigned) for a high, rare flood. Reinforced dikes, or super-dikes play an important part in flood protection of urban areas in Japan (cf. Kundzewicz & Takeuchi, 1999). An effective flood protection system is therefore a mix of structural and non-structural measures. Those latter approaches better conform to the spirit of sustainable development.

As stated by Smith & Ward (1998, p. 5): "[f]luvial channels can carry only a fraction of the flood flows so that the remaining must spill on to the floodplain. In flood conditions, therefore, channels and their adjacent floodplains are complementary and together form the proper conveyance for the transmission of floodwater. In many cases even major floods simply spill their waters on to unocuppied floodplains or "washlands" where they do little damage and may even be beneficial. Floods constitute a "hazard" only when human encroachment into flood-prone areas has occurred."

Discussion is offered of results reported in the literature for both analysis of the past data and of scenarios for the future, emphasizing the existing uncertainties. The general statement that high floods are becoming more frequent is supported by several studies, being challenged in analyses, where a frequency rise could not be distinguished, or when the finding was: "wetter but less extreme".

A regional change in timing of floods has been observed in many areas, with increasing late autumn and winter floods and less ice-jam-related floods. This has been a robust result. Yet, intensive and long-lasting precipitation episodes happening in summer have also led to disastrous recent flooding (e.g. the Odra / Oder deluge in 1997, cf. Kundzewicz *et al.* (1999)).
It is difficult to disentangle the direct anthropogenic and climatic component in the flood data subject to strong natural variability and influenced by man-made environmental changes: urbanization, deforestation, human occupying hazardous areas, reduction in storage capacity, etc.

All in all, future change of flood risk may be complex. In many places flood risk is likely to grow, due to a combination of anthropogenic and climatic factors. Yet, quantification of flood statistics is difficult and subject to high uncertainty. As stated in IPCC (2001, Technical Summary, "[t]he analysis of extreme events in both observations and coupled models is underdeveloped" and "the changes in frequency of extreme events cannot be generally attributed to the human influence on global climate." Some recent studies show that the flood hazard is likely to rise in the future and that plausible climate change scenarios result in future increases of both amplitude and frequency of flooding events. Yet, there has been no conclusive and general proof as to how climate change affects the flood behaviour, based on the data observed so far.

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Extreme Events in the New Brazilian Water Resources Management System

By

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Abstract: This paper will describe the recent changes in the Water Resources Management System of Brazil and its proposal on how to be more effective when dealing with extreme events. The geographic extent of the country, its regional differences, and the difficult economic conditions, lead to a comprehensive reform in the water resources sector in order to increase efficiency of the water uses, to reduce costs and to promote development. The major change occurred in 1997, with the promulgation of the National Water Resources Management Act, which established the National Water Resources Policy and the National Water Resources Management System. A primary strength of the new system is its decentralization. Different geographical regions of the country must cope with different extreme events. The developed South suffers with frequent flood events due to large urbanized areas and impervious floodplain areas and water scarcity due to excessive use. The rural Northeast is frequently devastated by severe drought periods with consequences such as migration and poverty. In both cases, the decentralized decision process is a powerful tool to better manage such problematic areas. In intermittent rivers of the Brazilian Northeast, participation of users associations can help finding the best water allocation scheme. When it comes to flood control, community participation in the selection of solutions is essential. Flood protection is a community rather than individual benefit. Decision on the land use will only be accomplished with the participation of different government levels together with the community.

Introduction

Adequate water management is essential to sustain development. Competing needs for this beneficial resource include municipal supply, industry, and agriculture, among others. With rapid population growth accompanied by accelerated urbanization, such problems are aggravated and the need for flood control management is added. Two decades ago, with Brazil already facing these conditions, decisions regarding water issues had to be based on the Water Code, which was promulgated in 1934. It was time for change.

The Federal Constitution of Brazil, issued on October 5, 1988, stated that it is a Federal duty to implement the National Water Resources Management System, responsible for, among others, to plan, to regulate and to control the use, preservation and restoration of country's waters. It also defined the water as a public good, a government property. Whether it is a Federal or a State property, it depends on the territory occupied by the watershed. If it encompasses more than one State or if the river is an international boundary, than it is a Federal property, otherwise it is owned by the State.

Such statements of the Constitution were a recognition of the importance of a renewed water resources management system for Brazil. It opened a natural path for water managers to work in the development of a more appropriate system, based on sound policies and invigorated institutional arrangements. On one hand, the technical approach for the new system had to be formulated taking into account the extensive regional diversities, the interdependency among sectors and the protection of the environment. On the other hand, the institutional approach was to emphasize the need for efficiency in water management through economic instruments and decentralization of the decision process.

The major change occurred in 1997 with the promulgation of the National Water Resources Management Act, which established the National Water Resources Policy and the National Water Resources Management System. There are many challenges facing the country as the government seeks to implement the Act. Despite Brazil's size and its regional differences, the country is undergoing a major change in the way water is perceived and managed by different sectors of society. The new system, described in this paper, provides useful tools to water management, mainly regarding extreme events, when appropriate management is critical to lessen the burden of floods or droughts on people.

The challenge of overcoming the country's diversity

Brazil is a federal republic of 8.5 million km^2 located in the southern hemisphere, between the Equator and the Tropic of Capricorn. The country is divided into 26 states and a Federal District, in which the capital, Brasilia, is located.

Brazil is known as a country of plentiful water, with the highest total renewable fresh water supply of the planet (Gleick 1998). The average amount of water available per capita exceeds 1700 m^3/person.year, estimated to be the threshold below which the country will not provide itself with sufficient food production (Postel, 1997; Gleick, 1998). However, the availability of 6950 km^3/year in fresh water must be viewed as merely an indicator of the average situation. In fact, 70% of the water is in the Amazon Basin where only 7% of the population lives. The remaining 93% of the country's population depends on only 30% of the available supply. The per capita availability varies from 1460 m^3 per person, per year in the semi-arid Northeast to 634 887 m^3 per person, per year in the Amazon region. Table 1 shows some of the most significant regional diversities concerning water issues (Azevedo and Simpson, 1995).

In addition, Brazil currently has one of the most uneven distributions of per capita income in the world. The State of São Paulo alone, with 20% of the country's population, is responsible for 40% of the GNP. The country's population is young, 50% under 19 of age, the illiteracy rate is high (19%) and 75% of the people live in urban areas.

Water is recognized as a fundamental resource to promote development and it is also a critical issue throughout Brazil. Thus, an efficient and sound water management system that addresses these various inequities is imperative.

The National Water Resources Management Act

The National Water Act of 1997 (Law No. 9.433) defines the objectives, principles, and instruments of the National Water Resources Policy and the National Water Resources Management System. The law establishes the institutional arrangement under which the country's water policies are to be implemented (Porto et al., 1999).

The National Water Resources Policy was proposed to achieve:

(1) ***sustainability***-- to ensure that the present and future generations have an adequate availability of water with suitable quality;
(2) ***integrated management***-- to ensure the integration among uses in order to guarantee continuing development;
(3) ***security***-- to prevent and protect against critical events, due either to natural causes or inappropriate uses.

Table 1 Main water resources issues by each geographic region of Brazil

<table>
<tr><th>Region</th><th>Main Water Resources Issues</th><th>Region</th><th>Main Water Resources Issues</th></tr>
<tr><td>North</td><td>Abundant water resources
Good water quality
High hydropower potential
Erosion and sedimentation due to agriculture
In mining areas, water quality problems
Water-borne diseases</td><td>Southeast</td><td>Localized scarcity of water supplies due to pollution and excessive use in large urban and industrialized areas
Water conflicts due to scarcity and excessive use
Frequent urban floods
Trans-basin diversions
Intensive pollution of water supplies</td></tr>
<tr><td>Northeast</td><td>Scarcity of water resources
Water conflicts
Water quality problems due to untreated sewage
Water-borne diseases</td><td rowspan="2">South</td><td rowspan="2">Localized scarcity of water supplies due to pollution and excessive use in large urban and industrialized areas
Water conflicts due to scarcity and excessive use
Frequent urban floods
International water conflicts
Soil erosion and degradation caused by agriculture</td></tr>
<tr><td>Center-West</td><td>Abundant water resources
Pantanal wetlands constitutes a unique ecosystem
Potential use for navigation and recreational purposes
Intensive erosion and sedimentation due to agriculture
Water-borne diseases</td></tr>
</table>

(Source: Adapted after Azevedo and Simpson, 1995.)

To achieve such objectives, water management must be implemented according to the following principles:
(1) water is a public good;
(2) water is a finite resource that has economic value;
(3) the use of water required to meet people's basic needs shall have priority, especially in critical periods;
(4) water management shall comprise and induce multiple uses;
(5) the river basin is the appropriate unit for water management;
(6) water management shall be decentralized, with the participation of government, stakeholders and society.
These same principles are viewed today as the embodiment of modern water management. Together they encompass such themes as protection of the environment, economic development, and improvement of social conditions-- all of which are intended to achieve sustainability.

The general guidelines for implementing the water resources policy emphasize the need for integrated management, flexibility to accommodate regional differences, coordination among the different sectors, land use planning (relevant to water management), and integration between inland and coastal water management.

The specific tools outlined in the Act to implement the policy include:

(1) water resources plans;
(2) classification of water bodies related to water uses and ambient water quality standards;
(3) permit system for water withdrawals and effluent discharges;
(4) water pricing;
(5) water resources information system.

The National Water Resources Management System in Brazil comprises the following institutions:
(1) The National Council on Water Resources;
(2) The National Water Agency;
(3) The State Councils on Water Resources;
(4) The River Basin Committees;
(5) Agencies at the Federal, State and Municipal levels with areas of competence related to the management of water resources;
(6)The Water Agencies, the executive branch of the river basin committees.

A primary strength of the new system is its decentralization. The goal is that decisions should be made at the lowest appropriate level with effective participation by stakeholders. After observing several river basin committees that are already in place, it seems clear that decisions on water allocation tend to be made through consensus rather than conflict. Participation by government, stakeholders, and organized society increases the willingness to implement the decisions and even prevents misuse and degradation of the resource, including flood prevention measures.

The National Water Resources Council is formed by (1) representatives of the federal government, who have some level of jurisdiction over water and related issues; (2) representatives designated by the state water resources councils; (3) representatives of the stakeholders; and (4) representatives of non-governmental organizations involved with water resources management or water use. The main responsibilities of the NWRC are to arbitrate, as a final administrative instance, conflicts between states; and approve guidelines regarding the permit system for withdrawals and water use, and also for the implementation of bulk water charges. The Executive Secretariat of the Council is under the responsibility of the Office of Water Resources, Ministry of Environment.

The National Water Agency is the executor of the water resources policy and is in charge of managing the permit system in federal rivers. It is mainly a technical entity, created to discipline water use in federal rivers, in coordination with the states, and to integrate all uses. As a prerogative of the federal government, the Office of Water Resources will remain responsible for elaborating the country’s water policy.

The composition and the responsibilities of each State Water Resources Councils are established by the corresponding state law but, in general terms, it is very similar to the NWRC. The State Council arbitrates conflicts between river basin committees and establishes guidelines for water resources programs at the state level.

Each river basin committee is formed by representatives of the federal and state government (depending on the administrative jurisdiction for each river belonging to the basin), stakeholders, and the civil society. They collectively decide how to allocate water, implement new development projects, arbitrate conflicts among stakeholders, and impose pollution control restrictions;

Each river basin agency should perform all the executive work related to water management in the basin. A single river basin agency may serve as the executive office for one or more river basin committees. Funds for financing the operation of these river basin agencies should be provided through the collection of bulk water fees. The water agency is responsible for all the technical work required to locally manage the water resources. Supplying expertise for database management, conducting hydrologic studies to evaluate water availability, ensuring adequate water withdrawal decisions, assessing and evaluating new water resources projects, as well as providing technical support to the committee on any other technical issue, are all responsibilities of the agency.

Implementation Instruments and Extreme Events

Extreme events can be related to hydrological conditions, as in case of floods and droughts, but it can also happen as a consequence of overexploitation and pollution. The five implementation tools provided by the National Water Act represent a very important and useful set of non-structural measures to be applied in water resources management.

Water resources plans are developed to guide future decisions and are to be developed for each river basin and state, as well as the country. The objective is to coordinate efforts and establish guidelines and priorities for water allocation and water pricing. Each plan must be approved by the corresponding river basin committee. The priorities established for water allocation will be used in critical drought conditions. Those with the highest priorities will be the last users to have water shortages. The water resources plans must also address land use conditions regarding floodplains. The directives there decided will help municipalities to control occupation in floodprone areas. If the water use is planned, it is supposed to avoid overexploitation and pollution. Therefore, water resources plans can be considered as a strategic non-structural measure. Since it has the approval of the watershed committee, it is most likely that the decisions will be implemented with less conflict.
The ***water quality classification of water bodies by different classes of use*** is the basis for truly integrating the quantity and quality of water management. Water quality standards in water bodies are to be enforced based on the decided use of the water in the river basin. The classification is a planning device that is intended to balance water quality standards and waste treatment costs, either to keep the standards or to restore the quality of degraded rivers and lakes. It is also inteded to avoid water quality problems, unless the drought conditions are too severe.

The ***permit system for water withdrawals and effluent discharges*** is being organized to set the rules for using rivers and lakes, either to divert water or to dilute and/or transport pollutants. Permits are granted for a fixed period of time, never longer than 35 years. All withdrawals and uses of rivers and lakes must have a permit-- except those in insignificant amounts, which are determined by each river basin committee. Permits are to be issued according to the priority of uses as established in the water plan of the river basin. Permits may be modified, suspended, or canceled if water is not used for three consecutive years, or if critical hydrologic situations exist.

Water use permits should apply either to quantitative uses of water, such as irrigation or urban supply, or to qualitative uses, such as dilution of industrial and urban waste. In most cases, however, quantitative and qualitative permits are issued by different government agencies, which are often rivals. Ideally, both kinds of permits should be issued by the same agency. Because of this, the same yardstick should be adopted to reduce quantitative and qualitative uses to common ground. The parcel of river flow that each water user makes unavailable for the downstream users may be this yardstick. In case of quantitative (consumption) use, the parcel is just the quantity of water withdrawn from the river. In case of qualitative use, the parcel is the quantity of water necessary to dissolve the pollutant to an accepted concentration level in the river. It may decrease as it moves downstream due to the oxidation of some pollutants.

The permit system is probably the most valuable tool to manage drought conditions. Due to well established water use conditions, each user knows up to what point his rights are valid when in drought periods. A well managed permit system is also a very effective non-structural measure.

Water pricing is the single most controversial instrument of the law. The pricing system is also the most difficult step to implement. The pricing system recognizes the economic value of water, as stated in the principles of the policy. The expression "economic value", refers only to the use of water as a natural resource, and not the related water services. For example, in France, charging for water use has been common practice for more than three decades, and that system appears to be effective in promoting sustainability and efficient operation of the infrastructure (Barth et al. 1987). The tradition in Germany for sharing investment and maintenance costs of common infrastructure at the river basin scale started before World War I. More recently, Mexican Water Law introduced charges for exploitation and use of surface and groundwater (Solanes and Gonzalez-Villarreal 1999). In Brazil, several states are also introducing pricing of bulk water in their laws and regulations. The main reasons for charging water users are twofold:

(1) To send them an economic message that they may be constraining the water use of others. The Brazilian system is unique among the world's water policies because it tries to use water prices to capture these externalities as much as possible in order to internalize them for water use. In this way, balance between water demand and supply can be reached by augmenting supply and decreasing demand;

(2)To provide the necessary funds for adequate operation and maintenance of existing systems at the basin scale and to implement new projects. Funding may also contribute to environmental conservation and restoration.

Experience shows that the revenues collected from bulk water fees must be invested in the same basin where they are generated. This is the single most efficient way to increase the user's willingness to pay. Otherwise, the stakeholders perceive such payments as taxes. If this happens, it could spur rejection of the system, which would be very difficult to overcome.

Pricing bulk water should not be a source of revenue for governments, because there is a widespread disbelief in Brazil that the government is capable of carrying out new policies, such as the rational use of water resources. Instead, the corresponding river basin committee should preferably use the revenue in the same river basin where it originated. Ideally, revenue should decrease with time because the money raised with the bulk water fee should finance improvements for the river basin as a whole.

Pricing can also be used in drought periods when the revenue collected from such payments can be used to pay-off some users, in order to reduce demand. Those users, for whom water have the highest aggregated value, will be glad to pay and guarantee their rights.

The development of a new, modern, and complete ***water resources information system*** is one of the basic needs for the implementation of the water resources management system. The decision process in drought or flood conditions, and also in overexploitation cases, can only be correct if based on a reliable information system. A complete and comprehensive database on water availability, users, water quality monitoring, current technologies (like geographical information systems), is certainly the way to produce an efficient frame work for decision making. Lack of information is one of the most critical points regarding the development and implementation of the new management system.

The importance of public participation

Public participation is of paramount importance to guarantee efficiency of the system, to facilitate the implementation of the decision process and to legitimize the most polemic decisions. In the Brazilian system, the participation is guaranteed in all levels of the decision process. It is not easy to implement and to attract people to enter the decision process. It is most efficient when a potential conflict is present, but it can be also very useful for the sake of guaranteeing transparency of the process.

River basin committees do not need to be established just to comply with the law. Committees should be formed only in basins, or sub-basins, which have some water conflict, actual or potential. Local problems may induce the formation of committees for some of the upstream sub-basins. In this case, it is necessary to create a hierarchical relationship between basin and sub-basin committees, preferably to ensure the right of the committee of the larger basin to impose boundary conditions for the river flow, quantity and quality, leaving the sub-basin. This means that the sub-basin committees would be free to decide matters internal to the sub-basin without external interference, provided that the boundary conditions are respected.

The proper mix of representatives on a river basin committee can make a big difference. Limited experience has shown that if the NGO's outweigh the users' representatives (e.g., water-supply/sanitation companies, industries, irrigation districts, power companies), the decisions of river basin committees tend to be unfeasible because those who make the decisions do not have to pay the consequences of their decisions. On the other hand, if decisions are left only to users, there is a risk that the environment would not be properly preserved for present and future generations. Also, the composition of the committees often requires many members, especially when they accept the "one man, one vote" concept. To avoid the associated transaction costs, the committees have adopted a decision-making process based on "weighted votes" for each category represented on river basin committees (similar to what happens in an assembly of shareholders of a private company). Decisions within each category would be made by members of the category.

In intermittent rivers of the semi-arid region of the Brazilian Northeast, continuous flow of water is assured for limited river reaches downstream from each dam. In these circumstances, it is more relevant to establish users association for each reservoir, rather than river basin committees.

When it comes to flood control, community participation in the selection of solutions is highly useful. However, because flood protection is a community rather than individual benefit, government financing is unavoidable.

Another step to overcome in participation is regarding the water pricing. Pricing bulk water use, or alternatively, pricing the water permit, may generate a substantial cash flow. The formation of river basin committees, which would be formed only in basins with water allocation conflicts, actual or potential, and where stakeholders would be sufficiently committed to oversee the water issues, aims to reduce any tendency to centralize the decision-making process. If these conditions are satisfied, then a river basin water agency should be created to function as an executive branch of the river basin committee. These water agencies would be Brazilian equivalents of the river basin agencies in Germany or France, or to the water district in the United States. However, river basin scale management is proper in most cases, but not all. Hydroelectric power plants in different river basins can be electrically interconnected. When a drought strikes a particular river basin, sometimes for several years in a row, the system may be sustained by power plants located in different river basins, separated by thousands of kilometers. In these circumstances, the electric power sector will tend to plan and operate the reservoirs from the interconnected system perspective, rather than from the river basin perspective.

Conclusion

Water managers in Brazil, both at Federal and State level, have come to the conclusion that a transparent management process, supported by the participation of water users and the civil society, is the only means available to promote effective implementation of a viable water management system. This is also true if they want to ensure that fair and equitable opportunities for water use, thus development and better social conditions. It also complies with the objective of promoting a more efficient use of the country's water resources and the maintenance of the hydraulic infrastructure.

The system is very new, making it difficult to positively conclude that it is the right model for Brazil. It is important to notice though, that the essential components of the integrated water resources management systems are there. The institutional arrangement is evolving and the stakeholders and the society are willing to participate. It is also very positive that all such measures are non-structural, what can be of great value to guarantee the sustainability of the whole process.
Integrated water resources management systems are a very broad and fertile environment for the adoption of non-structural to face water related critical events. The Brazilian water managers are decided to pursue this challenge and, up until now, the results are very positive. The system is far for the completion of its implementation but the country expects a very positive outcome, since this can be a very stimulating way to promote development.

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Flood Management in Japan - From Rivers To Basin

By

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Abstract: The River Commission of the Ministry of Construction, Japan recommended the basin response to floods in its December 2000 Interim Report to Minister of Construction. This is practically an official declaration of the policy accepting inundation in habited areas. By this policy shift, it is anticipated that more basin response measures and non-structural measures against floods will be promoted to complement structural measures such as continuous levees and dams. Such a policy is not new in the world but is a significant governmental move in Japan, a densely populated, highly developed and highly flood hazardous country. Although living with floods is a universal strategy to cope with floods, the implementation measures should be different in region by region reflecting its nature and socio-economic conditions. This paper reviews the flood fighting history of Japan and her statutory evolution against floods and shows the process that the ever-increasing flood damage potential and the recent increase of flood damages necessitated the official move in flood control management from rivers to basin.

Keywords: flood control, basin management, nonstructural measures, river laws

Introduction

Half a century history of River Commission of Ministry of Construction, Japan ended in December 2000 by issuing a new flood management policy "Flood Management including Basin Responses". On the first of January 2001, the reorganized new Ministry of Land and Transport started functioning assuming the responsibility of implementing it. The new policy accepts flood inundation in habited areas by such as open dikes and secondary dikes. It is partly an extension of 1977 Comprehensive Flood Control Measures policy designed in the rapidly developing urban basins to all the basins. But more substantially it is a major policy shift from no floods allowed in habited lands to some floods accepted in habited lands. The shift may be described as "from rivers to basin" as the strategy of confining floods within rivers by continuous levees and dams was changed to managing floods by river basin as a whole. This is due to the fact that the recent increase of flood events and damages cannot be reduced only by the traditional no inundation strategy.

By this shift, the various basin response measures such as open dikes, ring dikes, infiltration and retardation facilities etc. and the non-structural measures such as zoning, flood proof buildings, awareness raising by hazard maps etc. will further be promoted. This is a large stride towards "Human adjustment to floods", a dissertation submitted by Gilbert White in the 1940's. In the US, the 1993 Great Mississippi Floods accelerated the human adjustment policy. In Japan, the recent increase of flood events in the 1990s was an accelerator. The ways of human adjustment to floods or the ways of living with floods are naturally different in different regions as natural environments, people's living patterns, national economy and social structures are all different. The paper reviews the background of this shift in Japan and explains the new policy. Also emphasized is the increasing role of professionals in non-structural and human adjustment measures as the individuals are to make more decisions on their living conditions based on scientific information where scientists are relied upon as interpreters of scientific knowledge to the public.

Overview of Japanese Experiences of a Century

2.1 Chronology of death tolls, economic losses and flood control investment

Figures 1 and 2 show the outline of a century long experiences of fighting floods in Japan. Figure 1 shows the chronology of the death tolls and the economic losses of floods in 1990 values since 1870 to date. It can be seen that there were high death tolls during 1945-59 and less than several hundreds since 1960. Yet the economic losses have not been decreasing since 1960. While the decrease of death tolls was made possible by the various kinds of flood management efforts, what does the continuously high economic losses till today mean? It should be because the type of floods that is difficult to control such as land slide and urban floods does not decrease and the flood damage potential in flood plain is increasing. For more detail, see Kundzewicz and Takeuchi (1999).

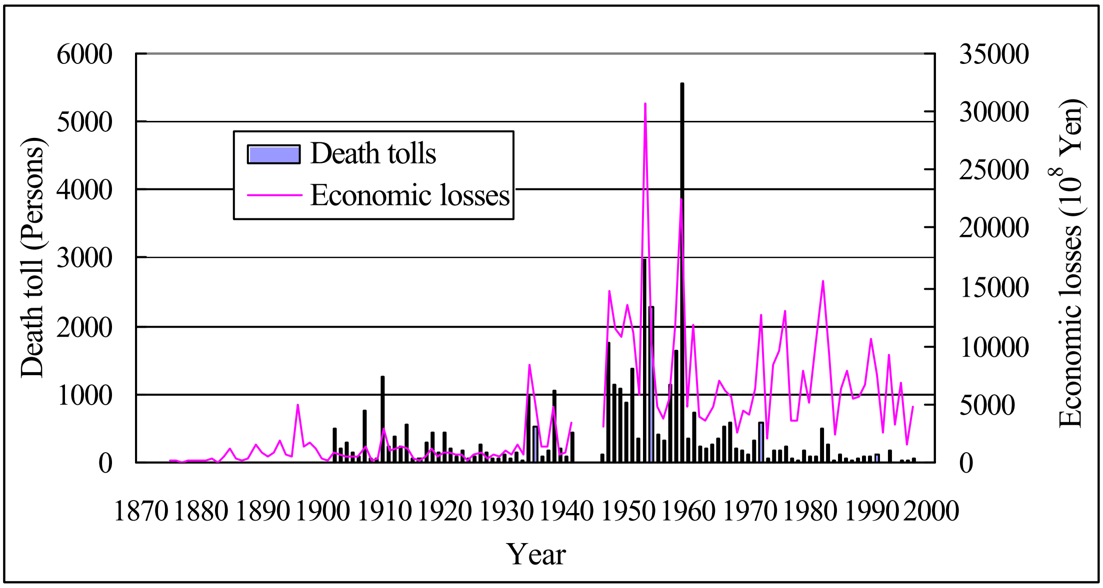

Figure 1. Annual death tolls and economic losses (1990 value) of floods in Japan (constructed from River Bureau, 2000)

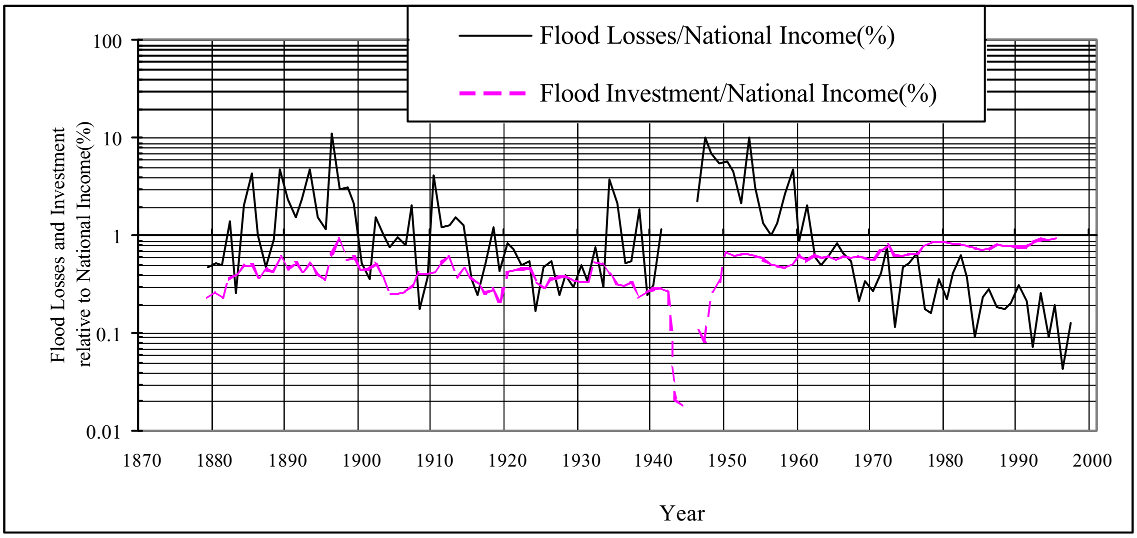

Figure 2. Annual economic losses and flood control investment relative to national income (constructed from River Bureau, 2000)

Figure 2 shows the chronological change of economic flood losses and the flood control investments relative to national income since 1880 to date. It can be read that the economic losses have been in 0.1-10% of national income and the investment in 0.2-0.9%. A remarkable decrease of investments is marked at wars: the Japan-China War (1894–1895), the Japan-Russia War (1904–1905), and World War I (1914–1918), when the investment dropped to about 0.25–0.35%, and World War II (1939–1945) when it fell below 0.1% and was very close to zero. In general the economic losses exceeded the flood control investment a great deal till late 1960s. But after then the relation reversed. The discrepancy seems continuously increasing to date. During 1990s, the ratio of investment to losses reached a factor of 4.

Although it is nothing wrong to have more investment than losses as the flood losses are suppressed at the expense of flood control investment, there are the basic questions arising among tax payers such as: Who pays and who benefit? How can the losses be further reduced? Are there any ways to reduce the necessary investments?

Takeuchi (2001) poses three questions as follows:

(a) If the benefit-cost ratio is the investment criterion, how can it be possible to maintain fairness between the beneficiaries and the tax payers? Do people in the flood-free areas agree that the government should use their taxes to protect people in the flood plains?

(b) As the central government now tends to be distributing power to regional or local governments, the basic trend is that the beneficiaries pay the cost of providing safety in the areas which they occupy. This is similar to the polluter pays principle (PPP) in environmental protection.

(c) If river structural works are the major subjects of flood damage, is it not possible to reduce the structural works in the first place? Weaker protection produces weaker counteractions.

It is obvious that the physical control measures should be reconsidered if all those questions have to be answered. Before introducing the new human adjustment policy of 2000, an evolution of flood control policy of Japan will be briefly reviewed in the next section.

2.2 Evolution of Flood Control Policy

It was in the Meiji Era started in 1868, Japan started employing the modern engineering for river improvement works, first for navigation and then flood control. The first River Law was enacted in 1896 reflecting the occurrence of a series of tragic floods in 1880s. It declared the public ownership of rivers and river water and assigned the central government the flood control responsibility to the works that demand large funds, high technology and the nationwide planning while the local governments assumed the principal responsibility on ordinary flood management. The Law authorized the water having had been used in rice paddy irrigation as the historically vested right.

The basic strategy for flood control was to lead water off to the sea as soon as possible. The means of the control were continuous levee system, divergent canals and sediment control by Sabo works. In 1950s, dams joined to the means. All flood control works were built within rivers. Flood warning based on advanced meteorological observations and weather forecasts gradually became available through radio and, later in 1950s, TV.

During the first 15 years after World War II, as seen in Fig. 1, Japan experienced a series of devastating floods killing more than 1000 people nearly every year. Such a tragic spell was realized by at least two reasons, wet climate and low maintenance of levees and channels during the war. The wet climate eventually ended and the flood control works gradually improved that made the 1959 Isewan Typhoon that took about 6000 lives the last flood that took more than a thousand deaths in Japanese modern history. It was obvious that the improvement of weather forecasts and dissemination by radio and TV greatly contributed the decrease of the death tolls.

Since late 1950s, the floods became prevailing in the areas of rapidly urbanizing areas where paddy fields and hill slopes were converted to residential and industrial areas. This sprolling urbanization continued and floods in relatively small urban rivers and sporadic landslides became the major source of flood damages. The 1977 Nagasaki floods by a torrential rain with 180 mm/hr, that was a record of hourly rainfall intensity in Japan and took 375 lives, was a case due to extensive hillside development of urban areas.

In 1977, the River Commission of Ministry of Construction recommended the "Comprehensive Flood Control Measures" in rapidly urbanizing basins. It suggested that not only retardation by dams upstream and river channel improvement downstream, the residential area should be developed so that no new extra discharge was generated. The methods were the promotion of installation of infiltration facilities and retardation facilities in newly developed residential areas. In 1987, the River Commission recommended the high standard levee policy and the construction of super levees started such as in the downstream of the Sumida River, Tokyo. A super levee is usually a land elevation behind the original narrow laser-like levee. The base length of a levee is typically 100 to 150 m long. The supper levee protects the urban areas where there are extensive urban facilities exist and absolutely no levee breakage is allowed. The levee construction is part of urban redevelopment and the benefit is not only from the hinterland where the protection is provided but also the levee itself where the land value is increased due to redevelopment of the riparian areas.

River Law of 1997

In 1997 the third amendment to the original River Law of 1896 was declared including "environment" in the purposes of the Law and the "public participation" in a planning procedure whenever necessary. The original River Law of 1896 was once amended in 1974 for inclusion of "water resources development". By the 1997 amendment, the River Law finally became comprehensive including water right, flood control, water resources development, river environment and public participation. The articles of 1997 River Law say:

Article 1. The purpose of this Law is to contribute to land conservation and the development of the country, and thereby maintain public security and promote public welfare, by administering rivers comprehensively to prevent occurrence of damage due to floods, high tides, etc., utilize rivers properly, *maintain the normal functions of the river water by maintaining and conserving the fluvial environment*.

Article 16-2-3. When river administrators intend to draft a river improvement plan, they shall consider *opinions from persons with experience or an academic background* when necessary.

Article 16-2-4. In connection with the previous paragraph, river administrators shall take necessary measures, such as public hearings etc., *to reflect the opinion of the people concerned* whenever necessary.

They were the official endorsement of the societal preference that had been obvious for many years by then.

Human Adjustment to Floods in Japan

The River Commission of Ministry of Construction, Japan issued a new policy "Effective Flood Management including Basin Responses" in December 2000 and passed the implementation role the reorganized new Ministry of Land, Infrastructure and Transport. The new policy accepts flood inundation in habited areas with such as open dikes and secondary dikes. It is partly an extension of 1977 Comprehensive Flood Control Measures policy designated to the rapidly developing areas to any basins. But more substantially it is a major policy shift from no floods in habited lands to some floods accepted in habited lands. The shift may be described as "from rivers to basin" as the strategy of confining floods within river lines by continuous levees and dam reservoirs was changed to manage floods by river basin as a whole. This is due to the fact that the recent increase of flood events and damages cannot be reduced only by the traditional non-inundation strategy.

From August to September 1998, serious floods occurred all over the world. The great Yangtze floods and the Songhua floods took more than 3000 lives and 20 billions USD losses. Happened also in Korea, Iran, the Philippines, Thailand etc. In Japan, the Naka River was hit by a serious flood. In 1999, several record breaking torrential rains hit. In Fukuoka and Tokyo, underground streets were inundated and in the Nagara river, the major levee was broken. In 2000, floods were also all over the world including Japan where Tokai floods hit the Pacific side Central Honshu. Climate change seems increasing the frequency of torrential rains of high intensity. The recent 20 years of AMeDAS (Automated Meteorological Data Acquisition System) observation records indicates that the number of heavy rainfall events with more than 100 mm/hr has been increasing nearly a double (River Bureau, 2001). In Nagoya City experienced a remarkable increase of intensity in 1999 and 2000. It is true that the Naka river floods, the inundation of subways and underground streets and the Tokai floods accelerated the new policy issuance.

In the 1977 Comprehensive Flood Control Measures, the rapidly developing basins were concerned. The basic policy was to make the development least effective in increase of rainfall discharge by providing infiltration facilities, retardation storage and ponds to compensate the increase of impermeable land. At the same time, various other measures such as rainfall radars and information dissemination network FRICS (Federation of river integrated communication systems), super levees, underground rivers etc. were promoted. In the 2000 Basin Response Measures policy, on the other hand, focused are not necessarily the rapidly developing areas but the ordinary flood plains. The main picture is described below. As seen there, it is a supplement to the traditional flood control measures and not a replacement of them. Yet since the new policy partly admits inundation of habited land, it is also true that it is a change of the basic principle.

The basin response measures consider a river basin composed of the following three categories of areas.

Flood Management including Basin Responses 2000 (River Commission, 2000)

The basin response measures consider a river basin composed of the following three categories of areas. Areas I, II-1, II-2 and III correspond to those indicated in Figure 3.

1. Rainfall discharging area where no floods occur (Area I).
   Storage facilities should be properly constructed, maintained and operated. As the private storage facilities may be closed when the ownership changes, it is desirable to move the ownership to the public. The release operation should be in accordance with the basin wide recession process.
2. Flooding area where floods occur and human activities exist.
   (1) Extensive flood plain where floods extend widely if occur (Area II-1).
   Continuous levee system is the basic protection. But open dikes and secondary dikes in parallel to the main levees may be introduced to reduce the potential damages. Land use and building regulation should be established in the possible flooding areas between open dikes.
   (2) Narrow flood plain where there is no space for continuous levee system (Area II-2).
   Ring dikes, land elevation, flood proof buildings etc. may be introduced.
   (3) The flood plain where extensive floods had been experienced before.
   If construction of continuous levees, channel improvements, land elevation as such are not proper, land use regulation including replacement of existing buildings, building code may be introduced to minimize the damages when the historical floods are realized again.

3. Urban flooding areas where floods result in extreme damage and should be well prepared when they happen (Area III).
   (1) Combined management of sewerage with rivers.
   Operation of drainage pumps and sewerage discharge are important not to increase the danger in the main stream.

   (2) Flood proofing of urban facilities.
   Life lines, underground shops and streets, metro facilities and etc. should be made flood proof.

   (3) Soft preparedness.
   Hazard maps and other necessary information to the public should be well disseminated. Evacuation routes and places should be publicized and emergency foods should be stored. The emergency flood control facilities such as sand bags to protect levees should be prepared and maintained.

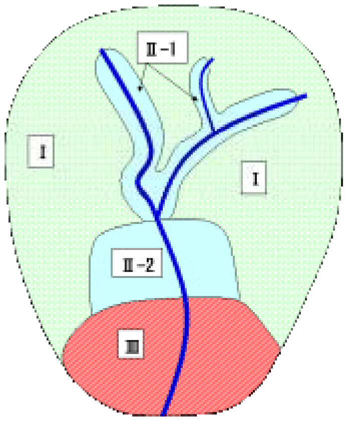

Figure 3. Division of a basin

Use of open dikes, ring dikes, secondary levees, various kinds of flood proofing, land zoning, flood hazard maps are nothing new in the long history of Japanese flood management. But the administrative declaration of their use has a significant implication in practice. Obviously more human adjustment measures will now on be introduced.

Concluding Remarks

The Asian Pacific region shares in general many common features such as volcanic mountains and geology, steep and narrow basins, Monsoon climate, high sediment production, living on rice and high population density. Nevertheless, there is no universal way for living with floods. Flood control is a part of national economy. The relation between flood control investment and increase of flood damage potential is an inevitable cycle but not necessarily a vicious cycle as long as it is socio-economically sustainable. It is to say, the level of cycling depends on nations' nature and socio-economic conditions.

In a civic society, the public participates more directly in decision making process of the society with wide disclosure of information and take more responsibility on the decisions made. Human adjustment to floods also implies higher individual responsibility. The role of hydrologists as a science interpreter is increasing.

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Collective Capacity: Regional Information Sharing in Support of Floodplain Management

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Abstract: An approach to assess the potential for inter-organizational sharing of information within a high-risk area is presented. Attempts to evaluate regional receptivity based on resident floodplain management practices are provided, with emphasis placed on non-structural approaches to hazards mitigation. Stated information needs and practices were evaluated within a case study region in hopes that the results would yield a clearer understanding of the decision-making community, collaborative opportunities in the area of flood risk reduction, and procedural variability related to information sharing within a cross-border setting. The Red River of the North was chosen as the case study area, largely owed to its repeated history of extreme flood events in combination with fairly a advanced means of coping with them. This study was designed to characterize cross-border communications patterns within the case study area, synthesize expressed user needs for region-wide information sharing, identify collaborative risk reduction opportunities that are potentially transferable, and devise a means to assess inter-regional adjustments to flood risk reduction. The results suggest that the shared risk approach used in support of this study provides a suitable framework in which to perform inter-basin comparisons.

Keywords: Floodplain management, risk reduction, non-structural hazards mitigation, shared risk

Background

The concept of sustainable mitigation has been asserted within the field of hazards research, as evidenced by recent activities stemming from the International Decade of Natural Disaster Recovery (IDNDR) and the "Second Assessment" in the United States. These initiatives call for "linking wise management of natural resources with local economic and social resiliency, viewing hazards and mitigation as an integral part of a much larger context" (Mileti, 2000, 2). This is an extremely ambitious goal, suggesting an expansive hazards management field and the need for active and continuous stakeholder engagement.

Measurable success along such lines will be best achieved at the community level, which is where the disasters occur and the critical decisions are made. A helpful step in the hazards mitigation diffusion process involves our ability to gain a clearer understanding of the collective capacity exhibited at that community level. This would become, in essence, an attempt to gauge the inherent nature of the social system within high-risk regions of interest. Measures of resident characteristics - such as communications patterns, expressed common needs, and cultural receptivity - are needed to gain a sense of what approaches are best suited for any particular area in question. Not all mitigation measures, in other words, are neatly transferable from one region to the next. This paper presents an attempt to capture the collective socio-technical and institutional capacity as a means of supporting the envisioned process of sustainability in a tailored and practical manner.

In a broad sense, sustainability relates to a given community's overall quality of life. Community in this case refers to the social activities contained within a combined physical and climatic hazard boundary. It has been further suggested that in order to be considered truly sustainable that that community must "evaluate its environmental resources and hazards, choose future losses from hazards and disasters it is willing to bear, and ensure that disaster and redevelopment policies adhere to the goals of sustainable development" (DeRouen Darlington and Simpson, 2001, 43). This rather holistic approach requires greater collaborations among practitioners, researchers and policy makers in order to have meaningful effect.

The hazards management field is undergoing a fundamental transformation, thereby providing a framework in which to foster inter-organizational collaborations. Our overall ability to characterize, understand and reduce the effects of natural hazards has improved dramatically in recent years, and this can be greatly attributed to the tremendous growth in information technologies. We can gather, store, retrieve, and disseminate ever-increasing amounts of information. Within developed countries this growth is improving our ability to coordinate activities throughout the disaster and hazards management field. That field is richly comprised of key decision-makers and a range of often overlapping support interests from public, private and non-profit organizations. With such a diverse resource base it is clear that no one sector can effectively shoulder the burden of responsibility for comprehensive hazards mitigation. Since the disaster threat often extends beyond single jurisdictions, our means of planning for and responding to that threat is further challenged when one considers the number of regional organizations involved, along with their associated management practices.

To realistically embark upon the ambitious pathway that sustained hazard mitigation implies we will need to understand the basic functional nature of the affected community, along with the receptivity of its stakeholders. Close attention must be paid to collaborative opportunities and levels of communication within this increasingly complex playing field. Within the context of sustainability, therefore, this study was conducted to assess a particular region's approach to hazards management within a specific functional domain - flood risk reduction. It was designed to gain a clearer understanding of community (regional) dimensionality through an evaluation of the institutional framework, technical capabilities, and cultural values within a specific case study area.

It is therefore suggested that hazards management is an inherently shared responsibility - one that increasingly crosses local and national boundaries. Our ability to cope with extreme events ranges from literally doing nothing and letting nature take its course to performing advanced measures based on an effective combination of structural and non-structural solutions. It is assumed that, within at least developed societies, the goal is to advance towards a self-organizing body, i.e., one that acts purely in the public's best interest. However, measuring the complex interplay associated with the physical character of the risk environment and the "core institutions and central values" can be extremely problematic. The latter consist of "economic and political ideologies and systems; attitudes towards social inclusion and exclusion; the growth or decline of insecurity; attitudes towards land use and sustainable development; differential access to power, decision-makers and resources; and other structural forces such as rapid urbanization and inadequate institutions" (Parker, 2000, 12).

This study attempts to establish a framework to measure collective capacity within a regional setting. The primary steps taken were to:

- Itemize and categorize expressed user needs for region-wide information sharing,
- Identify collaborative risk reduction opportunities that are potentially transferable, and
- Devise a means to assess inter-regional adjustments to hazards mitigation.

The risk sharing approach used for this study is based on previous work performed by Dr. Louise Comfort in relation to seismic response (Comfort, 1999). Her work prescribes that a broad-based understanding of regional adaptability can be achieved through the simultaneous gauging of resident institutional, cultural and technical capabilities. This project is designed to build on her accomplishments by focusing on risk reduction measures. The research domain of choice is floodplain management, with particular attention paid to non-structural hazard mitigation measures that are conducive for performing inter-basin comparisons.

As Table 1 suggests, there are a wide range of general activities that support floodplain management. Although these functions are classed according to the commonly termed phases of preparedness, response, recovery and mitigation they are optimally viewed within the cyclical context that marks the disaster and hazards management process. In order to transition the shared risk concept to a separate hazard domain it was first advisable to evaluate actual and planned mitigation measures within a case study area. Cross-border communications patterns were assessed as an initial step to determine inter-organizational capacity building potential. The results from directed workshop proceedings, questionnaires, and topical reports were then evaluated to identify collaborative functions and eventually derive inter-regional measurement indicators. The various groupings and regroupings were performed using the grounded theory (Strauss and Corbin, 1998), thus establishing a framework in which to measure the information sharing potential in conjunction with flood risk reduction.

The Case Study Environment

The Red River of the North Basin became the case study area of choice due to its combined cross-border character, repeated history of flooding, and relatively advanced means of coping with flood episodes. This is at once a very rich agricultural and urban area that is juxtaposed against high risks that are the result of a unique hydro-meteorological and geo-physical setting. The area encompasses large portions of Minnesota, North Dakota and Manitoba (Figure 1), with some of the world's richest soils that were originally deposited some 9,000 years ago as the lakebed of Glacial Lake Agassiz (Harris, 1997).

Table 1. Various Types of Floodplain Management Activities

Pre-Flood Activities: Preparedness	Post-Flood Activities: Recovery
• Risk communications • Contingency planning • Forecasting of future hydrological flow conditions • Flood detection	• Relief for immediate needs • Reconstruction of damaged areas • Subsidized relocation • Environmental recovery/restoration • Economic revitalization • Review of flood management practices
Operational Flood Management: Incident Response	**Risk Reduction: Mitigation**
• Warnings issued to authorities and public on flood extent and timing • Official and public response • Emergency measures • Removal of persons and property • Flood fighting measures	• Land use planning/management • Zoning: discouraging inappropriate development • Building codes • Buy-outs • Flood proofing • Insurance • Outreach: training and education • Physical control measures

Periodic flooding helps replenish the sediment load along both the main stem of the Red River and its tributaries. The Basin's eastern portion consists of a number of lakes and wetlands that attract tourism. The western portion is marked by "prairie potholes" that are ecologically rich depressional wetlands.

Since the Basin itself is actually the remnants of Lake Agassiz its topography is extremely flat. So flat, in fact, that its slope averages less than one-half foot per mile along a distance of 545 river miles (Krenz and Leitch, 1998). As a result, the floodplain extends over vast areas of land, threatening a large multi-use environment whenever the stream channel is overtopped. The slope also adds to extreme flow variability. In some locations zero flow conditions have been recorded, while during periods of extreme flooding flows have neared 100,000 cubic feet per second (Emergency Preparedness Canada, 1999).

In addition to the horizontal political divide that occurs along the 49th Parallel, there is a vertical climatic divide that creates separate risks within the Basin itself. The eastern continental temperate climate sets the pattern for periodic flooding, while the western semiarid zone is more prone to periods of drought. Since it lies within this transition zone any minor shift in the climatic pattern may lead to even more frequent and pronounced water shortages and excesses. The main stem of the Red River flows in a northerly direction, with Lake Winnipeg serving as its terminus.

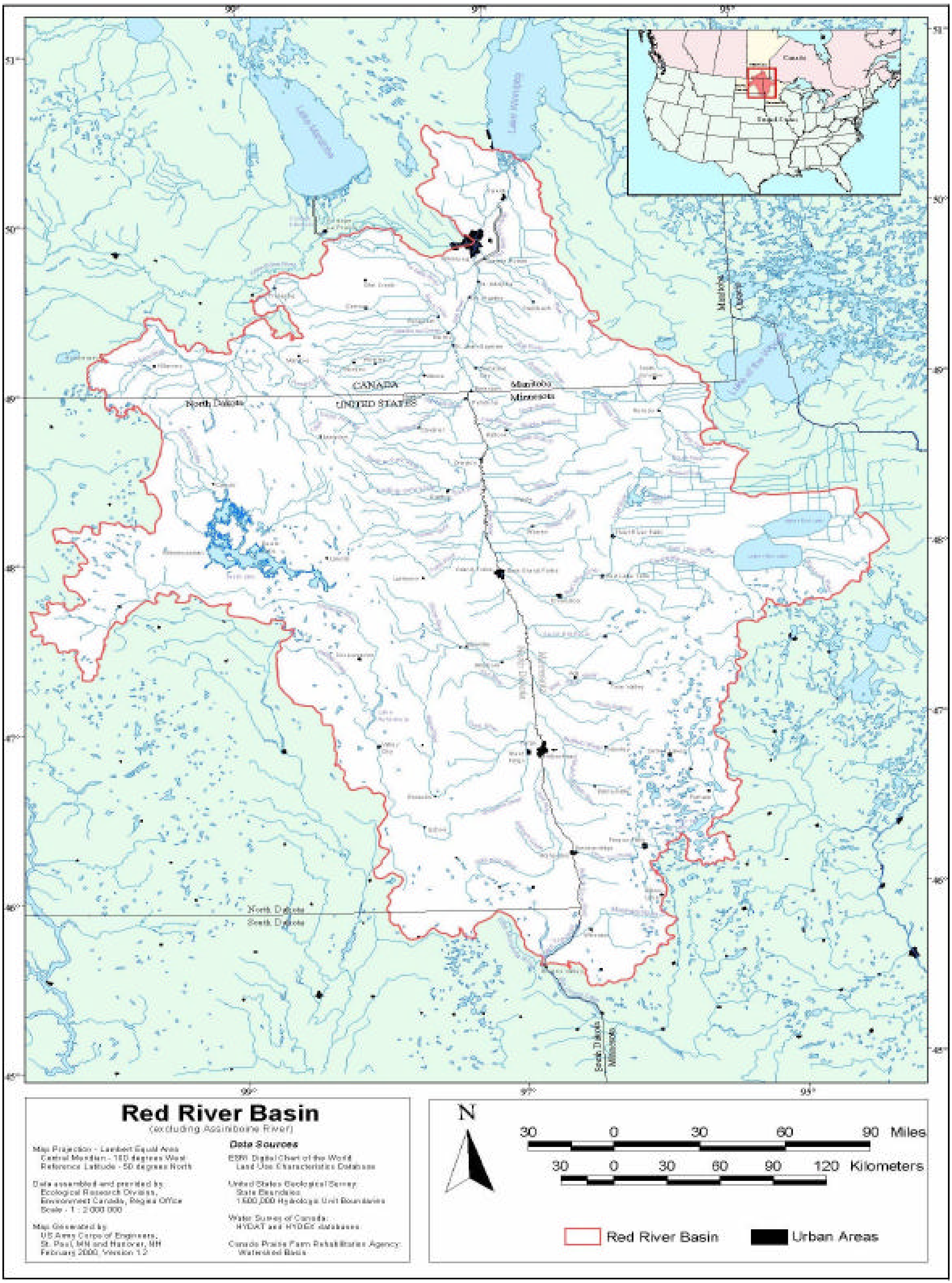

Figure 1. The Red River of the North Basin

Since the Basin is shared between Minnesota and the Dakotas and the U.S. and Canada it poses a number of management challenges in terms of how the various jurisdictions coordinate their respective flood risk reduction activities.

The flood that occurred in 1997 has been labeled the "most culturally destructive event to impact the Red River of the North Basin in recorded history", resulting "in the largest per capita evacuation of people in the history of the United States" (Mayer, 1997, 5). The major flooding that took place along the main stem of the river devastated the cities of Grand Forks, North Dakota and East Grand Forks, Minnesota. Some 75,000 people had to be relocated with the flood inundating approximately 80% of these two urban areas (Bluemle, 1997). The waters spread outwards up to 25 miles in some places, and rural and urban areas alike were severely impacted during the course of this springtime flood event.

As historical and geological records indicate, the Red River Basin is particularly prone to flooding. The right combination of the following conditions can set the stage for major flooding in the region (Bluemle, 1997):

- A wet fall
- A cold winter
- Heavy winter snow accumulation
- A late, cool, wet spring followed by sudden warming
- Widespread, heavy, warm rainfall during the thawing period

Topography is clearly the leading factor that contributes to flooding in the Basin. Owing to the nature of the terrain, floods approach in a slowly moving manner, with the floodwaters eventually transforming the region into what has been euphemistically termed "The Red Sea". Under extreme hydro-meteorological conditions the overland flooding in the Basin can result in areas the size of 1000 to 2000 square miles being inundated for periods that last from 4 to 6 weeks (Krentz and Leitch, 1998). Soils contribute to the longevity of these extreme flood events. The rich topsoil is underlain by 4 to 60 feet of clay, which has a low capacity to absorb floodwaters (Emergency Preparedness Canada, 1999).

Following the Flood of 1997, two separate task forces were formed to evaluate the event itself and to recommend improvements to the regional ability to more effectively reduce the adverse effects of future events. The International Joint Commission sponsored the International Red River Basin Task Force (IRRBTF), while the U.S. Federal Emergency Management Agency helped initiate the International Flood Mitigation Initiative. The sum total of these two efforts, along with several other separately related studies, has yielded a substantial body of work regarding intra- and inter-organizational hazards management capacities.

Building A Framework to Assess Regional Receptivity

An initial step in the process of devising receptivity measurements was to assess the general communication patterns within the case study area. A previous survey performed by Wachtendorf (1999) described the decentralized trans-boundary communications that took place in the period surrounding the 1997 flood event. Results from a separate International Joint Commission-sponsored workshop further supported Wachtendorf's findings. The combined results indicate a close-knit community where cross-border contact between specialists at the local, state/provincial and national levels is fairly routine and informal. This is further evidenced by the variety of water resource and emergency management venues, e.g., water district meetings, international workshops, available to interests on both sides of the international border. Such evidence of open and continuous communication reinforced the notion that this was a region well suited for establishing a risk-sharing framework focused on flood reduction measures.

The steps that followed related to constructing the indices needed to measure collective capacity on a basin-wide scale. Combined input from directed workshops, questionnaires, and regional reports provided the data and information needed in which to create the templates that could be used to perform inter-basin capacity assessments. As previously mentioned, the areas of consideration centered on the organizational aspects, technical infrastructure and cultural values within the case study region.

The grounded theory concept was used to cluster, categorize and identify adaptive measurements. This is an information management approach that, in this case, allowed for collective capacity indices to emerge from the combined data and information. Quantitative methodologies were simply not suited to the shared risk approach used in this study, as it was largely directed towards assessing the receptivity of social systems. Ultimately, a series of descriptor lists was created from the source material in order to segregate the information gathered, such as individual needs expressed at each stakeholder meeting. The resulting tallies were then re-grouped and crosschecked to avoid redundancy. Results were further consolidated to produce a uniform list of user needs, as expressed solely by local practitioners. Prioritization was based primarily on the number of similar requests for the same information type. No other direct input was used for this information grouping, which was designed to gain a clearer understanding of what information sharing issues the various stakeholders explicitly addressed.

The user needs assessment performed in the case study area allowed for a fundamental understanding of how a developed region functions in a practical sense, and what its specific needs might be. Constant and basic themes began to emerge from the combined sources, such as who is in charge, why is there no basin-wide strategy in place, and what information is available. The challenge therein centered on identifying an institutional body to address these concerns. A number of organizations have been formed in recent years to address floodplain management issues within the Red River Basin. Stakeholders were grateful at the support they were receiving, but at the same time they were also frustrated by the lack of basin-wide coordination and leadership. Most felt that the Red River Basin Board (RRBB), which was formed around the time of the 1997 event, came closest to assuming the coordinative role. However, since this is a grass-roots organization with an extremely limited budget it has no means to regulate the activities of local, state, provincial and federal authorities. The International Red River Board (IRRB), established in 2000 under the auspices of the International Joint Commission, was not instituted at the time of these surveys and individuals within the Basin are only now familiarizing themselves with what it is and how it functions. It is likely that the IRRB would also have been considered to be an appropriate oversight body, but it also comes with limitations similar to the RRBB in that it functions as a coordinating body.

In addition to the basic need for a facilitative body, other institutional themes that were explicitly expressed from the combined assessment, included the need for:

- Chains of command during incident response;
- Disaster guidance, e.g., evacuation and communications plans;
- Basin-wide organization charts;
- Inter-organizational coordination procedures;
- Roles and responsibilities of support organizations; and

- Key points of contact.

Therefore, even though it was never explicitly labeled as such, the respondents were alluding to the need for a comprehensive management plan that would address contingency planning, incidence response, and post-crisis recovery on a basin-wide scale

In addition to these institutional concerns, there were a wide number of specific data and information needs expressed by stakeholders within the case study area. These were ordered and re-grouped and eventually assigned to four general categories - baseline and dynamic data and information, shared information data banks, public access information, and tailored products. The baseline data was divided between static and dynamic data sets. The former require only periodic updates, e.g., ten-year intervals. Since the Red River Basin is characterized by such flat terrain standardized data sets, such as the topographic elevation data released by the U.S. Geological Survey, do not often meet the needs of resident decision-makers. Accordingly, respondents expressed the need for:

- A basin-wide digital elevation model with a vertical accuracy of one-foot,
- Road elevations with vertical accuracies of one-half foot,
- Medium-resolution land use maps, and
- Structural surveys of dams and setback levees.

What the respondents did not state was how these products would be created and which organization(s) would bear the responsibilities for their collection and maintenance. They are currently derived from a variety sources, including *in situ* measurements, reports, medium- and high-resolution imagery (e.g., radar and multi-spectral), aerial photography and global positioning systems (GPS). On a basin-wide scale these needs would be extremely costly to achieve. Once gathered, however, the pay-off would be extremely high since the collected data would be useful for a number of years and could be applied to a broad range of hazards and environmental management analyses. The collection and management of baseline information, in other words, probably has the broadest potential in terms of capacity building, and is also the least contentious in terms of its information content.

Dynamic data and information refers to basic information that relates to the flood event itself and needs to be measured on a near real-time basis. For instance, hydrographs are graphs of river stages or discharges versus time that are plotted at specific points along the river. The U.S. Geological Survey is responsible for posting them on the World Wide Web within the U.S. at regular intervals, and in this case the respondents wanted the reporting intervals shortened. The paucity of hydro-meteorological collection points within the Basin was also clearly voiced, particularly in terms of the tributaries where none presently exist. The derivation of snowmelt conditions and predictions, on the other hand, requires more than augmentations to existing collections. In this case, a combination of accurate data inputs and sophisticated modeling techniques needs to be in place. Although a great deal of research has been conducted related to snowmelt prediction, no one agency currently has the responsibility for managing such information in an operational sense. To fulfill this wish list, in other words, would require the modification of organizational responsibilities, which is unlikely to occur any time soon. In the interim, related requirements could be more fully articulated through collective research projects.

Shared information data banks relate to the collective warehousing of data and information. Various respondents expressed the need for centralized information, which in this case consists of specialized data sets that might prove to be collectively beneficial once available. In addition to lists of pertinent individuals within the Basin (i.e., volunteers, scientific and technical experts, emergency managers and local authorities), archives of valuable lessons learned (e.g., after action reports) and other non-standard data sources would be made accessible. The data bank would serve as a shared repository in which different groups and individuals would be responsible for the management and integrity of their own source material. Since most of this type of information is benign in nature - that is, its use causes no residual harm due to misuse or misinterpretation - there should be few problems posed in its posting.

Public Access Information differs from shared data banks in that it is specifically geared for public access. In this case, it relates to raising awareness levels and providing the general public with more pertinent real-time river conditions. The awareness raising target areas, as expressed by the respondents, would relate to public interest issues such as evacuation procedures, pumping recommendations, building temporary dikes, sandbagging and flood-proofing techniques. Public access information pertaining to river conditions relates to simplified and clarified reporting procedures. One of the major challenges facing flood forecasters is the dissemination of their data for general consumption. Improved and timely information on road closures, river stages for the main-stem and its tributaries, road conditions and closures, and real-time reports from the field were all expressly asked for. One respondent was particularly distrustful of the federal officials, suggesting that they might be purposely withholding vital information.

The generation of tailored products involves step-intensive measures and techniques that would be conducive to inter-organizational collaborations. One respondent suggested the need for an expert's repository, which would house valuable lessons that have been accumulated throughout the years and no longer available once seasoned individuals leave their positions. Such an idea is akin to a decision support system where expert views and trade-off decisions can be derived in an automated manner. The cumulative effect of flood episodes is another example of a tailored product that would be extremely useful but also extremely model-intensive. The need for map-displayed forecasts was also mentioned, along with a detailed basin-wide map of the various flood boundaries, i.e., 100-, 200-, and 500-year flood events.

Some also expressed the need for information related to historical floods, such as their boundaries and damages incurred. These would obviously be best derived from a multi-disciplinary team of experts. The 1997 flood was severe, but not necessarily unusual when placed in a historical and geo-spatial context. It would be advisable for archaeologists, geomorphologists, hydrologists and historians to work together to evaluate the historical impacts of hydro-meteorological extremes - including both floods and droughts - on the Basin. For instance, a 1950 flood severely impacted the Winnipeg area, forcing almost the total evacuation of individuals living in the Valley south of the city, along with an additional 85,000 residents from within the city itself (Bumstead, 1997). An 1826 flood is believed to have had an even greater impact on Winnipeg but records are scarce and the area was sparsely settled at the time. Clearly, geo-spatial comparisons between flood events would be particularly useful exercises in making the public aware of flood impacts.

Identifying Collaborative Opportunities

The next step in the distillation process was performed to identify the key functional areas within the Basin related to flood risk reduction. These categories were further refined in an attempt to integrate other information deemed relevant from the open literature review. This step was conducted to define collaborative areas that might be analogous to other regions of the world. The expressed stakeholder intent was not compromised in the course of this process, but it was necessary to ensure that the eventual comparison tables were complete and were in fact transferable. This information coding was necessarily performed on an iterative basis to ensure that gaps did not arise from the literature review and the individual stakeholder requirements. Through a synthesis of the results collaborative focus areas were identified which served as the basis in which to modify Comfort's three adaptability measurement tables.

The consolidated results of the research eventually yielded five primary focus areas that were, in fact, well suited to collective capacity building – basin-wide strategic planning, flood forecast and warning improvements, baseline information consolidation, risk and vulnerability assessments, and heightened awareness campaigns. As previously noted, a common theme that ran through the various proceedings related to the need for basin-wide strategic planning. The question of who would be responsible for such a plan on a region-wide basis is unresolved within the case study area. The development of such a plan on its own would demonstrate the self-organizational concept in action, i.e., ability of a community to act on its own behalf. Within the case study area some type of incentive or mandate will need to be devised to initiate the draft process. In whichever form the development of such a plan takes, the work needs to be carried out with broad stakeholder input.

The second focus area of flood forecasting and warnings is replete with technical and social issues that are well suited for being addressed collaboratively. The goal of flood warning is "to enable and persuade people and organizations to take action to increase safety and reduce the costs of flooding" (Elliott and Stewart, 2000, 391). Many of the functions that comprise flood-warning systems are typically performed in a closed manner, owed in large part to the complexity of the hydrologic modeling process. However, the growing interest in hazards management, in combination with the growth in information technology, indicates that a more inclusive process is unavoidable. As distinguished by Parker (2000), flood predictions are used for planning purposes, such as the design of a dam to protect against flooding of a given magnitude, where magnitudes are related to flood frequencies or probabilities. Forecasting methods, on the other hand, are developed to give advanced warning on the timing and magnitude of specific flood events. Forecasts directly support the flood warning process by providing lead times (weeks, days, hours) for specific events. In the United States, the federal government is responsible for issuing forecasts, which become an integral part of the local decision-making process.

Baseline information, the third focus area, in this case refers to standard and non-standard data sets of relevance to basin-wide floodplain management activities. There are many types of information sources available to support topic areas such as land use planning and flood insurance designations. The federal government plays a critical role in the generation of baseline information by setting standards and producing many products on a nation-wide scale. For instance, in the United States the Federal Emergency Management Agency is responsible for developing Flood Insurance Rate Maps and the U.S. Geological Survey produces Digital Elevation Model (DEM) data. These products are readily available in both paper and digital form.

The problem with national data sets is that they often fall short of meeting local needs. In an area with terrain as flat as the Red River Basin, for instance, the need for a detailed digital elevation model is crucial in support of a wide range of activities, including floodplain delineation, risk and vulnerability assessment, and hydraulic and hydrological modeling. The level of granularity available on national products is simply too coarse to support analyses related to these application areas. Compounding the problem is the border itself, which translates into map-based products that are incompatible with one another. Since this is a fairly major problem within the Red River Basin, where advanced geographic information system (GIS) techniques have been in place for a number of years, it is likely that this will continue to be a ubiquitous problem.

Based on discussions with individuals in the Basin non-standard data collects have only recently begun to be coordinated throughout the region. Highly resolved data sets are expensive to acquire and differences between data type, spatial resolution and time of collection will complicate any type of basin-wide mapping strategy. What is suggested, therefore, is that the generation of a comprehensive baseline data set, as espoused by many of the Red River Basin stakeholders, becomes a shared responsibility. In the case of high-resolution digital terrain data the incentive for collaboration is high. In essence, baseline data have high capacity building potential through an inherent ability to support multiple functions, thereby serving to catalyze once disparate interests.

The fourth focus area - flood risk and vulnerability assessments - is a key element of the hazard management process. A risk assessment relates to studies performed to evaluate the probability that a specific set of conditions will occur. There is considerable work to be done in this area and as more baseline information becomes available to a broader user community - in conjunction with more practitioners becoming proficient in the use of GIS technology - more studies are likely to be performed. This is a key intersect between the research arena and policy makers, and is highly conducive to cross-organizational collaborations at both national and regional scales, since so very little is actually known regarding the actual risks we face. For instance, as noted by Pielke: "the actual amount of U.S. land in floodplains has not been clearly determined, nor has the amount of property and other economic investments at risk to flooding been firmly established" (Pielke, 2000, 150).

Vulnerability assessments refer to the various measures used to determine a society's inherent capacity to withstand specific hazards. They are " developed from a range of socio-economic approaches to hazards and what we would call the disaster of everyday life" (Cannon, 2000, 45). Variables such as the occupants of flood-prone areas, literacy rates, economic status, coping abilities, gender and ages are all examples of vulnerability measures. Vulnerability analysis, in essence, relates to the social science aspects of hazard management, as opposed to purely hydro-meteorological dynamics. It plays a crucial role in increasing our understanding of the regional origins and causes of extreme flood events that directly impact society as a whole.

As an example of a collaborative modeling approach, James and Korom (2001) evaluated the Red River Flood of 1997 and suggest that more integrative approaches are clearly warranted. The development of an "integrated physically based weather-hydrologic-hydraulic modeling" (*Ibid*, 22) capability could eventually be used in support of a broad range of risk and vulnerability assessments. As amended from their study, the following blend of research and operational tasks could be undertaken to achieve such an integrated model:

- Conduct an inventory of all regional baseline data and information;
- Produce a large-scale basin-wide map that incorporates detailed physical and cultural features;
- Develop a meteorological model that simultaneously simulates precipitation, temperature, clouds and radiation in a seasonal manner;

- Develop a basin-wide hydrologic model to simulate the runoff volumes from the meteorological model;
- "Map channel and floodplain characteristics and calibrate a hydraulic model that simulates spatially distributed stage, velocity, and turbidity" (*Ibid*, 26);
- Generate several possible flood scenarios for the basin of interest, including the effects of climate change; and
- Develop a suite of risk and vulnerability modules to measure and predict the geo-spatial effects of given flood events.

None of these capabilities presently exist within the case study area, and most likely any other area. This is a comprehensive approach that is best developed in a highly inter-disciplinary manner.

Lastly, heightened awareness simply relates to specific activities designed to increase the general public's sensitivity towards the various risks posed within their community. This focus area is largely reserved for social scientists and may be considered immeasurable or too "soft" by other scientific experts. In spite of its seemingly intangible nature, however, heightened public awareness is crucial in terms of sustainable hazard management measures. Examples of public awareness campaigns include kindergarten through high school education modules, civil defense training and drills, and targeted advertising campaigns, e.g., leaflets, posters, commercials.

Collective Capacity Indices

The adaptive sub-system types that Comfort used to perform her seismic response measurements – non-adaptive, emergent adaptive, operative adaptive and auto-adaptive - have universal application within the field of hazards management. These also should be viewed along continuous lines, with the first two sub-types broadly typifying developing regions. Accordingly, a subsystem that is considered non-adaptive scores consistently low on institutional, cultural and socio-technical aspects of disaster and hazards management, as Table 2 indicates. Inter- and intra-organizational communications are routinely poor, technical diffusion capacity is essentially non-existent, the resident culture's capacity to embrace new concepts is low, and the institutional framework for sharing data and information is largely untested. An emergent adaptive subsystem in some ways resembles a non-adaptive one, but shows a clear potential for improvement. Under this setting, and as applied to flood risk reduction, there is a general willingness among regional stakeholders to adopt new sustainable procedures for sharing risk-based information.

The last two subsystems apply to more advanced societies. Communities exhibiting operative adaptive tendencies possess fairly advanced response procedures and at the very least recognize the need for mitigation measures in their disaster management practices. These communities demonstrate medium to high cultural, institutional and technical capacities. There is clear evidence of cross-border communications during the preparedness and incidence response phases of particular disaster events. Organizational mechanisms are in place to encourage regional cooperation during non-disaster periods. Sustainable mitigation measures are best achieved through a combination of regional incentives. The auto-adaptive subsystem remains, in large part, an ideal at this point. Any community exhibiting auto-adaptive tendencies achieves and sustains high marks in each of the three adaptability categories.

Table 2. Scoring the Capacity Categories

Subsystem Type	Institutional Factors	Technical Infrastructure	Cultural Values
Non-Adaptive	Low	Low	Low
Emergent-Adaptive	Low - Medium	Low - Medium	Low - Medium
Operative-Adaptive	Medium - High	Medium - High	Medium - High
Auto-Adaptive	High	High	High

Their institutional framework is such that inter- and intra-jurisdictional coordination and cooperation is wholly decentralized - operating in a self-organizational manner. Limited incentives are required due to the high rate of open information sharing that occurs between the various sectors. There is a marked cultural openness to new ideas, and an advanced technical infrastructure in place to facilitate ne arly seamless modes of operation within the disaster and hazard life cycle process. The typical command and control system is considered outmoded under this schema and is rarely evident during operational procedures.

What remained, therefore, was for the individual indicators from each of the three subject areas – institutions, cultural values and socio-technical systems – to be modified to suit flood risk reduction approaches that were culled from the case study assessment. Selective coding of the previously derived information sets was used to create these revised tables. This step relates to the final integration and refinement of the collected information. The indicators were identified based on mitigation practices that were traceable and transferable. These categories were primarily chosen based on a combination of expressed user needs with minor input from regionally targeted flood reduction studies.

The results of this information distillation process are shown in Tables 3 through 5. The bcal input proved particularly helpful, providing a practical view on what is needed within a high-risk basin. The available literature also helped support the rationale behind which topic areas were deemed pertinent. A description of each of the three assessment categories follows, along with their association to the case study area.

<u>Institutional Framework</u>. As the case study needs assessment demonstrated there is a critical need to address the organizational aspects of regional capacity building. The institutional framework provides the basis by which all actions are taken, and an assessment of its functional character helps determine the collaborative potential. The resulting criteria for measuring a given community's institutional capacity can be found in Table 3. As a reminder, community in this case refers to the region that is bounded by the given risk, i.e., drainage basin.

Stakeholders in the case study area stressed the need for basin-wide flood management plans. The presence of such a document is a strong indicator of self-organizational tendencies, since it is unlikely that any governing body will aggressively promote the drafting of a cross-border document. Ideally, such a plan would also be expanded to address the full range of risks associated with surrounding water resources, e.g., water shortage and water quality. A region exhibiting a strong institutional framework would also have developed national mitigation strategies, a demonstrated capacity to communicate between jurisdictions during all time sequences, a network of trained technical and emergency management specialists who are aware of each other's roles and responsibilities, a sound policy environment and a decentralized decision-making environment that encourages local autonomy.

Those regions exhibiting low to medium tendencies lack a combination of these institutional traits. In this case their management plans may be limited to the national level and only address incident response measures, for instance.

There may be bi-lateral agreements in place but little or no evidence to suggest that they are being acted upon during routine periods. Local autonomy may be weak in an environment that still favors vertical command-and-control procedures. Emergency management staff within the affected jurisdictions may be negligible and technical support weak or non-existent in some instances.

Table 3. Capacity Assessment: Institutional Factors

High

Basin-wide management plan has been drafted
National mitigation strategy in place
Basin-wide coordination and communications strategy instituted
Trained emergency management staff coordinating at the regional level
Effective regulatory policies that address flood-plain occupancy
De-centralized decision-making with a high degree of local autonomy

Medium

Evidence of an updated national response plan
Bi-lateral response agreements
Evidence of regional preparedness and response training
Some trained emergency management staff at the local and/or national level
Evidence of some regulatory policies designed to address flood-plain occupancy
Attempts to de-centralize decision-making; moderate local discretion

Low

No existing flood response plan
No evidence of mitigation-related activities
Poor local- and national-level coordination and communications
Little or no evidence of flood preparedness and response training
No regulatory policies addressing floodplain occupancy
Centralized decision-making; no evidence of local autonomy

Technical Infrastructure. The regional technical infrastructure refers to the overall technical means in place to support decision-making within the given basin of interest. As Table 4 shows, a high rating in this sense would indicate a region that possesses a dense and standardized network of automated hydro-meteorological instruments with a long period of record, i.e., 30 years or better. A free and open exchange of standardized data and information would occur between scientific and technical stakeholders in the basin of interest. Risk and vulnerability assessments would be coordinated between multiple organizations in support of consensus-based requirements. A distributed network of scientific and technical individuals would have been identified from the academic, private and non-profit sectors to support the decision-making process.

Conversely, regions scoring medium to low under this heading might possess a sparse hydro-meteorological network that was partially automated in a non-standardized manner. The resident technical staff would be restricted to a few individuals within a few organizations where coordination is limited and resources few.

Communications within the basin would be largely restricted to emergency response measures. Risk and vulnerability assessments would be limited, based on lack of resources and poorly defined requirements. Data and information sources are not routinely shared and are often proprietary in nature.
And dialogue between regional policy- and decision-makers and the scientific and technical community is demonstrably weak or non-existent.

Table 4. Capacity Assessment: Technical Infrastructure

High

Possesses a dense regional network of automated hydro-meteorological instruments
Clearly stated standards for basin-wide data and information sharing
Regionally integrated staff trained in key technology areas
Evidence of regional risk and vulnerability assessment having been performed
Validated flood risk reduction requirements
Coordinated information management facilities within the basin

Medium

Fairly dense network of combined automated and manual hydro-met. instruments
Some regional standards for basin-wide data and information sharing
Trained technical staff within select areas
Evidence of national- or local-level risk and vulnerability assessment performed
Some evidence of flood risk reduction needs
National and/or local information management facilities

Low

Sparse network of mostly manual hydro-meteorological instruments
No evidence of data or information standards
Poorly trained national and/or local staff
No evidence of any risk and vulnerability assessment having been performed
No evidence of flood risk reduction needs
Isolated or non-existent information management facilities

Cultural Values. Cultural values are the most difficult of the three categories to gauge, owing to the purely qualitative nature of social systems. On the other hand, they are also the most important to try and measure since they are the fundamental determinant of effective adjustment. The cultural capacity for environmental adaptation, put another way, is the primary system driver and is often overlooked in hazards and disaster studies. The cultural value parameters found in Table 5 do not substantially deviate from those derived from Comfort in her seismic studies.

Accordingly, a region exhibiting high cultural values marks would have struck an effective working balance between structural and non-structural approaches to floodplain management. There would be a distinct openness to flood risk reduction measures on the regional scale. Hazard- and disaster-related data and information would flow freely and openly among stakeholders to the greatest extent possible. An open commitment to sustainable mitigation measures would be evident through public awareness campaigns and regional training programs. The aggressive adoption of new concepts and ideas to promote sustainable measures would be apparent, along with the open sharing of lessons learned from previous activities.

Table 5. Capacity Assessment: Cultural Values

High

Clearly focused on a balanced approach to structural and non-structural solutions
Open to innovative ideas regarding flood risk reduction on the regional level
Regional commitment to protecting life and property
Free and open information exchanges between individuals and organizations
Evidence to suggest that new ideas and approaches are actively being sought out
Clear evidence of after action reporting and regional solutions being pursued

Medium

Starting to address the behavioral aspects of flooding
Clear evidence that non-structural solutions are being considered at the national level
National-level concern for protecting life and property
Information exchanges occur largely between national organizations and jurisdictions
Decisions are made based largely on experience
Evidence of after action planning, but not in an integrative manner

Low

Solely focused on issues related to flood control measures
Unwilling to consider new ideas related to flood risk reduction
Little or no value placed upon the public or community at risk
Limited information exchanges
Lack of trust between citizens and neighboring nations
Little or no interest in after action planning

Regions with medium to low levels of cultural values capacity would just be starting to address the behavioral aspects of flood events, if at all. They would have a determined commitment to the structural approach to floodplain management or else still adhere to the principle of God's will. The exchange of information would be typically along intra-organizational lines, and decisions would be largely experience-based. Regional openness to new ideas and concepts is limited and inter-organizational trust has not been established.

Once constructed, the capacity tables and associated subsystem types can be used in a number of ways in support of inter-basin comparisons. The scoring designations shown in Table 2 can be measured in a variety of qualitative and quantitative ways. The natural research tendency would be to apply various statistical measures to compare and contrast inter-basin characteristics. As these are essentially social systems that are being assessed, however, quantitative analyses may at times prove to be extremely problematic.

Within the case study area a high, medium or low rating was assigned to each of the subsystem elements related to institutional factors, technical infrastructure and cultural values. These individual ratings were derived based on the integrated results of all available information resources. The findings suggest that the Red River Basin exhibits operative adaptive subsystem tendencies. That designation is greatly attributed to the fairly high ratings in relation to cultural values. The fact that its cultural values capacity is generally high reflects a l basin-wide receptivity towards new concepts and ideas. As evidenced by the works produced in support of the International Joint Commission and the International Flood Mitigation Initiative, several studies in the Basin have been performed that recognize the need to strike an effective balance between structural and non-structural floodplain management solutions, as well as the behavioral aspects related to floodplain occupancy.

The individual indicators related to technological infrastructure registered significantly lower than the cultural values. That would not be the case had these measures been solely focused at the national level. Both nations exhibit strong technical abilities, but at the regional level there is great room for improvement. The existing hydro-meteorological instrumentation network is automated but extremely sparse, and stream measurements do not appear to be standardized between the responsible organizations. Standardized measurements for much of the baseline data and information have been identified, but have not been fully instituted on a regional scale. There are significant problems that have been identified by stakeholders and researchers alike associated with the regional forecast and warning procedures. Although there is an initiative in Canada to perform a national hazards assessment (Etkin, 2001), regional risk and vulnerability assessments have yet to be performed for the case study area and data do not exist to support highly resolved analyses should that need be further articulated. Scientific and technical exchanges do not appear to be routinely performed between the existing centers of expertise. The recent establishment of the Red River Institute, however, holds promise that the research will be better coordinated within the Basin. In spite of the various shortcomings, therefore, the long-standing issues are starting to be resolved and organizational vehicles exist to facilitate that improvement process.

Conclusions

This study was performed to assess the collaborative potential within a single high-risk region. The Red River Basin proved to be an excellent setting in which to evaluate the potential for collective capacity on a regional scale. The region demonstrates the ebb and flow of attempts at flood risk reduction within an international setting. Situated in a climatic transition zone, it is an area that is both highly susceptible to bouts of extreme flooding and prolonged periods of drought. Each flood event brings with it incremental improvements to the floodplain management process. The importance of sustainable hazard mitigation practice as a leading part of the solution base is becoming increasingly recognized throughout this stakeholder community.

The implementation of a sustainable hazards mitigation program within any one high-risk area will require the active engagement of a broad base of participants. That is, social scientists who are willing to work closely with engineers who are working with physical scientists. It dictates that policy makers take into account the needs of the decision makers. And unfortunately for some, it requires that the once insular host of technicians and researchers learn to more clearly communicate their findings to an increasingly informed and involved general public. That effective stakeholder balance may be best achieved at the regional level where disaster events often occur. A facilitative structure of some type will need to be in place within each region to guide the transition towards a truly self-organized body.

The weakest link within the case study area proved to be institutional in nature. Sustained success related to basin-wide mitigation measures will be extremely dependent upon the degree of stakeholder participation. Arguably, emergency management is a government function, where the roles and responsibilities across the various governmental layers remain problematic. The first inclination is to suggest a governmental body that is best suited to develop and direct a sustainable regional mitigation process. At first glance, at least in terms of the United States, offices at the county level would appear to be the logical choice. Federal and state levels are too broadly focused and lack the resources to effect sustainable measures that are locally felt. As Sylves and Waugh (1997) point out, however, local governmental bodies lack the authority and responsibilities needed to assert risk reduction activities. They are often viewed as agents of the states lacking the necessary autonomy and resources to effect change.

Within the past few years the concept of Public-Private Partnerships (PPPs) has been promoted within the United States (DITF, 1997; P.L. Ward, 2001) as a substitute to the traditional governmental management approach. A non-profit organization is formed, in this case, which serves essentially as an information management conduit between government agencies and private institutions. This approach clearly has appeal as a means to de-conflict inter-organizational rivalries and streamline information flows, but it also suggests the addition of yet one more centralized organization to the emergency management mix. Quarantelli (1998) also warns that the PPP organizational model may only be effective within a few countries.

As technologies improve and the information resource base expands there will be an increasing demand to empower a wider network of interests. The question remains, therefore, as to what comprises the proper decision-making body, as it is no longer advisable to expect sole guidance to come from the national level. Self-organization, simply put, is a system that allows stakeholders or individuals to act in their own best self-interest. Problem solving becomes a collective activity - one that no longer exclusively resides in governmental hands. Table 6 lists key attributes that characterize a fully coordinated flood risk reduction approach. A regional system that could claim these principles might also boast a self-organizing body that possesses a sustained hazard mitigation program.

Within the case study region it is too early to tell whether the combined charters of the Red River Basin Board (RRBB) and the International Red River Board (IRRB) have a potential to effectively guide a self-organizational process. At this point, they provide the best organizational model within the Basin to bring the full range of stakeholders together to effect sustainable measures. Ideally, it would be possible to combine their charters in order to:

- Assure that high-level federal and state goals are consistent with the local and regional needs;
- Solicit innovative ideas from lower-level governments, and vet them with the regional stakeholder community;
- Promote processes and goals that increase the intergovernmental sharing of ideas, resources, and projects; and
- Facilitate the development of a basin-wide hazard mitigation strategy.

The shared risk capacity measures described in this paper will be helpful in determining regional strengths and weaknesses, and thereby serve as a useful tool in determining the strategy that might prove most effective within given areas of interest. Results from this research suggest that well coordinated, open-channel approaches that emphasize basin-wide strategic planning, improvements to the flood warning and forecast process, baseline information consolidation, risk and vulnerability analyses, and heightened awareness campaigns stand the best chance of achieving sustained flood risk reduction. It is hoped that this baseline approach will prove useful in assessing other community and/or regional management practices. Such a "model" might be of further use in suggesting tailored improvements used to promote trans-boundary collaboration, to recommend areas for improvement, or to support long-term humanitarian assistance efforts.

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Two New Non-Structural Measures for Sustainable Management of Floods

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Abstract: The modern flood mitigation is increasingly non-structural. Well- established, traditional non-structural measures such as zoning, building codes, flood proofing, early detection and warning, emergency planning, flood insurance, etc., appear today as indispensable complements to structural, engineering solutions. Advancement of computer sciences and communications provides an opportunity for further broadening of the context of non-structural flood mitigation. Two new concepts: (a) flood management virtual database; and (b) flood management decision support system; are presented in the paper. Their benefits are demonstrated through the development of prototype systems for the Red River basin in Manitoba, Canada. Firstly, it is shown that the Internet technology is mature enough to support the development of virtual database for a complex domain such as floodplain management. It is also quite clear that this mode of support has many advantages when compared to more traditional centralized database model. Secondly, we concluded that the decision support system approach provides an opportunity to meet the expressed needs of residents living in flood-prone areas for improvement in the flood management and a major change in the decision-making process. Decision support system is envisioned as a tool for analyzing alternative mitigation and recovery strategies. It is proposed in this work as a way of making flood management process more transparent and efficient in reducing future economic, environmental and social flood damages.

Keywords: Floods, non-structural measures, mitigation, computers, virtual database, decision support system, Red River basin

Introduction

There are a large number of strategies and methods available today to address flood hazards and disasters. Floods are natural environmental events (Smith and Ward, 1998). From time to time extreme rainfall or excess snowmelt cause rivers to overflow their banks and reclaim floodplains. These natural events are not a problem. They present a hazard and may cause a disaster only after humans construct a build environment on flood-prone lands (NRC, 1989; IHP, 1999; Parker, 2000; Kumar et al, 2001). Building structures within floodplains is a development strategy chosen frequently by many societies all over the world. As a result, floods and floodplains need to be 'managed'. Today the common framework for dealing with floods (Parker, 2000) comprises of four general types of activities: (a) modifying flooding, (b) modifying susceptibility to flooding, (c) modifying the impacts of flooding, and (d) preserving the natural and beneficial functions of floodplains. Modifying flooding refers to structural flood control measures that are designed and constructed to keep the flood hazard away from people and buildings. Modifying susceptibility to flooding refers to activities designed to keep people and buildings away from the flood hazard. These are generally called non-structural mitigation measures and include a broad set of tools. Modification of impacts of flooding on people includes floodplain management activities. These activities do not reduce the amount of damage that floods might cause, but they help 'spread' the costs associated with those damages. The fourth set of management activities seeks to preserve the natural and beneficial functions of floodplains from an ecological perspective.

In this paper the focus will remain on the non-structural mitigation measures. Examples of traditional non-structural measures commonly used today include zoning ordinances, building codes, flood proofing, early detection and warning, emergency planning, education, and flood insurance among others. For example, the zoning measure is used to limit the type and extent of development in the floodplain. Building codes can be designed to ensure that new structures built in flood-prone areas are resistant to damage. Flood proofing can include building retrofitting in the form of sealing gates or small floodwalls. Other flood proofing options include relocation of vulnerable contents to higher floors in a building. Flood detection and warning systems provide sufficient time for individuals and communities to limit their losses in a flood.

Contemporary flood mitigation calls for a more integrated approach including both, structural and non-structural measures. This combined approach is intended to reduce human vulnerability to flooding rather than to rely exclusively on a physical confrontation with flood events. More intensive use of non-structural measures and the possible use of two new measures proposed in this paper can be viewed within the wider context of the need for all flood-prone communities to develop more hazard-effective and sustainable relationships with their environment.

The remaining part of this paper will focus on the two new measures that can be attributed to the advancement of computer sciences and information technologies in general. These advancements can be referred as revolutionary (NRC, 1993; GDIN, 1997) and measured for example by the growth in the number of space-based sensors, equivalent voice communication circuits and computers connected to the Internet. They provide an opportunity for further broadening of the context of non-structural flood mitigation and offer the potential for reducing flood disaster costs through better application of information technology to flood management.

Two new concepts: (a) flood management virtual database; and (b) flood management decision support; are presented in the following two sections of the paper. Their benefits are demonstrated through the description of prototype systems for the Red River basin in Manitoba, Canada, developed following the recommendations of the Red River Task Force and the International Joint Commission (IJC, 2000). Paper ends with a set of conclusions.

Flood management virtual database

Flood management data consists of a variety of data sets, each of which is used for specific purposes (Birkenstock et al, 2000). These purposes include flood forecasting, land use planning, emergency management planning, and other activities that are critical to dealing with floods. The types of data related to flood management include (Bender et al, 2000):

- **Topographic data** (elevations, land use, soils, vegetation, hydrography, etc.);
- **Imagery** (satellite images, aerial photographs, etc.);
- **Administrative data** (political boundaries, jurisdictional boundaries, etc.);

- **Infrastructure data** (roads, levees, wells, utilities, bridges and culverts, hydraulic structures, properties, facilities, etc.);
- **Environmental data** (threatened and endangered species, critical aquatic and wildlife habitat, archeological sites, water quality, etc.);
- **Hydrometeorologic data** (floodplain delineation, stream flows, precipitation, temperature, wind, solar radiation, soil moisture, discharge rating curves, flood frequency, etc.);
- **Economic data** (stage-damage relationships, insured values, industries, etc.); and,
- **Emergency management data** (emergency plans, census data, organizational charts, etc.).

There is a large amount of relevant flood management data that is usually maintained by various agencies, each with different levels of complexity. In general, each data series may consist of several data sets. Each data set may contain several features. For example in the Red River basin, the stream flow archive data series consists of several data sets: one for each hydrometric monitoring station. Each station includes several data features (or perspectives) such as peak flows, daily flows, monthly flows, etc. This typology is used to describe the available data, since some data sets are 'known' more than others.

A database system is a combination of one or more databases and a database management system. A database is a collection of data, and a database management system is a collection of programs that enable users to create and maintain a database.

The Internet technology can be used today to support data collection, processing and dissemination. At present, the Internet can be accessed through the local area network (LAN), telephone line, cable, or wireless (mobile) technology. Convenience that the Internet provides includes information browsing, database access and file transfers at any time and from nearly anywhere.

Two approaches can be considered in building an Internet-enabled database system: centralized and distributed. Centralized approach involves collecting data from different sources and storing them in a single dedicated database at one location. A web site connecting to this database is necessary to supply query interfaces to web clients. Distributed approach does not require centralized data storage. Instead, the data can be stored in the database of data provider and accessed through the Internet. This type of database solution relies on more advanced Internet and computer science technology and is known as the Virtual Database.

The virtual database (VDB) was described as "fundamental for success" in the IJC Report (IJC, 2000) and is considered one of the three main components of the decision support system being developed for the floodplain management in the Red River basin (Simonovic, 1999).
The virtual database is an Internet based data catalog that facilitates search by data type, custodian, location, and other attributes from a distributed confederation of data holding organizations.

Proposed concept has been tested through the development of the prototype VDB for the Red River basin that involved a number of steps presented below.

Evaluation of user data needs

At the beginning of VDB prototype development a series of communications have been conducted within the basin (Science Applications International Corporation, 1999). The intent of these communications was to help capture the data needs, critical communication links, and processing requirements necessary to perform emergency and floodplain management functions within the basin. Prototype focus was on the rural municipality (RM) of Ritchot. The users identified three types of information as necessary: numerical and descriptive information; spatial information and modeling tools for data analyses.

Virtual database functions

Red River VDB prototype was developed to test the following functional requirements of the flood management database: (a) data downloading and uploading; (b) spatial presentation and manipulation of flood-related data; and (c) distributed data processing. A large number of tests has been conducted (Huang, 2000) to investigate all database functions in a realistic environment.

Virtual database architecture

The conceptual architecture of the VDB as being developed for the Red River Basin is presented in Figure 1 (PhaseFour, 1999).

It shows the general configuration in terms of communication and data accessibility across a distributed or remote network of sites. Data providers have several options for providing access to data sets. These include:

a. Data Provider 1 stores its metadata on an external web server, but then retrieves information from within its firewall from internal operational systems. Data can be retrieved from this data provider online through a transactional system.
b. Data Provider 2 stores its metadata on an external web server and replicates relevant public data also to the external web server. No access through the firewall is permitted. The replication is intended to synchronize internal data sources with the external data store. Data can be retrieved from this data provider online via an application or FTP service.
c. Data Provider 3 stores its metadata on an external web server and posts static public data to an FTP site on the external server. Data can be retrieved from this data provider online via an FTP service.
d. Data Provider 4 stores its metadata only on an external web server and provides no access to internal or external data sources. Data cannot be retrieved from this data provider online. A formal request for required data may be fulfilled in an offline process.

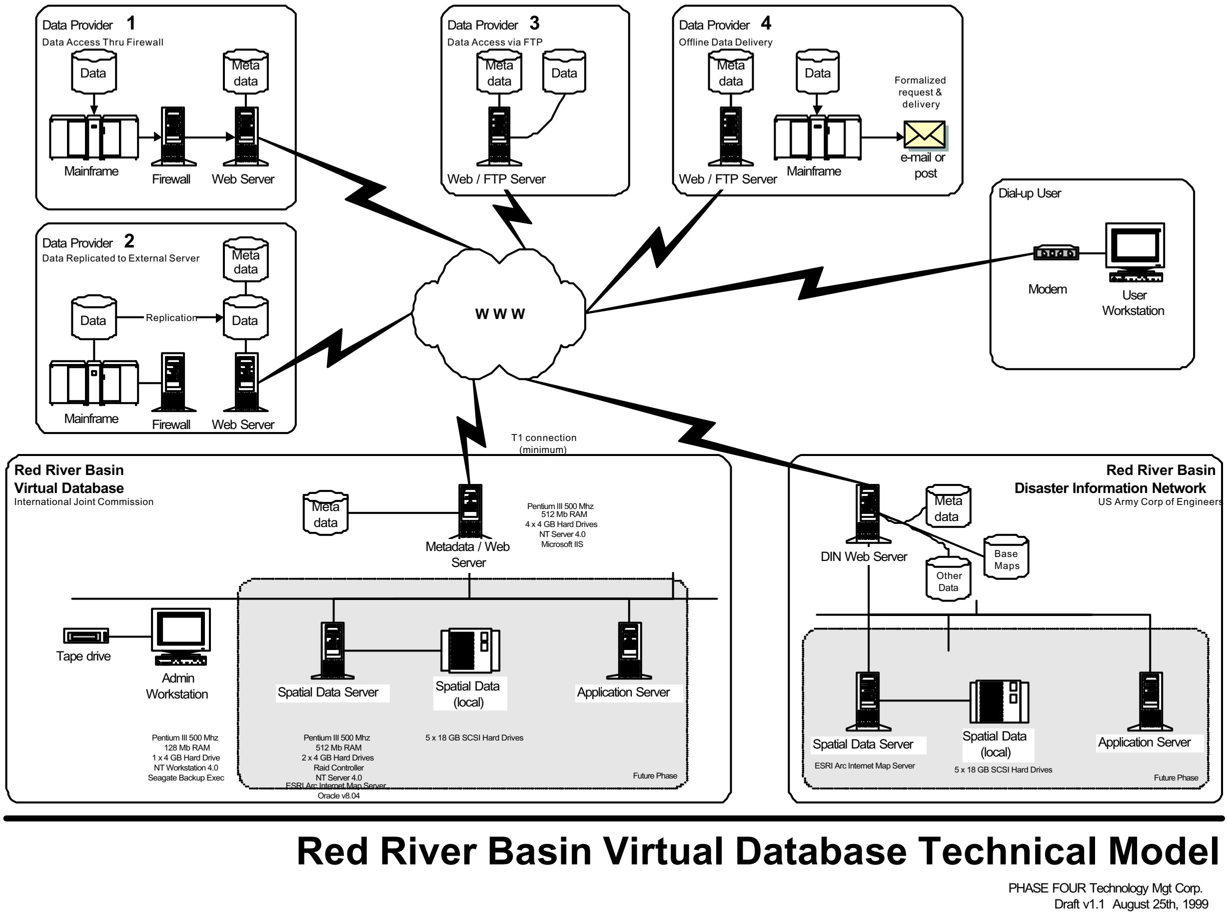

Figure 1. Schematic presentation of the virtual database concept (after Phase Four, 1999)

Prototype development has been conducted using a simple four-component architecture that includes: (i) user interface; (ii) data query; (iii) map query; and (iv) data processing tools library. *User interface* of the prototype VBD is developed in the form of a web page written in HTML and Java. It is designed to provide assistance to the user in accessing data, maps, and different modeling tools. *Data query* allows access to: (a) four water level data stations (Winnipeg floodway - upstream and downstream, St. Adolphe, and Ste. Agathe); (b) weather data (daily high and low temperature, and daily precipitation at Winnipeg airport and Glenlea); (c) information on available volunteers; (d) information on available material for emergency temporary flood protection; (d) information on available construction equipment; and (e) some information on the 1997 Red River flood. *Map query* allows user to access the following spatial data: (a) topography; (b) roads; (c) flooded area; (d) power lines; (e) communication network; (f) infrastructure; (g) buildings; and (h) land use. *Data processing library* contains programs for analysis of basic data. Prototype VDB for the RM of Ritchot includes four types of simple tools for the analyses of: (a) hydrologic data; (b) hydraulic data; (c) economic data; and (d) emergency assistance data.

Examples of user interface for accessing data, maps and models are shown in Figures 2a, 2b, and 2c and 2d, respectively.

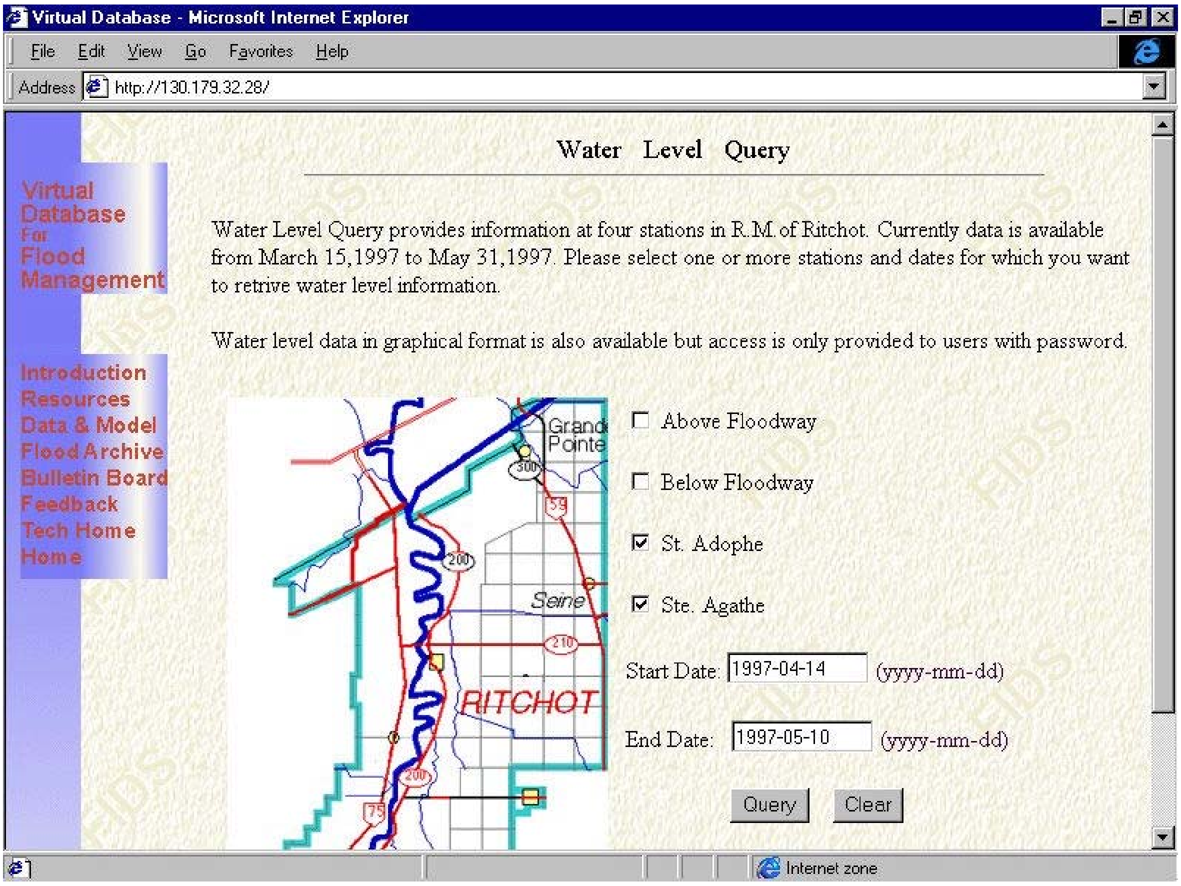

Figure 2a. Example of prototype VDB interface - Data query

Virtual database technical requirements

Implementation of four-component system architecture requires complex technical solutions (hardware and software). Prototype development was implemented within the research *Facility for Intelligent Decision Support* at the University of Manitoba using three servers to simulate different data providers connected by the Internet. One computer was used as the HTTP (web) server containing number of user interface web pages written in HTML and Java and supported by Java applets.

The same computer was serving as the database access server which provided for the connection to the relational database and transfer of the data from this database to the user. Technical solutions for this server may differ based on the type of database being accessed and the type of user. For example, a public HTTP server can provide the same function if a metadata is not used. In the prototype VDB for the RM of Ritchot access to one database is provided through the database access server.

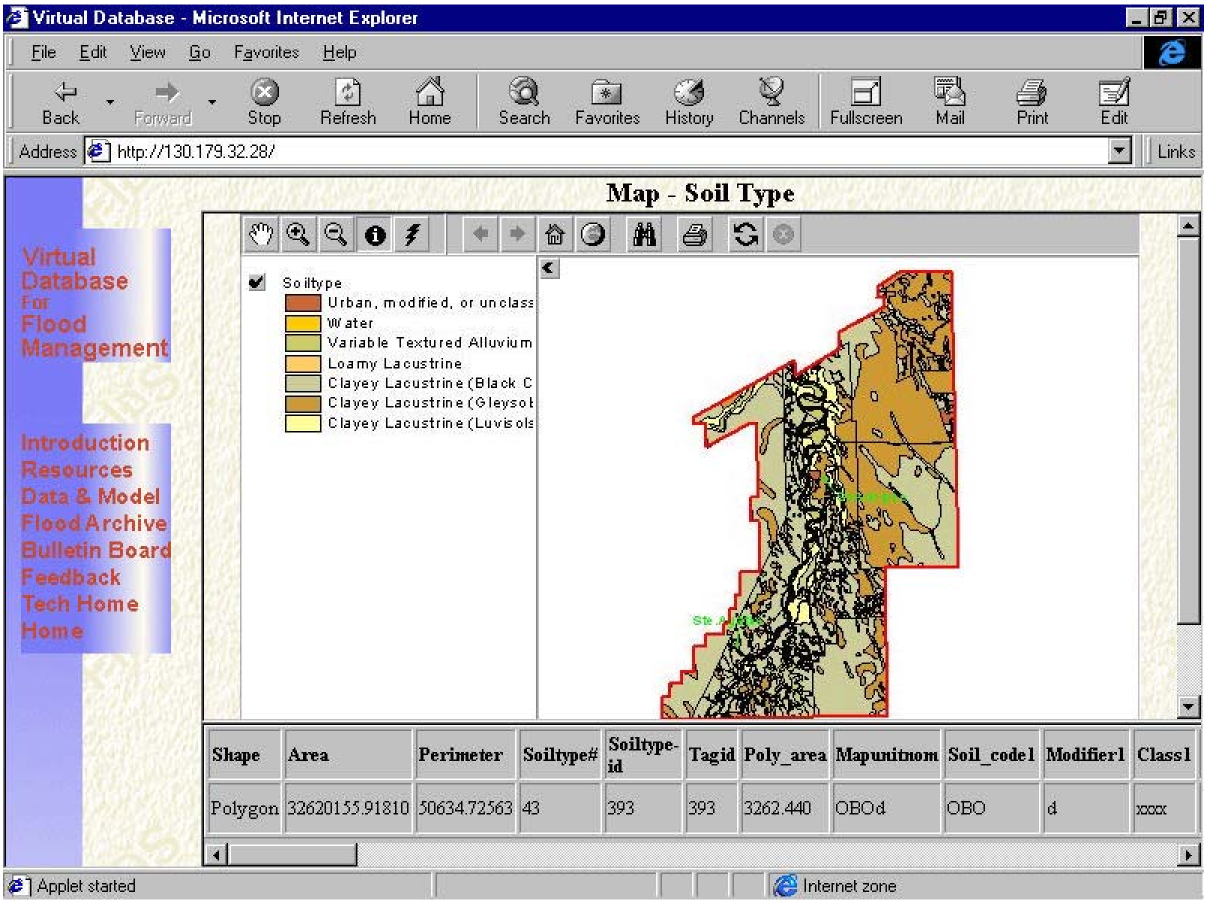

Figure 2b. Example of prototype VDB interface - Map query

The data query programs in the prototype VDB are written using Java servlets (a standard extension to the Java language) and therefore a Java servlet engine is also needed as a part of the public HTTP server.

The second computer provides support for the VDB map query. Three main tools used to support map query include an HTTP server, a GIS computer program and an Internet map server. Prototype development included VDBR HTTP server (known as MS Personal Server), ArcView GIS program, and ArcView Internet Map Server. Link between HTTP server and ArcView GIS program is provided through a Java applet.

The third computer was serving as the support for the model library. Models in the prototype VDB for the RM of Ritchot are written using Java applets and Java servlets and are installed on the public HTTP server. More complex modeling efforts will require further investigation in the appropriate technical support for efficient execution of models, submission of input data and access to modeling results.

The International Joint Commission has extended work on the Red River VDB prototype (www.rrbdin1.org). The Red River Basin VDB when completed will have no single data repository thus eliminating the need for regular updates of data to a central data clearinghouse. The data will be managed and maintained current by the existing responsible agencies where the appropriate scientific and engineering capability exists for sustainable and cost-effective data management. Over 800 data sets are cataloged using the selected metadata model (Bender et al, 2000). Over 600 key data sets are available for online distribution. Metadata, or documentation for each data set, is available from the Red River Basin Virtual Database (www.rrbdin1.org).

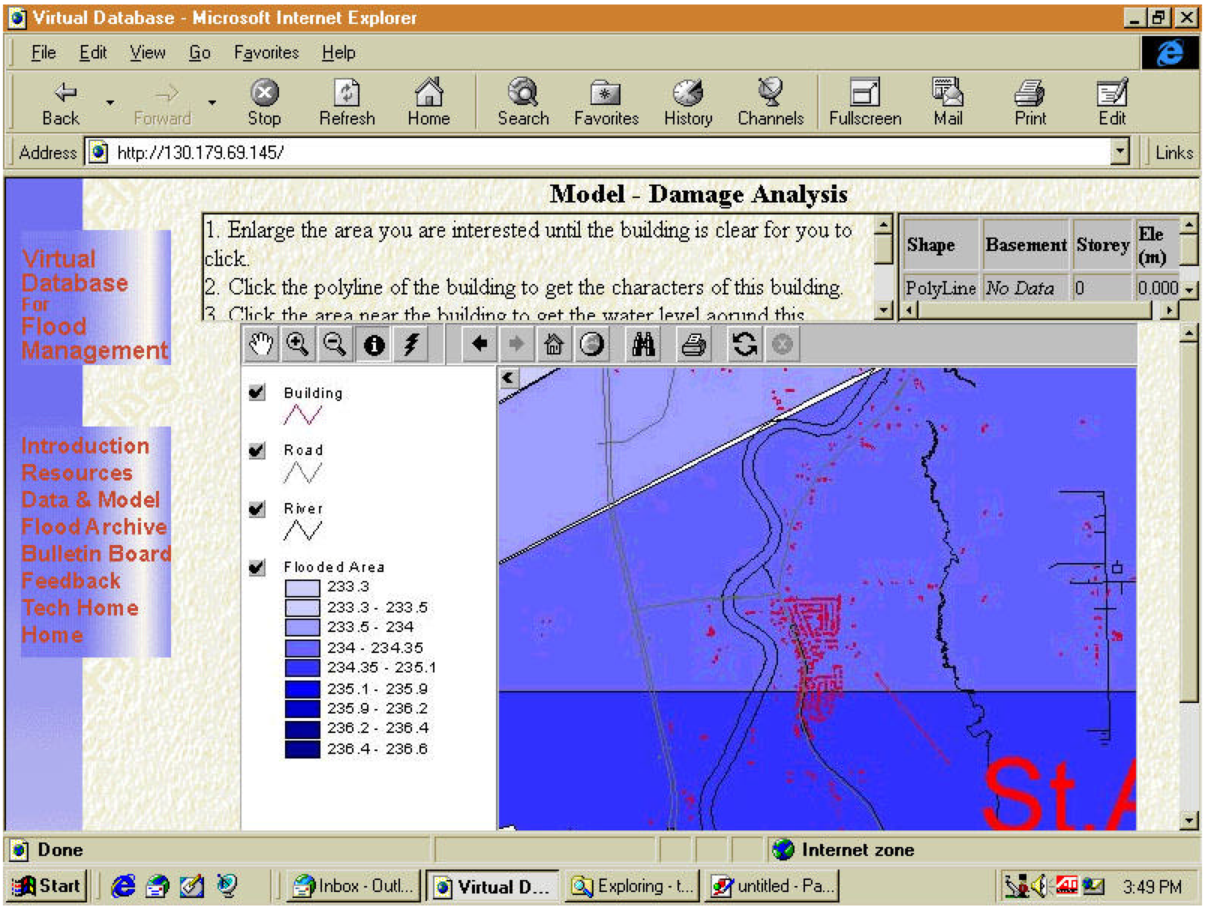

Figure 2c. Example of prototype flood damage model – Selection screen

Development of Decision Support Systems (DSS) is closely related to computers. An acceptable definition in the context of water resources management is: ‘A Decision Support System allows decision-makers to combine personal judgment with computer output, in a user-machine interface, to produce meaningful information for support in a decision-making process.

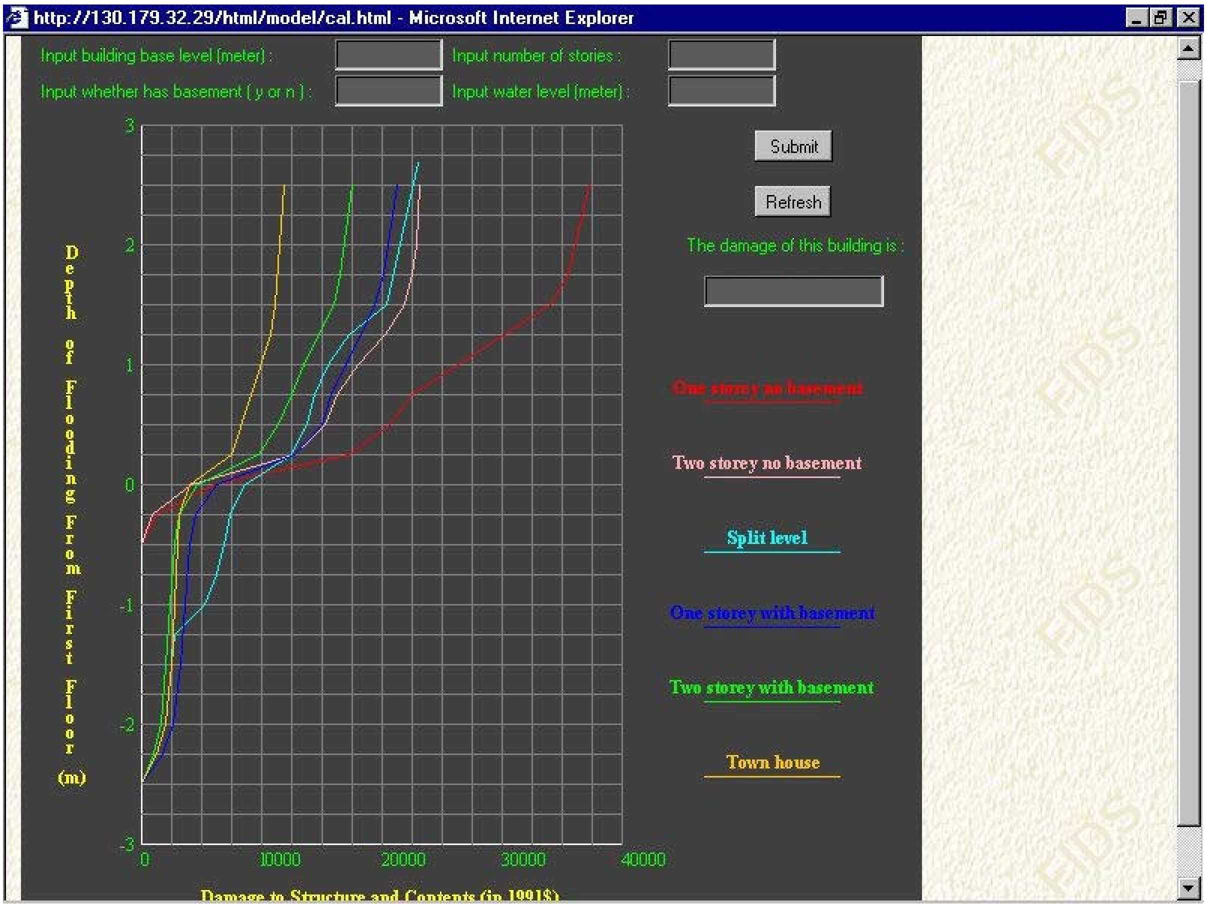

Figure 2d. Example of prototype flood damage model – Stage-damage calculation screen

Flood management decision support

Such systems are capable of assisting in solution of all problems (structured, semi-structured and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision-maker's approach to problem identification and solution', (Simonovic, 1996; 1996a).

Sustainable development principles are imposing a new set of requirements on the tools to be used in management of floods (Simonovic, 1999):

*(a) Problem identification***.** Sustainable flood management contains a number of semi-structured and non-structured problems (characterized by lack of data or knowledge, non-quantifiable variables, and a very complex description). Structuring of the problem, in this case, must be done by the human in the man-machine system using: analogy; problem redefinition; deduction; intuition; and approximation.

(b) Problem formulation (learning). DSS support in problem formulation focuses on two definitions of a problem. In the first case, a problem is viewed as unsatisfactory objective reality discovered by observations and facts. The decision-maker or expert has to define the problem. As a problem exists objectively, all participants in the decision-making process see it in the same way (even if there are different alternative solutions). Here, problem formulation is a preliminary step to DSS design. The second case presents an alternative view, considering a problem to be a subjective presentation conceived by a participant confronted with the reality

perceived as unsatisfactory. Here, common threshold values have to be defined by the different participants in the decision-making process before another procedure can take place. This approach requires integration of problem formulation process into the context of a DSS. It is important to note that problem formulation in sustainable flood management is more a social process than a technical one.

(c) 'What If' capability (adaptability). Many issues related to the implementation of sustainable flood management can be examined using the 'what if' approach. A typical 'what if' approach example is question of flood protection equity. In this example there is no need to rely on a flood specialist. The ability to ask 'what if' questions, to quantify uncertainties, and to recognize the sensitivity of results to varying assumptions stimulates creative and analytical process of decision-making. The process provides a common ground for communication.

(d) Use of analytical models (facilitation). Since sustainable flood management is principally concerned with the future and the implications of today's decisions, modeling capability is very important to grasp and manage flood damage reduction systems. This fact underlines the need for DSS modeling capabilities for: retrieval of data; execution of ad hoc analysis; evaluation of consequences of proposed actions; and proposal of decisions. The scope of a DSS is in the integration of such different facilities. The idea of DSS integrates different fields of science, and puts weight on social circumstances, which may decide or influence problem definitions and solution approaches.

(e) User-machine interface (interaction). DSS supports an interactive processing mode incorporating a user-machine interface that provides answers to identified problems or 'what if' questions. The user-machine interface provides answers that decision-makers can understand, when such information is needed, under their direct control. Therefore, DSS are intended to help decision-makers throughout the process of identifying and solving their problems. The merging of the computer output with the subjective judgment of the decision-maker provides a better basis for making efficient decisions.

(f) Use of graphics (fast response). Closely related to the previous two characteristics is the use of color graphics and GIS. In a DSS environment, graphic display of results allow users to quickly grasp the essence of large amounts of physical data and reduce considerably the printout into a few readily understandable graphs, charts and maps. It is the way to select the important information in a user-machine interface such that the user retains control during the decision-making process.

Prototype requirements

Floods are affecting growth and development at community and regional levels and have major impact on surrounding environment. There is a growing understanding, far from complete, of the interaction between physical processes causing floods and human activities (Smith and Ward, 1998). Public hearings and workshops organised in the basin by the Red River Basin Task Force of IJC have indicated desperate demand for public participation in decisions about the flood management, particularly at local and watershed scales. These trends are creating new demands from managers, policy makers, and the public for assistance in understanding flood related issues, developing and evaluating alternatives for flood damage reduction, and projecting the consequences of different courses of action. Consultations in the basin have also revealed many potential conflicts among social, economic and environmental values associated with flooding.

New computer technologies are providing access and analytical capabilities to wider audiences. The main objective in developing prototype decision support system is to provide assistance to decision-makers, including database access, descriptive and predictive models, geographic information systems, methods to involve stakeholders in the basin, and other tools and services.

Users of the decision support system

Flood management in the Red River Basin involves numerous participants such as: governments (local, provincial and federal in Canada and local, state, and federal in the USA); agencies (among others Manitoba Emergency Management Organization, Manitoba Environment, Prairie Farm Rehabilitation Administration, Environment Canada, Manitoba Rural Development in Canada and U.S. Army Corps of Engineers, U.S. Geological Survey, U.S. National Weather Service, Federal Emergency Management Agency, North Dakota State Water Commission, Minnesota Department of Natural Resources in the USA); private organizations (for example Red Cross, Salvation Army, and others); interest groups (such as Red River Water Resources Council, Red River Basin Board, North Richot Action Committee, Pembina Basin Conservation District, and others); and general public.

They all have different needs and responsibilities during planning, emergency management and flood recovery periods. Prototype proposed design provides support for all of them. Multiple-user needs and access to the system can be accommodated through the multiple-level user interface structure to be described later. Three levels of functional support can be provided within the decision support system to different users: (i) *Information support* includes maps, plots, animations, video, spatial data and reports to all potential users classified as information users. Possible groups of information users include general public, private organizations and other interested stakeholders; (ii) *Technical support* includes access to databases (archival, spatial, real-time, etc.) and modeling tools (descriptive, predictive, hydrologic, hydraulic, economic, environmental, etc.) to all technical users responsible for flood management in the basin. Most likely users of technical support are, between others, engineers of Manitoba Water Resources Branch and US Army Corps of Engineers. This level of support allows for data retrieval, analysis, processing and presentation as well as hydrologic and hydraulic forecasting, modeling, simulation and optimization analyses; (iii) *Application support* is provided mostly to decision-makers and managers at different levels of governments. Application users should be able with the assistance of the decision support system to focus on a practical problem for initial implementation, test and fine tune various aspects of strategy and supporting infrastructure.

Roles of the Decision Support System

Flood management is a decision-making process bordering between the art and science of making choices for desirable change, to solve problems and minimize negative impacts of floods. There are six major roles for the flood management decision support system: (i) guiding role through the decision-making process during planning, emergency management and flood recovery; (ii) assisting role in establishing the social, economic and environmental goals for managing floods in the Red River Basin; (iii) supporting role in describing the problem to be solved in terms of predefined objectives, and constraints for generation of alternative actions; (iv) active role in collection and integration of information that will support problem description, evaluation of consequences of actions, and learning; (v) aiding role in evaluation of alternatives using multiple and often conflicting objectives; and (vi) educational role in learning from the decision process itself and from outcomes of the implemented decisions.

The Design Architecture of Flood Management Decision Support System Prototype

Flood management in the Red River Basin is a unique process due to: (a) international character of the watershed (responsibility of different agencies; differences in decision-making process; different level of dependence on government support, etc.); (b) direction of the river flow (one of eight rivers in the world flowing North); (c) physical characteristics of the watershed and land use; (d) geographical location; and (e) climate of the region. Therefore the design of the prototype was adapted to particular conditions of the Red River Basin.

Proposed schematic presentation of prototype architecture is shown in Figure 3. Flood management decision support system prototype is proposed to include a web-based user interface that provides easy access to distributed virtual databases (through a shared metadata catalog),

and modeling tools. One of the main components of the proposed architecture is a virtual database discussed earlier in this paper. Improved flood management calls for more coordinated and integrated use of descriptive and predictive modeling tools. Hydrologic, hydraulic, economic, and environmental models are required to support decision-making in the basin and are included in the decision support system modelbase.

Hydrologic models combine precipitation and other inputs to forecast runoff in a river system. During the flood of 1997 on both sides of the border residents of the basin have expressed lack of confidence in the ability of responsible agencies to provide accurate forecasts because of out-dated technology, staff shortages, and inadequacy of the hydrometric network to provide essential information for flood forecasting. Prototype modelbase includes an original model for prediction of floods in the basin that is based on the use of artificial neural networks (Ahmad and Simonovic, 2001).

The need for hydraulic models that could be used to route forecasted flood volumes in the Red River Basin and, in particular, handle overland flow was identified in the IJC study (IJC, 2000). The purposes of such models fall into two categories: real-time flood forecasting, and planning and design.

Identified needs are: (a) real-time flood forecasting (determine flood levels and timing of peaks; determine hydrograph shape and inundation; account for overland flows; conduct backwater calculations at critical locations; incorporate infrastructure changes such as breaches and blow outs; carry out what if analyses); and (b) planning and design (post flood analyses for infrastructure evaluation and design; determine effects of flood operations; analyze structural and non-structural peak reduction proposals; conduct what-if and sensitivity analyses; define data and monitoring requirements; evaluate the aerial extent and volume of the 1826 flood).

Preliminary testing of one-dimensional unsteady flow models from Emerson to the Winnipeg Floodway inlet has shown that many requirements can be met by such modeling. It is also clear that in some regions needs for more powerful two-dimensional models exist. Wind effects, in particular, are a concern. Existing one- and two-dimensional models are available within the prototype (MIKE-11, MIKE-21).

Economic models that will help decision-makers to compare the flood-related economic factors of alternative means for flood damage reduction are also included in the prototype modelbase.

Their purpose is economic assessment of alternative flood damage reduction measures and investigation of potential incentives/disincentives facing individual activity in the floodplain. Economic models included in the modelbase are: expected annual flood damage (EAD) computation (U.S. Army Corps of Engineers, 1989); SID, structure inventory for damage analysis package (U.S. Army Corps of Engineers, 1989a); and flood damage analysis (FDA) package (U.S. Army Corps of Engineers, 1988)r.

Prototype modelbase also includes a social behavioral model for flood evacuation (Ahmad and Simonovic, 2001a).

A variety of decision modeling tools is incorporated in the modelbase to assist the decision-makers. Sustainable flood management is built on the assumption that an acceptable compromise must be achieved between the three main sets of objectives: ecological, economic and social. Each of these three sets constitutes a larger subset of specific objectives. The quantification and evaluation of the objectives and their associated trade-offs are the main tasks of multi-objective analysis tools. One of the possible ways for dealing with the complexity of sustainable flood management is a modified multi-objective framework. It requires definition of objectives for all stakeholders. Application of this formulation produces a set of nondominated solutions, as opposed to a single optimum followed by a subjective process to select one of the nondominated solutions, as a 'best compromise' solution. A special tool has been developed for the application in flood management that takes into consideration multiple objectives of the decision making process and different uncertainties involved (Bender and Simonovic, 2000).

Conclusions

Flood management virtual database and decision support system are presented as two new non-structural options. The distributed nature of four-component prototype VDB provides flexibility in selecting the location for, and type of hardware platform containing data necessary for floodplain management. VDB prototype for the RM of Ritchot demonstrated that the Internet technology is mature enough to support the development of virtual database for a complex domain such as floodplain management. It is also quite clear that this mode of support has many advantages when compared to more traditional centralized database model. It is important to point out that there are still some very important outstanding issues associated with providing online data access to the public. They are: network and data security for each data provider, cost recovery programs operated by some data collection and distribution agencies, and some concerns over inappropriate use of some data by the public.

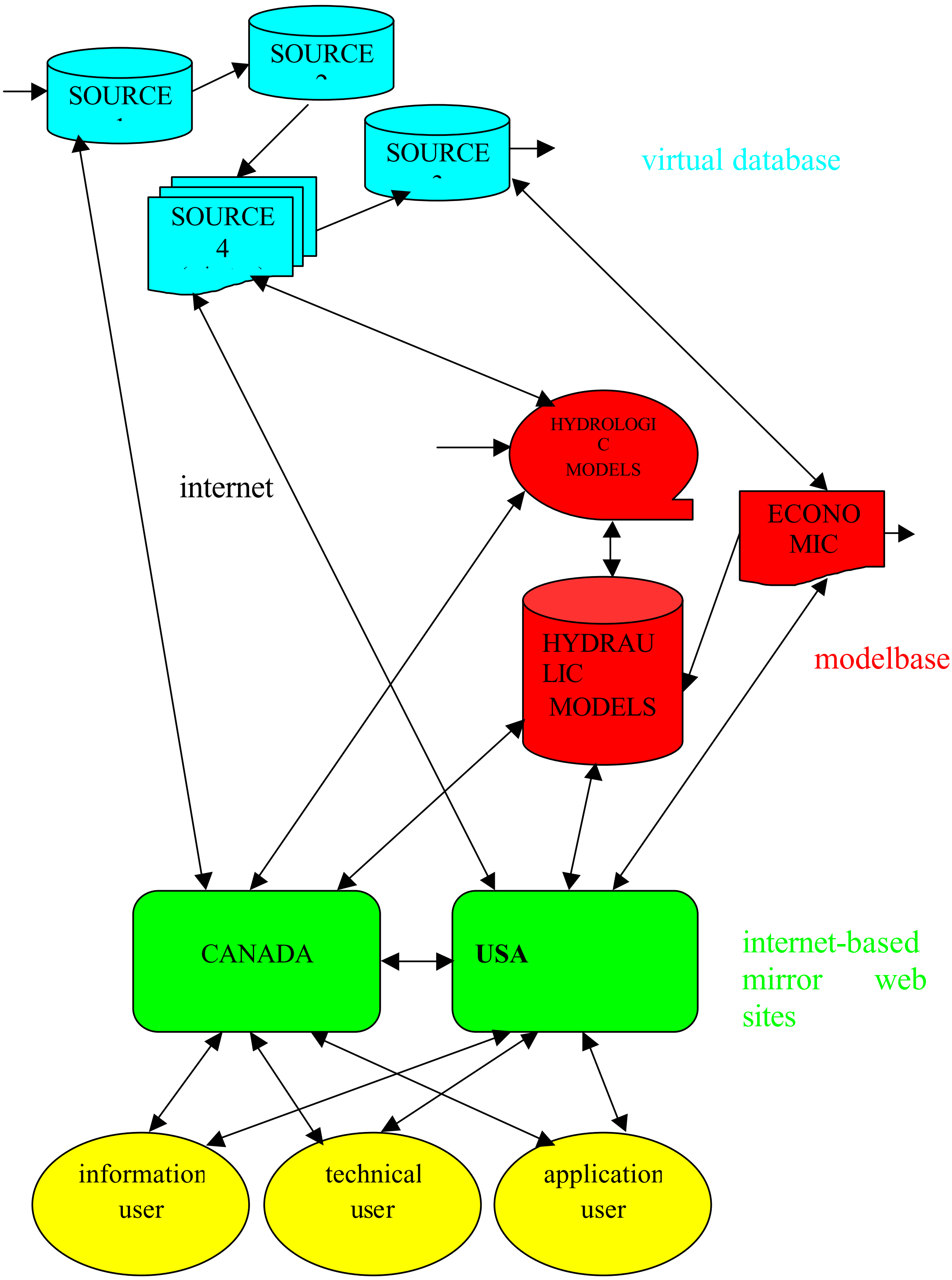

Figure 3. A prototype decision support system diagram

A decision support system approach provides an opportunity to meet the expressed needs of residents living in flood-prone areas for improvement in the flood management and provides support for a major change in the decision-making process. The initial impetus for developing flood management decision support system prototype was the need of the Red River Basin residents for more transparent and participatory flood management. Decision support system is envisioned as a non-structural tool for analyzing alternative mitigation and recovery strategies. It is proposed in this work as a way of making flood management process more transparent and efficient in reducing future economic, environmental and social impacts of floods. This concept has been very aggressively pursued in Europe after recent floods and with the assistance of the European Union (Bronstert et al, 2000; Toesmann and Koch, 2000).

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Use of Mathematical Tools in Non-structural Measures for Irrigation Water Management

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Abstract: Irrigation water management has significant economic implications in developing countries like India. While the structural infrastructure has been created with a huge financial investment in these countries, it is vital that appropriate non-structural measures be taken up for proper water management. Scientific policies of operation of irrigation reservoir systems need to be developed with the aid of mathematical tools and implemented in practice. In this paper, an overview of the available mathematical tools for irrigation system operation, crop water allocations and performance evaluation is presented. Recent tools and techniques of fuzzy optimization and fuzzy inference systems that incorporate imprecision in management goals and constraints and also address the interests of stakeholders are also discussed.

Keywords: Irrigation, reservoir operation, fuzzy optimization, performance evaluation, Stochastic Dynamic Programming, crop yield.

Introduction

Irrigated agriculture is by far the largest consumptive user of water in many developing countries like India. Irrigation water management thus has enormous economic implications for these countries. While the structural infrastructure for irrigation -comprising of reservoirs, canal networks, drainage works and delivery systems - is created at a huge financial investment, a commensurate effort is also essential on developing scientific water management policies. Developments in systems science, operations research and mathematical modeling for decision making under uncertainty have been usefully exploited for water resource management in many technologically advanced countries. Applications of such mathematical techniques in irrigation water management in the developing countries - at both macro as well as micro level - will lead to significant economic benefits. In this paper, an overview of the mathematical tools available for irrigation reservoir planning, operations and performance evaluation is presented.

Irrigation water management is characterized by uncertainty not only due to randomness of hydrologic variables such as streamflow, rainfall and evapotranspiration but also due to imprecision of management goals, constraints, crop response and stakeholder interests. Mathematical tools used in deriving policies for irrigation water management must address both these uncertainties. The stochastic optimization techniques (such as the stochastic dynamic programming, SDP) explicitly incorporate uncertainties due to randomness of hydrologic variables. The recent tools of fuzzy optimization and fuzzy inference systems address uncertainties due to imprecision in various components of the management problem. In addition, the Monte Carlo simulation technique is often used for evaluating the performance of an irrigation reservoir system. Table 1 shows the purposes for which these tools are used in water resources management problems, along with some examples in literature where the tools have been applied. Although the mathematical tools and techniques discussed in this paper are general in nature and are applicable to any irrigation reservoir system, they are particularly useful in extreme water deficit situations, such as those existing in many parts of South India.

Figure 1 shows water requirements for different sectors in India in the year 2010, emphasizing the importance of irrigation water management in that country. Similar situation exists in many other developing countries, also. Increasing the efficiency of irrigation through scientific operating policies therefore forms a major nonstructural measure for irrigation water management in such developing countries.

Table 1. Mathematical Tools Commonly Used in Water Resources Management

Objective	Mathematical Tools	Features	Examples
Long-term, Steady State Reservoir Operation	Stochastic Dynamic Programming	Uncertainty due to randomness of hydrologic variables	Loucks et al., (1981),Dudley (1988), Dudley and Scott (1993), Vedula and Mujumdar (1992), Vedula and Nagesh Kumar (1996)
Field-level Irrigation Scheduling	Dynamic Programming; Linear Programming	Allocation of Deficit Water; Competition Among Crops; Crop yield optimization	Rao et al., (1990) Dariane and Hughes (1991), Mannocchi and Marcelli (1994)
Real-time operation	Dynamic Programming; Linear Programming; Simulation	Adaptive operation; Real-time forecasts of hydrologic variables (inflow and rainfall)	Mujumdar and Ramesh (1997), Wardlaw and Barnes (1999)
Performance Evaluation	Monte-Carlo Simulation	Evaluation of reliability, resiliency, vulnerability and productivity index	Hashimoto et al (1982), Mujumdar and Vedula (1992)
Addressing conflict and stakeholders involvement	Fuzzy Optimization	Uncertainty due to imprecision in goals and Constraints	Kindler (1992), Fontane et al., (1997), Bender and Simonovic (2000)
Quantification of imprecision through fuzzy rules	Fuzzy Inference Systems	Fuzzy sets and fuzzy rules	Teegavarupu and Simonovic (2000), Despic and Simonovic (2000) Panigrahi and Mujumdar (2000) Shreshta et al (1996) Russell and Campbell (1996)

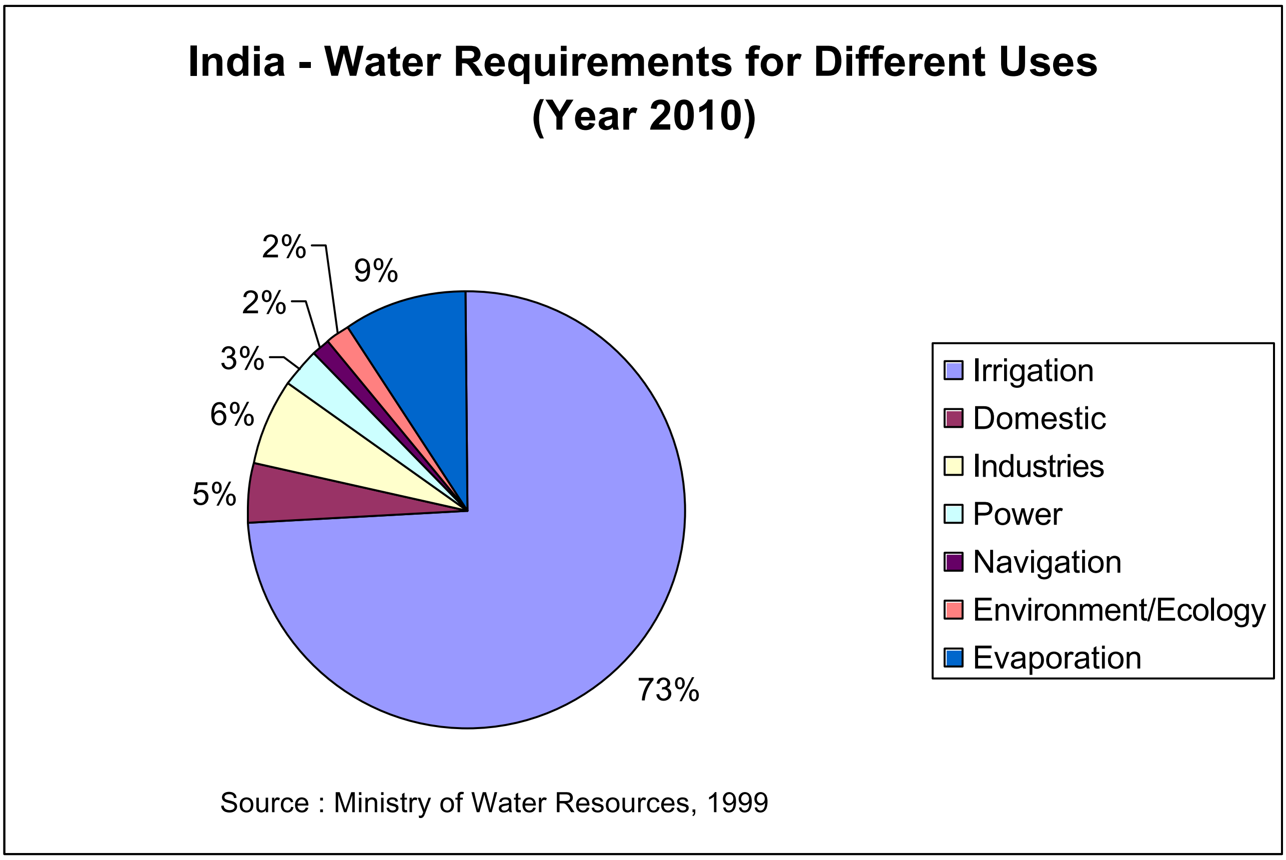


Figure 1. Water Requirements for Different Users – India (Year 2010)

The irrigation reservoir system to which most of the models discussed in this paper may be applied is schematically shown in Figure 2. The techniques are discussed with reference to this general system. The applications considered are for obtaining reservoir operating policies - both steady state, long term policies as well as real-time operating policies -, for field level crop water allocations and for the performance evaluation of the entire irrigation system as shown in Figure 2.

Stochastic Dynamic Programming

Decision making for reservoir releases for irrigation involves many subtle considerations such as the nature and timing of the crop being irrigated, its stage of growth, competition among crops for a limited amount of available water and the effect of a deficit water supply on the crop yield. From the point of view of efficient use of water at the field level, a single decision-making mechanism for the entire system – consisting of the reservoir and the delivery subsystem – is implied in the integration of the decisions at the reservoir level with those at the field level.

The decisions should be sufficiently explicit to indicate not only how much water is to be released from the reservoir in a given time period, but also how much of it should be allocated to a given crop. The uncertainty in various hydrologic variables involved – reservoir inflow, rainfall, evapotranspiration and the soil moisture – adds to the complexity of decision making.

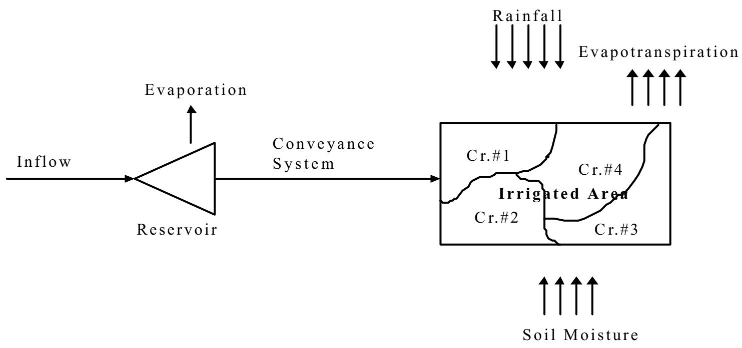


Figure 2. Components of a Typical Surface Water Irrigation System

Stochastic dynamic programming (SDP) can aid in the development of long-term reservoir operating policies for irrigation, given the complete cropping scenario in the command area. The irrigation release decisions are to be made in short time intervals such as a week, ten days or at the most, two weeks. Mathematical models which aid decisions over larger time intervals such as a month or a season are therefore inadequate, as they do not take into account the variability in irrigation demand within these time intervals. Mathematical models have therefore been developed to determine a long-term operating policy considering the intraseasonal irrigation demands of the crops, and competition among them in the face of a deficit supply (e.g., Dudley, 1988, Vedula and Mujumdar, 1992). The crop irrigation demands, which vary from period to period are determined from a soil moisture balance (Figure 3), staring with a known soil moisture (subscripted by m, in Figure3) at the beginning of period to obtain soil moisture at the end of the period (subscripted by n, in Figure 3).

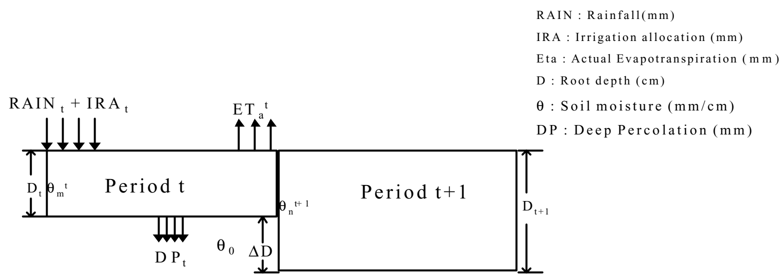
In the second phase, a stochastic dynamic programming model evaluates all the intraseasonal periods to optimize the overall impact of the allocation over a full year. The end result of this two phase analysis is a set of decisions indicating the reservoir releases to be made in each intraseason period and the distribution among the crops, of this release available at the crop level after accounting for losses between the reservoir and the application area.

Figure 4 shows the state transformation for the SDP problem for reservoir operation for irrigation. The four state variables being considered are: the reservoir storage, inflow, soil moisture and the rainfall in the command area. The recursive relationship for this 4 state variable SDP model is written as (Mujumdar and Vedula, 2000),

$$f_s^t\,(k,i,m,p) = \underset{\{l\}}{\mathrm{Max}}\,[G(k,i,l,m,p,t) + \sum_q \sum_j P^{t+1}(q)\, P_{ij}^{\ t}\, f_{s-1}^{t+1}\,(l,j,n,q)]\ \forall\, k,i,m,p \qquad (1)$$

where,

f_s^t (k,i,m.p) is the optimal value of the objective function in period t with s stages to go - with reservoir storage class k, inflow class i, soil moisture class m, and rainfall class p.



$$\theta_n^{t+1} D_{t+1} = \theta_m^{t} D_t + RAIN_t + IRA_t - Et_a^{t} - DP_t + \theta_0 \Delta D$$

Figure 3. Soil Moisture Balance

G(k,i,l,m,p,t) is a measure of the system performance, corresponding to the discrete classes k, i, l, m and p in period t, and is obtained by solving the allocation problem.
p is the rainfall class interval in period t
$P^{t+1}(q)$ is the probability of rainfall in class q in period t+1, and, P_{ij}^{t} is the transition probability of inflow being in class j in period t+1 given that it is in class i in period t.

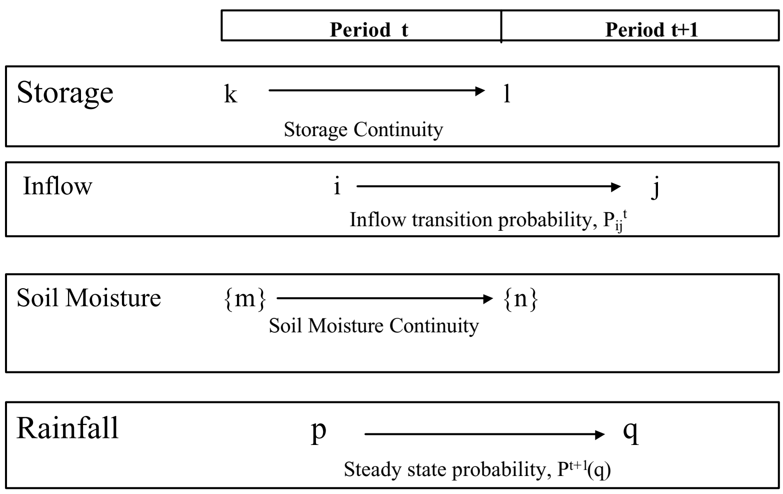


Figure 4. State Variables in the Stochastic Dynamic Programming Model

When this equation is solved recursively, a steady state solution is reached fairly quickly (within about 4 to 5 cycles). The steady state operating policy is specified as the end-of-the-period storage class, l*, to be maintained for a given initial storage, inflow, rainfall and soil moisture of each crop. The long term, steady state operating policy is essentially useful as a planning aid, and may be used to specify constraints on end-of-the-year reservoir storages to be maintained during real-time operation.

Real-time Operation

The real-time operation model is formulated as a dynamic programming problem (Mujumdar and Ramesh, 1997) for solution once at the beginning of each intraseasonal period. It uses forecasted inflows for the current period in real time (for which a decision is sought), and all subsequent periods in the year. These forecasts themselves are obtained using the latest available information on previous period's inflow. Solution of the real-time operation model gives the release decisions, and the crop water allocations for all periods in the year starting from the current period. Only the decisions on release and allocations for the current period are implemented and the state of the system (comprising of the reservoir storage, soil moisture of each crop and a crop production measure indicating the current state of the crop) is updated at the end of the period. Because the model is applied in real-time, the productive value of previous allocations to a crop, up to the beginning of the current period in real time would be known. This information is taken as an input to the model in deriving optimal releases for the subsequent periods in the year. The model thus updates the release decisions from period to period, making use of the latest available information. Actual rainfall in the command area, reservoir inflow, current production status and actual soil moistures of the crops all contribute to the updating of the release decisions for the subsequent periods. The irrigation allocation to a crop in a period is based on (a) its current production status, which is the net effect of water supplied to the crop (through irrigation allocations and precipitation) from the beginning of the season up to the beginning of that period, (b) available soil moisture in the root zone of the crop, and (c) competition for water with other crops. The first two conditions are introduced in the mathematical model through the use of two state variables, a crop production state variable and a soil moisture state variable for each crop. The third condition of competition with other crops is introduced through use of crop yield factors, K_y, in the objective function which indicate the sensitivity of a crop to a deficit supply, and which vary with the crop growth stages. The state variable for crop production indicates the production potential of a crop from the current period to the end of the crop season. Features of the real-time operation model are shown in Figure 5. In this figure, t_p is the current period in real-time, T is the last period in the year, and I_t is the inflow during period t. The operating policy model, which scans across time periods from the current period to the last period in the year is formulated as a deterministic dynamic programming model. The allocation model, which provides decisions on crop water allocations in an intraseasonal period, is solved for a given amount of available water, known soil moisture of each crop and a given crop production measure of each crop.

The recursive relationship for the operation model is written, for any intermediate period t, as,

$$f_t^j\ (k,\mathbf{M},\boldsymbol{\psi}_b) = \text{Max}\ [\varphi\ (k,l,\mathbf{M}, \boldsymbol{\psi}_b,t) + f_{t+1}^{j-1}\ (l,\mathbf{N}, \boldsymbol{\psi}_e)] \qquad (2)$$

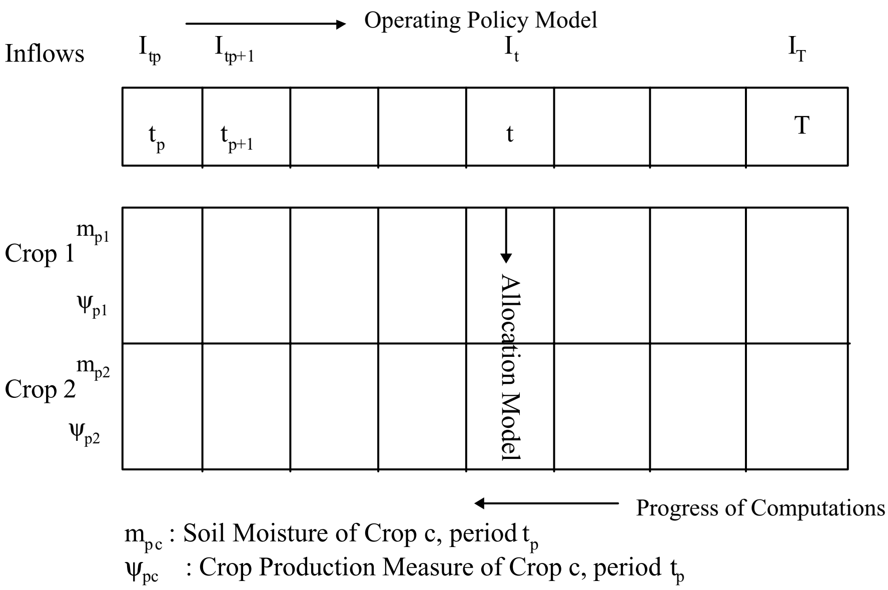


Figure 5. Real-time Operation Model

where,

$\mathbf{M}$ is the soil moisture vector, at the beginning of period, t
$\boldsymbol{\psi}_b$ is the crop production measure vector, at the beginning of period, t
$\mathbf{N}$ is the soil moisture vector at the end of period, t
$\boldsymbol{\psi}_e$ is the crop production measure, at the end of period, t
φ (k,l,$\mathbf{M}$, $\boldsymbol{\psi}_b$,t) is the system performance measure at period t, and,
f_t^j (k,$\mathbf{M}$,$\boldsymbol{\psi}_b$) is the optimal accumulated system performance measure upto period t

The system performance measure, φ (k,l,$\mathbf{M}$, $\boldsymbol{\psi}_b$,t), is obtained from the solution of the allocation model. The real-time operation model needs to be solved once at the beginning of each period in real-time specifying the current state of the system, in terms of the crop production measure, crop soil moisture and reservoir storage. The crop production measure may be computed from production functions, based on the actual allocations made to the crop up to the beginning of the current period in real-time. Solution of the real time operation model specifies the reservoir release for all subsequent periods, including the current period along with crop water allocations.

Performance Evaluation

When an operating policy is derived for an irrigation reservoir based on an objective function, the policy itself does not, in general, indicate how the system will actually perform, unless a criterion to this effect is embedded in the objective function. While a systems analyst is interested in arriving at the operating policy, the decision maker in charge of actual operations would look for implications of using the policy through answers to questions such as how often the system will fail and how quickly it will recover from a failure under a given policy of operation. It is therefore important that implications of reservoir operation with a given policy be studied keeping in view the interests of the decision maker. Three performance measures that are commonly used (e.g., Hashimoto et al., 1982) for performance evaluation of reservoir systems are, reliability, resiliency and vulnerability. In the context of irrigation, the vulnerability – which indicates the effect of failure – is replaced by a productivity index, which reflects the overall crop productivity under a given policy of operation.

The reliability of a system is defined as the probability that the system output is satisfactory. In case of irrigation systems, various interpretations of the concept of satisfactory output are possible. The system output in a period may be measured in terms of simply the water availability at the field level or it may be related to the soil moisture through the actual evapotranspiration of crops. Taking the output to be satisfactory in period t, whenever the water available for irrigation at the field level (after accounting for all losses from reservoir to the application area), is at least equal to the total irrigation requirement of all crops present in that period, the reliability may be computed as $P[X_t \geq D_t]$, where X_t is the water available at the field level in period t, and D_t is the total irrigation requirement in period t. This definition of reliability simply reflects the likelihood of a non-failure without specifying the extent of failure, when one occurs. It still provides a good measure of the ability of the system to provide the required irrigation.

While the system reliability gives the likelihood of a satisfactory performance, the resiliency gives the likelihood of the system recovery from a failure, once a failure occurs. If the recovery from failure is slow, it may have serious implications on the crop yield. A higher resiliency would mean a quicker recovery and hence one would prefer policies having high resiliency as well as high reliability. Mathematically, the resiliency γ, is defined (Hashimoto et al., 1982) as the inverse of the expected value of T_u, the length of time (number of periods, subsequent to a failure period) that the system output remains unsatisfactory. This is determined as,

$$\gamma = P\,(X_{t+1} \in Vt+1 \,/\, Xt \in U_t) \tag{3}$$

where X_t is the system output in period t, U_t is a set of unsatisfactory (failure) outputs in period t and V_t is a set of satisfactory (success) outputs in period t. Expressed in words, the resiliency is given by the probability that the system output in period t+1 is satisfactory, given that it is unsatisfactory in period t.

It is interesting to note that even with a high reliability and resiliency, the effect of failure can be quite significant on the crop yield, if such failures occur in critical preriods of the growth season of the crop and/or the extent of failure (deficit) is so large as to cause permanent damage to the crop. The performance of the system must also, therefore, be measured with respect to the crop yield resulting from a policy. An index called the productivity index, η, is defined as a measure of the relative yields of the crops. It is defined as the probability that the average of the relative yields among all crops in a year is greater than a specified value λ. That is,

$$\eta = P[(y/y_m)_{av} \geq \lambda] \tag{4}$$

where $(y/y_m)_{av}$ is the average relative yield resuling from the policy, determined from appropriate crop production functions, which relate the crop yield to evapotranspiration deficits occuring during various growth stages of the crop. The three performance indicators, viz., reliability, resiliency and productivity index are computed from the simulated operation of the reservoir system. Monte Carlo simulation technique is used to generate reservoir inflow sequences for a sufficiently long period of time (typically for one to two hundred years), and for a specified 'failure' event, the simulation results are examined for occurrence of failure, and the transition of failure to a success state. Reliability and resiliency are computed simply by a relative frequency approach, whereas the productivity index is computed from a crop production function (e.g., Doorenbos and Kassam, 1979), knowing the irrigation allocation and soil moistres for each crop during each time period, from the simulated operation.

Fuzzy Optimization

In most decision making problems related to water management, the objectives and/or constraints are often imprecisely stated and conflicting with each other. For example, in an irrigation water management problem, we may not have a clear (crisp) demarcation of crop yield returns. Instead what we would be looking for is to achieve "as high a crop yield as possible", when severe water deficits would constrain the irrigation in certain drought periods to "as low an allocation as possible". As the number of stakeholders increases in a decision making process, imprecision as well as conflict is bound to increase. Such imprecision and conflict in objectives (as well as constraints) may be incorporated in the decision models by using the concept of the fuzzy decision making introduced by Bellman and Zadeh (1970).

Bellman and Zadeh (1970) considered the following approach for decision making when there are *fuzzy goals* and *fuzzy constraints* for the set of alternatives (the decision vector) **X**, as decision making in a fuzzy environment. A fuzzy goal G and a fuzzy constraint C are fuzzy sets on the set of alternatives **X** which are characterized by the membership functions μ_G : [0,1] and μ_C: [0,1] respectively.

Fuzzy decision Z is defined as the intersection of a fuzzy goal G and a fuzzy constraint C. In other words, the fuzzy decision is defined by

$$Z = G \cap C \qquad (5)$$

And its membership function is defined by

$$\mu_Z(x) = \min\,(\mu_G(x), \mu_C(x)) \qquad (6)$$

In the general case in which r number of fuzzy goals G_1, G_2, ..G_r, and h number of fuzzy constraints C_1, C_2, ..C_h exist, the fuzzy decision Z is defined as the intersection of these.

$$Z = G_1 \cap G_2 \cap \ldots \cap G_r \cap C_1 \cap C_2 \cap \ldots . C_h \qquad (7)$$

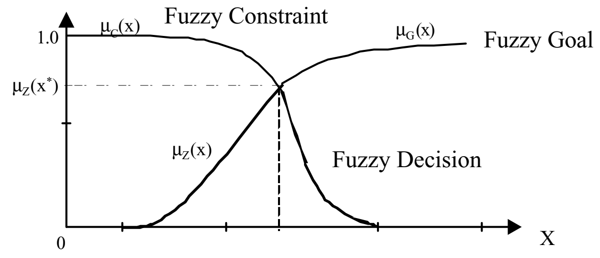
The fuzzy decision Z is characterized by the membership function,

$$\mu_Z(x) = \text{Min}\,(\mu_{G1}(x), \mu_{G2}(x), \ldots ..\mu_{Gr}(x), \mu_{C1}(x), \ldots \mu_{Ch}(x)) \qquad (8)$$

The optimal fuzzy decision corresponds to that x with the maximum degree of membership in Z. That is, the objective is to find x*, such that,

$$\mu_Z(x^*) = \max \mu_Z(x) = \max\{\min(\mu_{G1}(x), \mu_{G2}(x), \ldots\ldots \mu_{Gr}(x), \mu_{C1}(x), \mu_{C2}(x), \ldots \mu_{Ch}(x))\} \qquad (9)$$

This concept is shown in Figure 6 for one fuzzy goal G, and one fuzzy constraint C. In practical situations, a large number of fuzzy goals and fuzzy constraints will be present.



$\mu_Z(x)$: Membership Function of the Fuzzy Decision
$= \text{Min}\ [\mu_G(x), \mu_C(x)]$

x^*, Optimal Value of x, $\mu_Z(x^*) = \lambda^* = \max\ [\mu_Z(x)]$

Fig. 6. Fuzzy Decision

The space of alternatives X (that is, the decision space) is generally restricted also by precisely defined constraints and bounds known as the crisp constraints (e.g., reservoir mass balance, channel carrying capacity constraints, soil moisture limits of field capacity and wilting point, etc.). Incorporating such crisp constraints, the fuzzy multi-objective problem is stated as follows (e.g., Zimmerman, 1985, Kindler, 1992, Rao, 1993, Sakawa, 1995, Sasikumar and Mujumdar, 1998).

$$\text{Max } \lambda \tag{10}$$

Subject to

$$\mu_i(X) \geq \lambda \qquad \forall i \tag{11}$$
$$gj(X) \leq 0 \qquad \forall j \tag{12}$$
$$0 \leq \lambda \leq 1 \tag{13}$$

The objective function and the constrains together define λ as a "Maximum of minimum membership function", and is interpreted as maximization of the minimum 'satisfaction' among all stakeholders. In an irrigation management problem, the stakeholders may include decision makers at the field level, reservoir level, administrative level along with the farmers and the village groups. The response of the stakeholders to water allocations are incorporated in the decision models through the fuzzy membership functions $\mu_i(X)$, where i refers to a particular stakeholder. The upper and lower bounds of λ reflect two extreme scenarios in the system. The upper bound, $\lambda = 1$, indicates that all the goals have been completely satisfied and therefore represents a no-conflict scenario. The lower bound, $\lambda = 0$, indicates that at least one goal has a zero satisfaction level and therefore represents a total-conflict scenario. Any intermediate value of λ represents the degree of conflict that exists in the system. Kindler (1992) used fuzzy optimization for allocating water resources to multiple users in a river system. The level of water requirement together with the tolerance to a deficit in required quantity is interpreted in terms of the user's satisfaction. The objective of a user regarding the water quantity requirement is then transformed into a fuzzy goal. In the case in which the available water resources are insufficient to completely satisfy all the users, it is aimed to maximize the minimum satisfaction in the system through fuzzy optimization. The criterion of such an allocation has been termed a 'fair-compromise' principle.

Fuzzy Inference Systems (FIS)

Uncertainties due to imprecision exist in most decision making processes. In case of irrigation water management problems, these may stem from our lack of clear (crisp) knowledge on how a crop yield responds to variations in farm practices (e.g., type of seedlings, fertilizers, land preparation methods etc.), climatic variables (such as temperature, humidity etc.) and from a need to include social and cultural 'equity' criteria in the decision making process. Imprecision also stems from lack of adequate data, in which case assigning probability distributions to a random variable (such as reservoir inflow) may become impossible, and we may need to treat the variable as a fuzzy variable.

The fuzzy inference systems operate on "if – then" principle, where the 'if' part is a vector of fuzzy explanatory variables or premises, and the 'then' part is a fuzzy consequence. Operations such as fuzzification of inputs, formulation of fuzzy rule sets, application of the fuzzy operator, implication, aggregation, and finally defuzzification are carried out in obtaining decisions. Applications of the fuzzy rule based reservoir operations may be seen in Russell and Campbell (1996), Shreshta et al., (1996) and Panigrahi and Mujumdar (2000). Despic and Simonovic (2000) have provided an indepth discussion on the aggregation operators used in fuzzy inference systems.

Consider the example of addressing imprecision in the effect of temperature and farm practices on the relative yield deficit of a crop. The relative yield deficit, the temperature and the farm practices are all expressed as fuzzy sets and appropriate membership functions are defined as shown in the Figure 7. The farm practices are mapped to (0,1) with the aid of experts' input. These membership functions reflect the degree to which a particular variable belongs to a fuzzy set. For example, a relative yield deficit of 0.45 belongs to the fuzzy set, "Medium" deficit with a degree of 1, whereas a deficit of about 0.5 belongs to the fuzzy set of "Medium High" with a degree close to about 0.1 and also to the fuzzy set, "Medium" with a degree of close to about 0.5. Once the membership functions are defined for all fuzzy sets, the fuzzy rules are formulated based on experts' input on agronomic considerations. Typical fuzzy rules for this problem are expressed as, for example, "IF Temperature is *Low* AND Farm practice is *Poor* THEN the Relative yield deficit is *Medium*", "IF Temperature is *Low* AND Farm practice is *Average* THEN Relative yield deficit is *Medium Low*", and "IF Temperature is *Optimum* AND Farm practice is *Good* THEN relative yield deficit is *Low*". Such fuzzy rules are then used in conjunction with the crop water allocation model to optimally allocate a given amount of water among crops.

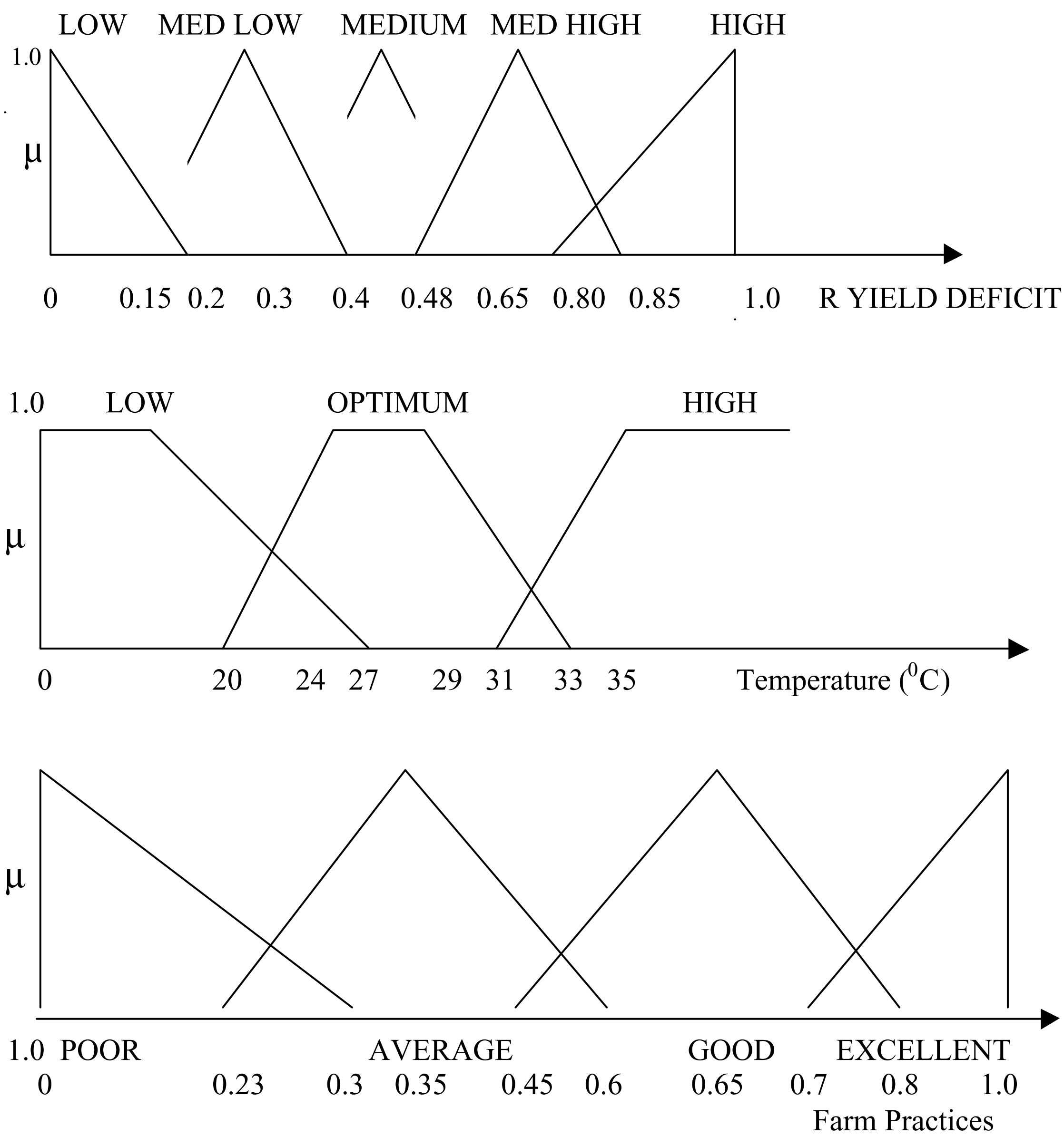


Figure 7. Fuzzy Membership Functions for Relative Yield Deficit, Temperature and Farm Practices

Concluding Remarks

Four decades of research on the development of mathematical models for water resources management has resulted in a number of useful mathematical tools for decision making. However, the actual implementation of results of the research has been rather slow. Simonovic (1992) has discussed various causes and possible remedial measures for closing the gap between theory and practice in reservoir operation decision problems. Decision support systems (e.g., Simonovic and Savic, 1989, Simonovic, 1991, Ahmed and Simonovic, 2001, Simonovic, 2002) that integrate mathematical models in a user friendly, knowledge-based and object oriented computer software serve the very important purpose of technology transfer to provide implementable decisions.

Mathematical models developed for aiding irrigation water management decisions must move closer towards ground reality for better applicability. Crisp idealization of various aspects related to crop yield response, operational objectives and long term goals of irrigation development may need to be relaxed and, instead of providing single valued 'optimal' decisions, the models should be capable of providing a band of acceptable, near optimal solutions. Also, for better acceptability of the mathematical models, inclusion of various stakeholders' interests must be ensured in the models. These conditions imply that a great deal of imprecision and conflict should be addressed in the mathematical models. The recent tools of fuzzy optimization and fuzzy inference systems are useful in this context. Applications of the fuzzy sets theory for modeling uncertainty due to imprecision in water resources management is relatively recent. For realistic applications, simultaneous considerations of both types of uncertainty, viz., uncertainty due to randomness of hydrologic and climatic variables and that due to imprecision of management goals and constraints, in a single integrated model is critical. Results from such mathematical models would then be able to serve as effective non-structural measures for irrigation water management.

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Estimation of Flooding Risk Indices Using GIS and EO Data

By

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Abstract: The risk of flooding is a major concern in many areas around the globe. In the latest years river flooding occurred quit frequently in Romania, some of which isolated, others-affecting wide areas of the country's territory. The modern management of spatial data related of river flooding largely relies on the functional facilities supplied by the Geographic Information System (GIS), combined with Earth Observation (EO) data and hydrological models. This paper assumes this approach, in view to establish a methodology, which should further allow determining the flooding risk, using representative indices of a region, at a scale compatible with a synthetic representation of the territory. There are stressed the facilities supplied by the geo-referenced information and the remotely sensed data to manage floods during their characteristic phases. Information obtained from EO data proved to be useful for the determination of certain parameters necessary to monitor flooding: hydro-graphic network, water accumulation, size of floodable surface, land impermeability degree, water absorption capacity, resilience to in-soil water infiltration, etc. The application was developed for the Arges basin in Romania, a critical area, keeping in mind that it withholds many localities, including the capital and also important economic centres. The GIS database allows obtaining synthetic representations of the hydrologic risk for the Arges basin, through separate or combined use of the risk parameters. The advantage consists in that the system allows greater parameters combination diversity, allocated with various weights associated to the three main criteria: morphology - hydrology, land cover/land use and vulnerability.

Keywords: Natural Hazards, Flooding, Remote Sensing, Earth Observation (EO), Risk Indices, Geographic Information System (GIS), Sensitive Area, Land Cover/Use, Image Processing.

Introduction

Flooding and the accompanying landslides (mainly caused by abundant precipitation) affect and destroy houses and households, bridges, roads, railroads, telephone and power network, crops, water supply systems, hydrometric installations, leading to dysfunction in the warning and hydrological forecast activity.

Ever since the first satellite observations of the Earth, numerous studies have been achieved using information from the satellite systems and the facilities of GIS technology in the topic of managing flooding connected phenomena. Satellite images are objective information sources, available in time and relatively cheap, for the determination of parameters necessary to monitor and assess floods and their consequences (Wang et al., 1995). Based at the beginning on the use of LANDSAT data, this activity gained peculiar interest once the possibility yielded for a combined use of remote sensing data from the optic and microwave domain respectively.
The management of data helping to monitor the generated high floods largely relies on the functional facilities supplied by the GIS systems, combined with satellite image-data and the

hydrological models (Harms et al., 1996). This approach may be used in different phases of establishing the sensitive areas such as: the management of the database - built up from the ensemble of the spatially geo-referenced information; the elaboration of the risk indices from morpho-hydrographical, meteorological and hydrological data; the interfacing with the models in order to improve their compatibility with input data; recovery of results and the possibility to work out scenarios; presentation of results as synthesis maps easy to access and interpret, additionally adequate to be combined with other information layouts resulted from the GIS database.

Study area – The Arges Basin

The study area represented by the Arges hydrographical basin (Figure 1) is affected by flooding as ascertained by the frequency of these phenomena: 1972 – 1973, 1975, 1979, 1983, 1991, 1997, 1998. This area is so much the more critical one, considering that it comprises the capital, as well as several other important economic centres. As regards the results damages, the high flood of March 29 - April 10 1997, alone affected nearly 600 households and annexes, over 4000 ha of arable land, 4 bridges, more than 40 footbridges and 40 Km of roads, along with important hydrotechnical constructions.

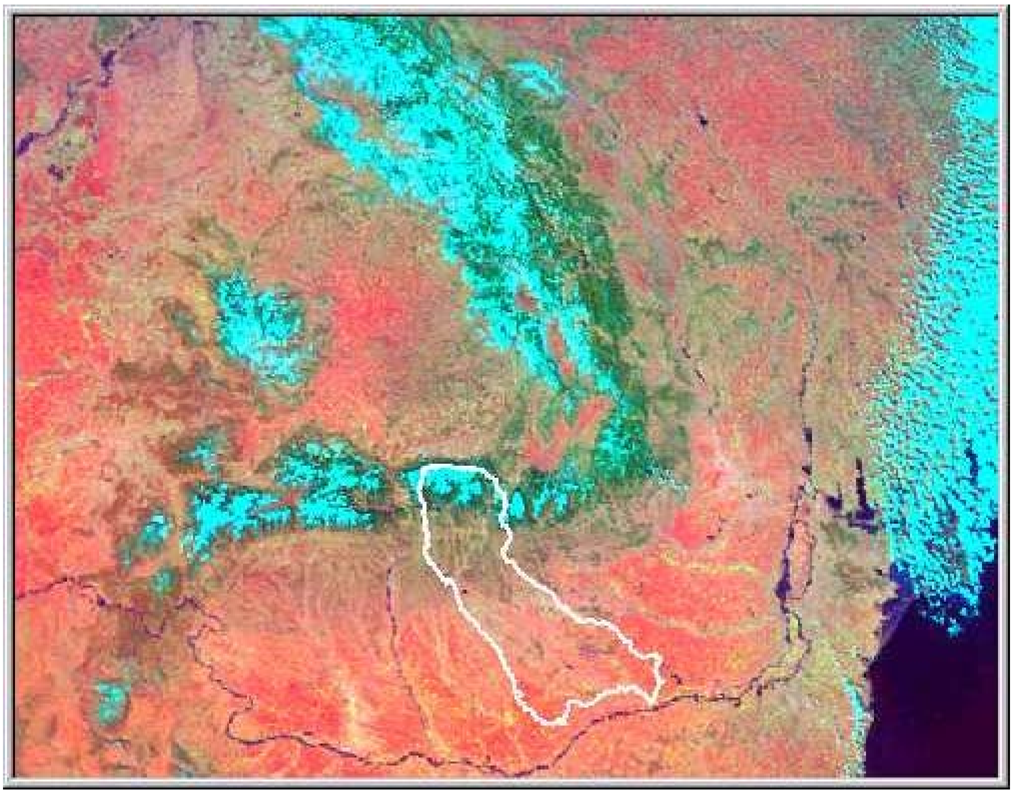

Figure 1. The study area represented by the Arges hydrographical basin

Situated in the south of the country, the Arges river, its tributaries included, constitutes one of the most important hydrographical basin in the country with respect to its hydro-energetic potential and the water supplies of the industrial centres and crop lands. Through the position it occupies in a physical-geographic ensemble with specified characters, with a moderate continental climate, sufficiently humid in the mountain areas and drier in the plain, is playing a large variety of the relief and lithology, the Arges river hydrographical basin has a complex hydrological regime.

Working Method

Forecasting and monitoring phenomena associated to torrential precipitation is very difficult, one hand because of the nature of these phenomena, characterised through violence and spontaneity and on the other – because of the basins' characteristics (size, geomorphology) which make the propagation time, i.e. the reaction interval, generally very short. In this context, prevention and forecast activities must be based on prior identification and localisation of the sensitive areas. Approaching the previously formulated issue was made at two levels:
that of the risk degree vis-à-vis the various parameters causing or not flooding;
that which takes into account the human presence in the sensitive areas. This implies to establish the vulnerability degree, defined function of the human and material cost that flooding may induce.
Integrating the notion of risk in quantifying the potential damages proves to be an absolute necessity, determined by the proportion of the human and economic consequences of the phenomenon.

Given the spatial length of the Arges hydrographical basin the initial work map scale was chosen 1: 200 000. The elaboration of digital maps concerning the elements of interest for floods monitoring and for the analysis of their consequences, aimed at answering to self evident small scale forecast necessities, but also to supply documents presumed to bring forth a certain number of answering elements, so as to use information regarding land cover/land use and territory management.

Having in view the sizes of the Arges basin and its physical-geographical characteristics, as well as the practical and lucrative constraints, the basin was divided into three areas: upper, middle and mower. The acquisition of the cartographic data and elaboration of thematic layouts as part of the GIS system under ARC/INFO software environment, was made corresponding to these three sectors. The system's facilities allow unifying the layouts of the mentioned basin sectors for ensemble representations as well as to combine the different thematic layouts.

The basic entity in hydrology is the sub-basin defined as the geographic environment, which supplies a water flow. The induced hydrological activity depends on its surfaces geological structure and disposition of the hydrographical network, as well as on the climatic and topoclimatic characteristics. In this sense, there was performed the division of Arges basin in its belonging sub-basins.

Structure, Attributes And Functions Of Geo - Referenced Database

The database was structured as an ensemble of file-distributed quantitative and qualitative data. Organising the files was focused on a relational structure as information thematic layouts. With this approach, spatial objects may be described through three main property classes: those determining the objects position on the Earth surface, those establishing spatial relations with other objects and those referring to the spatial objects attributes.

Coding the existing relationships between spatial entities was performed with the help of facilities supplied by the complete topology of the PC ARC/INFO software. The achievement was viewed of a database apt to allow elaborating indices of hydrological risk to flooding, made up of information associated to three main criteria:

morphology and topography: hydrographical network, dams and channels network, sub-basins, confluence order; hydrographical and/or drainage network density; mean slopes of the sub-basins; mean slopes in different river sections;
land cove/land use: land impermeability, in-soil water resilience to infiltration;
vulnerability to flooding: communication ways network (highways, railroads), localities, meteorological, hydrometric stations network and rain measurement points network.

The first information group allows describing the basin and sub-basins from the viewpoint of the physical-hydrographical characteristics. Classifications and hierarchizations may be made, function of the mountainside and riverbed slopes, of the confluence orders and network or draining density. Such analysis, vis-à-vis the risk degree associated to one parameter or combination of parameters (risks accumulation) may be performed for each sub-basin, basin sections or at whole basin scale.
As regard the notion of confluence order associated to a sub-basin, this can be defined function of the number of sub-basins it supplies directly or of the ensemble of sub-basins it supplies from upstream. Since the mean slope of a water flow is generally incorrectly correlated with the mean slope of the mountainsides belonging to the associated sub-basin, both parameters concerning the slope were taken into- account as risk factors.

The second group is useful to classify the sub-basins function of the main types of vegetation cove and land use, thus allowing their characterisation function of the land impermeability degree, of their absorption capacity or resilience to in-soil water infiltration. The notion of soil impermeability was connected to the necessity to determine the absorption capacity and resistance to in-soil water infiltration. It must be mentioned that these parameters represent "potential capacities", having in view that the dry soil hypothesis is considered. Certainly, results differ sensibly if the soil is already water saturated at the beginning of the period with precipitation; in this case, coefficients must be modified.

The third group characterises the degree of vulnerability to flooding, being mainly determined by the human presence (associated to localities) in the high-risk areas. It is thought that the vulnerability aspect may be evaluated taking into consideration the existence of inhabited areas in the vicinity of water flows, of dams and other protection hydrotehnical works, of the potential degree of afflicting the communication ways network, etc.

The database was connected so as to allow obtaining synthetic representations of the hydrological risk for the Arges basin, through using the risk parameters separately or combined. For instance, there can be considered the mean slopes of the mountainsides, the in-soil water absorption, the water resilience to infiltration and the vulnerability degree. The advantage consists in that the system allows greater parameters combination diversity, allotted with various weights and associated to the mentioned three main criteria.

The layout of the hydrographical network encompasses the network properly (including the temporary flows), as well as the existing lakes and storages. The basin was divided in 168 sub-basins, along with the basin rests belonging to a confluence or storage.

The layout of the communication ways comprises the roads network (motor highways, state highroads, and modernised and local roads), along with the railroad network. A separate layout was allocated to the locality network, comprising the capital, municipalities, cities, communes and villages. For example, figure 2 displays the thematic layout with the localities and communication ways network.

According to the structure of the hydro-meteorological data-collecting network, separate layouts were created, comprising the meteorological, precipitation and hydrometric measuring points.

Retrieving Flood Related Information From Satellite Data

Within the framework of flood surveying, optical and radar satellite images can provide up-to-date geographical information. Integrated within the GIS, flood derived and landscape descriptive information proved to be further helpful before a crisis for flood prevention perspectives, during a crisis for flood detection and mapping and after the crisis for impact assessment and damage evaluation. High and medium spatial resolution satellite images like NOAA-AVHRR, SPOT-HRV and ERS-SAR were use in order to produce different kind of flood related thematic information, depending on the data acquisition time (Tholey et al., 1997): before flooding, the image enables the description of the land cover of the studied area under normal hydrological conditions (assuming that the river's width is compatible with the image's spatial resolution); during flooding the image data set provide information on the inundated zones, flood map extent, flood's evolution; after flooding, the satellite image point out the flood's effects, showing the affected areas, flood deposits and debris, with no information about the initial land cover description unless a comparison is performed with a normal land cover description map or with pre-flood data.

After the geo-referencing in the stereographic map projection system, both visual and computer assisted photo-interpretation, as well as automatic digital image processing methods have been applied in order to assess the extension of the area covered by water and the major land cover classes within the flooded zones. It was necessary to merge the photo-interpretation with the knowledge of the topography of the zones, thus excluding some uncertain areas.

LANDSAT-TM and SPOT-XS data have been used to perform a first analysis for the inventory purposes under normal hydrological conditions as well as for determining the hydrographical network. The methodology for the achievement of the land cover from medium and high-resolution images obtained within the Remote sensing Lab of the National Institute of Meteorology and Hydrology is based on the observation of the following requirements:
the form of this type of information must be at the same time cartographic and statistic;
it must be apt to be produced at various scales, so as to supply answers adapted to the different decision making levels;
updating of this piece of information must be performed fast and easily.

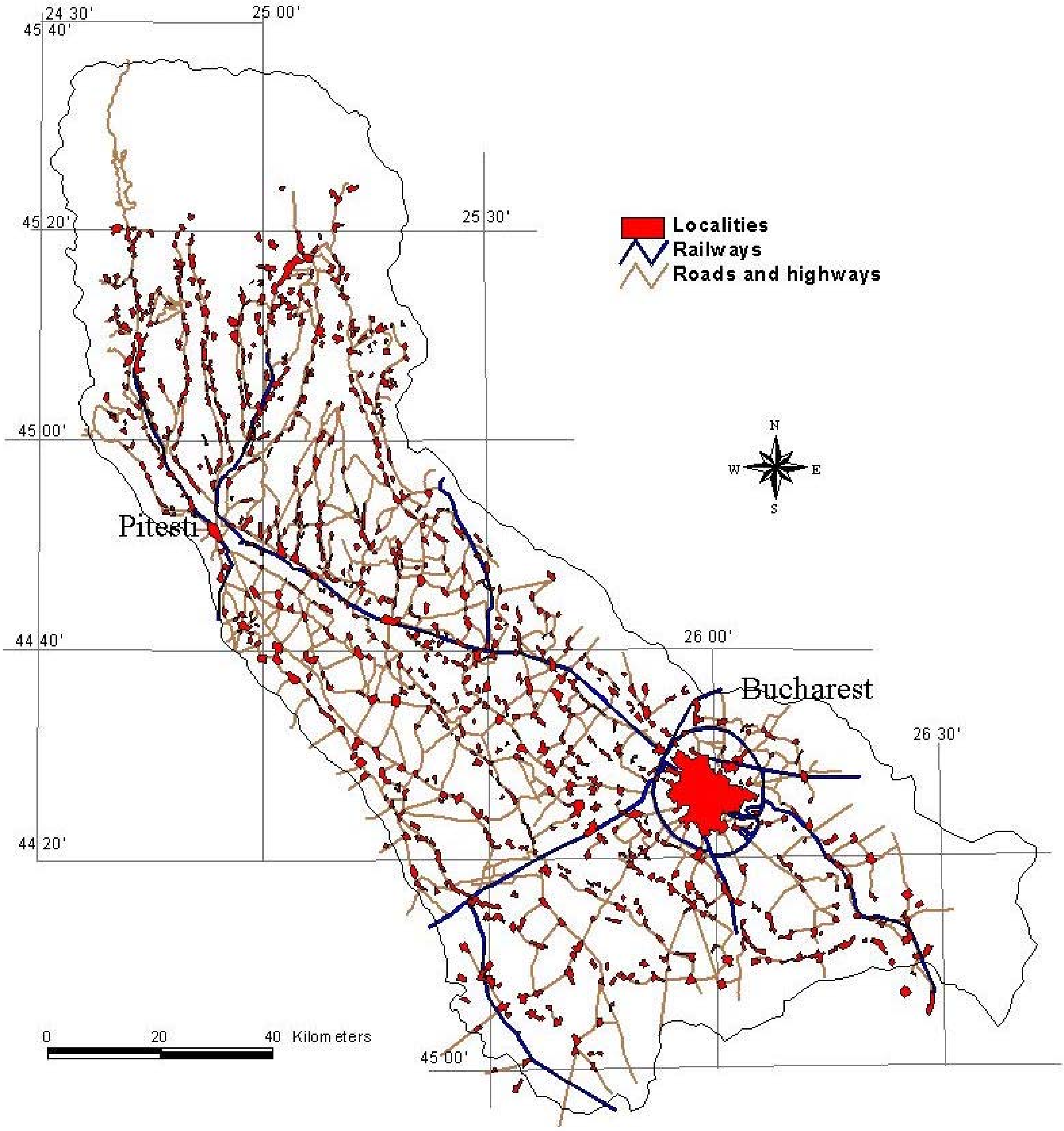

Figure 2. GIS thematic layout with localities and communication ways Network in Arges basin

The radiometric information contained in these images allows also the derivation of both biophysical criteria and those from human activity, through supervised standard classification methods or advanced segmentation of specific thematic indices. Once extracted, these geographical information coverages were integrated within the GIS for further water crisis analysis and management.

One of the purpose of the study was the elaboration of a methodical tool that is capable of allowing the passage from radiometric data to the information content, which offers an opportunity of interpreting the image with the consequent creation of relationships between the image structure an the elements of the corresponding real scene. The interpretation and analysis of remotely sensed data in order to identify, delineate and characterize flooded areas was based on relationships between physical parameters such as reflectance and emittance from feature located on the surface: reflectance and/emittance decreases when a water layer covers the ground or when the soil is humid; also reflectance and/emittance increases in the red band because of the vegetation stress cause by moisture; reflectance and/emittance changes noticeably when different temperatures, due to thick water layer are recorded. In the microwave region the water presence could be appreciated by estimating the surface roughness, where water layers smooth surfaces dielectric constant is then heavily correlated to soil water content.

In case of SAR images the multitemporal techniques was considered to identify and highlight the flooded areas. This technique uses black and white radar images of the same area taken on different dates and assigns them to the red, green and blue colour channels in a false colour image. The resulting multi-temporal image is able to reveals change in the ground surface by the presence of colour in the image; the hue of a colour indicating the date of change and the intensity of the colour the degree of change. The proposed technique requires the use of a reference image from the archive, showing the « normal » situation.

Estimation Of Flooding Risk Indices Based On Parameters Extracted From Satellite Images

Although satellite sensors cannot measure the hydrological parameters directly, remote sensing can supply information and adequate parameters to contribute to identify and map the hydrological risk at the basin level (Puyou-Lascassies et al., 1996). Of the numerous information deriving from analysing high spatial resolution satellite images (e.g. SPOT, LANDSAT), a series of criteria were determined from the radiometric information contained in image-data concerning the biophysical and anthropical parameters of basins.

The morphological characteristics were extracted by image processing and from the Digital Terrain Model (DTM). The nature of this information, through the spatial and temporal coverage attributes may contribute to build complete databases suitable to allow simulations or scenarios. The following parameters were organised in hierarchical form by classes, in order to produce synthetic and representative information:
hydrographical network density – defined as the ratio between the length of the water flows over a surface and the respective surface (sub-basin). The water accumulation as a risk factor may be estimated function of the hierarchically categories for the network density: the denser the network, the faster the access speed to this network and thus the occurrence of high floods is more likely.
water accumulation (usually associated to high flows) defined by the water amount captured by the hydrographical network; thus the larger the capturing area, the more important the water amount reaching the bed.
size of potential flooded surfaces – the larger the surface, the higher the risk.
soils impermeability degree – revealing the areas (sub-basin) with poorer vegetation coverage. These data are weighted through the slope and reported to basin surface.

These four parameters are weakly correlated: this explains through the complexity of the phenomenon and the parameters spatial extension used to define the hydrological risk.

Data resulted from LANDSAT-TM and SPOT-XS satellite images processing, by ERDAS Imagine Professional software, were used to compute the risk parameters. Also, the CORINE LAND COVER database obtained through computer assisted photo-interpretation constituted a valuable source of information. Classification of land cover/land use was performed according to EUROSTAT catalogue in 44 classes. An example of the obtained results for the Arges superior basin is presented in Figure 3.

Taking into account the necessity to obtain information concerning the parameters useful to quantify the flooding risk degree (impermeability degree, resilience in-soil water infiltration) regrouping of the land cover/use classes by the following 9 main types was performed: artificial (built) surfaces (AS), open spaces with little or no vegetation (OS), vineyards and orchards (VO), agricultural lands (AL), forests (F), pastures and natural grasslands (P), heterogeneous lands belonging to households (LH), humid surfaces (HS), lakes and water bodies (WB).

These are useful information for the determination of the impermeability degree, function of the identified classes that may be assigned with impermeability coefficients, within a scale ranging from 0 to 1, as exemplified in the table 1. These coefficients allow determining the mean impermeability coefficient by sub-basin, weighted with their mean slopes.

Table 1. Impermeability coefficients associated to the main land cover and land use classes in the Arges basin

Land cover/land use class	F	AL	VO	LH+P	OS	HS	AS
Impermeability coefficient	0.4	0.5	0.7	0.75	0.8	0.9	1.0

In view to establish the water absorption capacity over the basin surface, the land cover and use classes were regrouped by a number of four classes, to which specific coefficients have been assigned (table 2): artificial surfaces (AS), agricultural lands (AL), vineyards and orchards (VO), pastures and grass lands (P), lands belonging to households (LH).

Table 2. Water absorption capacity values associated to the main land cover and land use classes in the Arges basin

Land cover/ land and use class	AS	AL	VO	LH + P
Water absorption capacity (mm)	60	300	280	360

The allotted coefficients represent the precipitation amount, which a field is able to absorb. These coefficients are related with a runoff delay factor: the higher the coefficient, the higher the soil capacity to absorb water; also, the higher the water absorption capacity at the level of a spatial unit, the higher the precipitation necessary in a time unit for runoff occurrence.

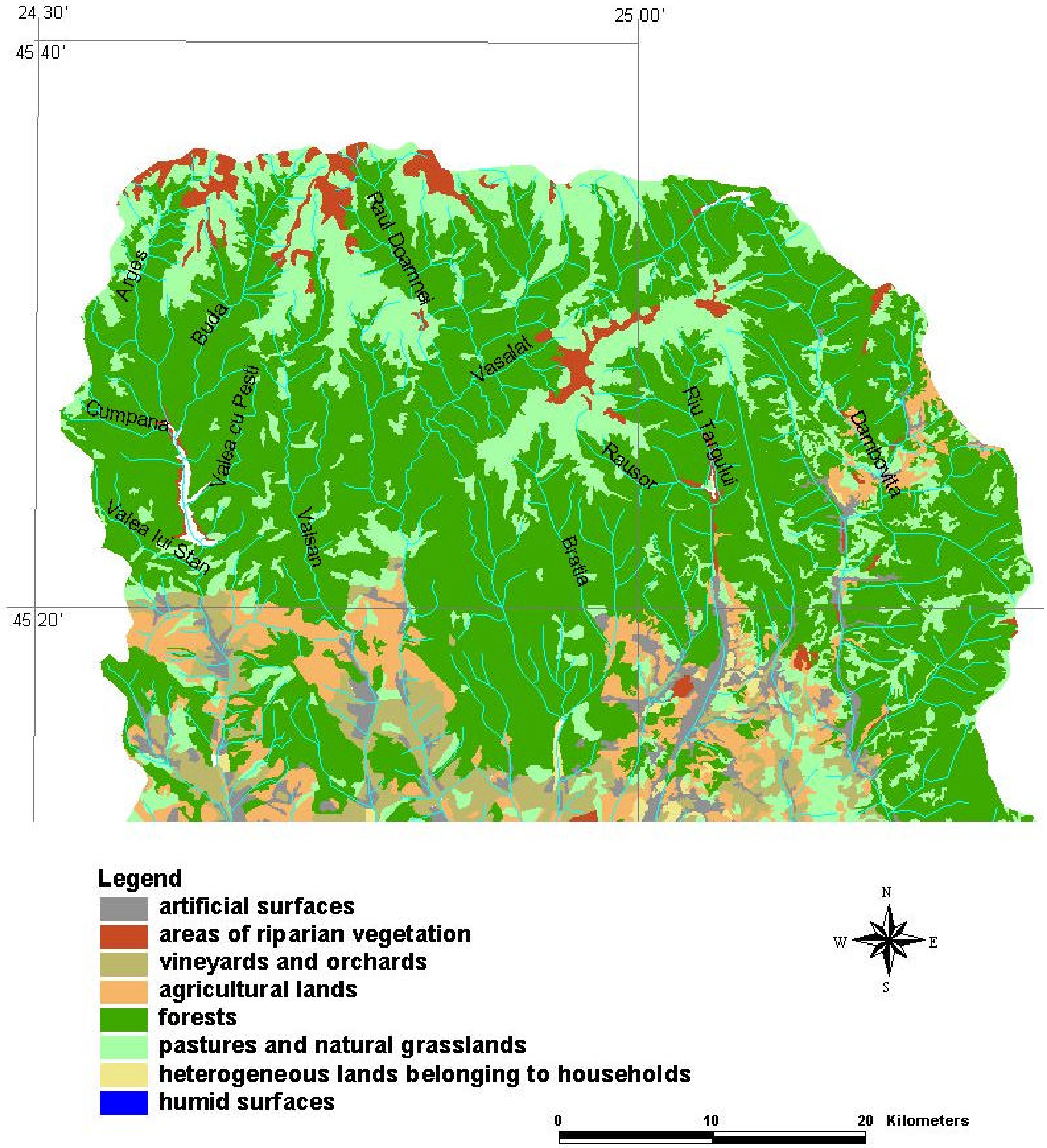

Figure 3. Main land cover/land use classes of the Arges superior basin obtained from LANDSAT-TM satellite data

The analysis concerning the water absorption capacity at the sub-basin level has allowed establishing a hierarchy of the basins function of their capacity to retain the water before the occurrence of the surface runoff.

Another parameter connected to the land cover and use is the resilience to the in-soil water infiltration. The respective coefficients represent the considered area capacity to retain water at the beginning of the precipitation episode, before surface runoff start. Coefficients are expressed as precipitation amount (in mm) necessary for runoff start on slope, assuming water-saturated soil. Actually this the water amount that the soil surface can retain, function of the various

coverage, such vegetation, built areas, etc. the notion of flooding risk is in this case directly connected to the water runoff on slopes, known that the more intense the runoff, the higher the flooding risk.
In view to establish the resilience to in-soil water infiltration, the land cover and land use classes were regrouped by a number of four classes, to which the specific coefficients were assigned (table 3).

Table 3. Resilience to in-soil water infiltration values associated to the main land cover and land use classes in the Arges basin.

Land cover / land use class	AS	AL	VO	LH + P
Resilience to in-soil water infiltration (mm)	10-20	3-7	3-5	8-15

On the basis of the mentioned risk parameters, as well as on the vulnerability degree expressed by the human presence (localities) seven classes were defined a qualitative scale (high – low degree).

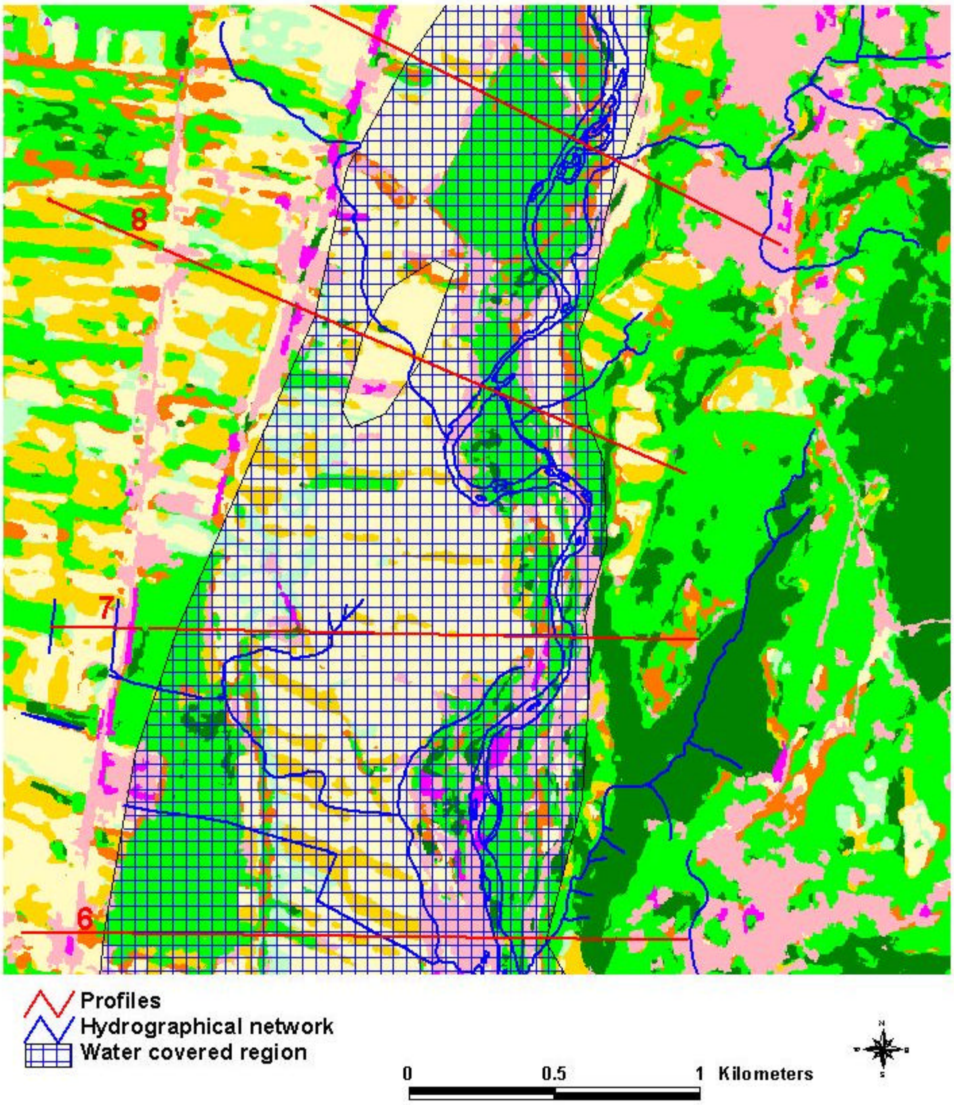

Figure 4. The potential flooded area with 0.1% probability obtained by hydraulically modeling merging with the land cover/land use. The middle section of Arges River - Maracineni region

Hydrological hazard related with the risk assessment to flooding requires a multidisciplinary approach. Coupled with the hydraulic modelling, the contribution of geomorphology can play an exhaustive and determining role especially with the application of remote sensing and GIS techniques. Using the GIS database that include the DTM, the land cover/land use maps and the vector info-layers (hydrographical, dams and canals networks, the communication and localities network, etc) outputs of hydraulical simulations can be superimposed in order to elaborate the hazard maps to flooding. This information allows an accurate location of the zones affected by flooding and inventory of the damages. For example in the figure 4 is presented the potential flooded area with 0.1% probability obtained by hydraulically modeling, merging with the land cover/land use map, in the Maracineni region located in the middle section of Arges basin.

Conclusions

Considering the necessity to improve the means and methods to assess and monitor flooding, the paper presents the capabilities offered by remotely sensed data and GIS techniques to manage flooding and the related risk in a basin-test of Romania.

High satellite images proved to be a very important tool, through the synoptic vision of the territory and the geo-morphological data they represent.

The analysis of the hydrological risk indices was associated to the topographic, morpho-hydrographic, and vulnerability characteristics within the Arges basin. The study encompassed both the risk degree levels associated with various parameters that condition and determine flooding, and the one, which takes into account the human presence in sensitive areas. This approach implies establishing the vulnerability degree defined function of the costs of human and material nature which flooding may determine.

It was planned to design and build a database, which will help to elaborate the flooding hydrological risk indices. This database contains information associated to three main criteria: morphology-hydrology (sub-basins size, density of hydrographical network and/or the drainage, confluence order, the mean slopes by sub-basin, the mean slopes by river sections, land cover/land use (land impermeability, in-soil water absorption capacity, resilience to in-soil water infiltration) and vulnerability to flooding. The database allows obtaining synthetic representations of the hydrologic risk for the Arges basin, through separate or combine use of the risk parameters, as well as for interfacing with the hydrological models in view to improve them as regards compatibility with input data, recovering results and the possibility to achieve scenarios.

The information extracted from satellite images of high spatial resolution represents useful data for the determination of certain parameters necessary to administrate flooding: hydrological network, water accumulation (usually associated to high discharges), size of potential flooded surfaces, land impermeability degree, etc.

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Flood Control Management System for Reservoirs as Non-structural Measures

By

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Abstract: Flood control operation of reservoirs can play a major role in alleviating flood losses. Flood control management system for reservoirs, an important non-structural measure, will benefit to make full use of the flood control capacity of the existing reservoir projects. The paper is a summary of the national programming about the flood control management system for reservoirs in China. The background, objectives, main challenges, contents and key technologies of the programming are introduced. The issues of the integration method and technology of the flood control management system are addressed. Emphasis is concentrated on object-oriented design of system, integration of models and methods, as well as database development.

Keywords: flood control; integrated management; object-oriented; database; non-structural measure

Introduction

Flood disaster is one of the most damaging natural disasters in China, with annual average losses more than 200 billion yuan(1 US$ equal to 8.3 CNY$) in recent years. As major structural measures to defend against floods, more than total number of 86,000 reservoirs have been established in the past fifty years. These reservoirs have great role on mitigating flood losses together with other flood protection measures. A typical example is the flood control operation of Gezhouba Reservoir, Geheyan reservoir and Danjiangkou Reservoir for 1998 floods of the Yangtze River. The three large-scale reservoirs are at the main stem and tributaries of the upper and middle reaches of the Yangtze River. Their joint operation with other flood control projects have avoided the use of division flood regions and decreased the losses with up to more than tens of billion yuan for the 1998 floods. The flood control operation of the four large-scale reservoirs at the main stem of the Liaohe River for 1995 floods is another example. Dahuofang reservoir, Qinhe Reservoir, Chaihe Reservoir and Guanyinge Reservoir had reduced the losses by 14.3 billion yuan for 1995 floods with magnitude in more than 100 years return periods. After 1995 floods in the Liaohe River and 1998 floods in the Yangtze River, the governments from national to local have realized that the flood control operation of reservoirs can play a major role in alleviating flood losses but there are some problems in flood control management for reservoirs. Most of the existing flood control management systems for reservoir were established for special purposes and are lack of data share and communication with governments, it is very difficult to for decision-making departments to get real-time information in short time. In order to make full use of the flood control capacity of existing reservoir projects and to improve the national level of the flood control operation for reservoirs, the National Flood Control and Drought Defying Chief Headquarters of China has commissioned Dalian University of Technology (DUT), Hohai University, and Wuhan Hydroelectric University to develop an integrated management system for flood control of reservoirs (IMSFCR) since 1998, with a duration of five years. The objectives are to establish a standardized flood control software system of multi-reservoir, integrated real-time data acquisition and processing, precipitation analysis, flood forecasting, reservoir system analysis, information query, multi-media tutorial and some of the recent methodologies of flood control based on large scale database management system.

This paper addresses the issues of the software integration of flood control management system for reservoirs. Emphasis is concentrated on object-oriented design of system, database development as well as integration of models and methods. The main challenges, structure framework and custom designed functions of IMSFCR are briefly described.

Main Challenges

The main challenges in developing IMSFCR lie in dealing with the complexity of typical systems, the interface integration and standardization of software system. It is because China is a country with a vast territory and there exist substantial differences in flood conditions determined by variations such as physical geography, hydrological and meteorological characteristics at different locations. Owing to these variations, methods employed in the reservoir flood control system are determined to a large extent by the purposes and the scope of the project. In addition, the data available has an effect on the choice of models. Hence, extensive model libraries will be established, which may take a lot of time and effort. Advances in computer technology have made it possible to simulate the flood control management processes in an integrated and comprehensive framework. The flood control management system for reservoirs involves directly with real-time data acquisition and processing, precipitation analysis, flood forecasting, reservoir system analysis, information query, as well as multi-media tutorial. Large-scale database management system (DBMS) is the basis of the integrated system. A distributed model requires the analyst to acquire, maintain, and extensively utilize a referenced database. It is greatly different from the traditional text files systems. Database sources including input, output, calculation, query and temporary procedure should be used in all operations. Another question, which arises here, is whether it is necessary to replace all the existing software. A lot of mathematical models, including professional models and general algorithms, are coded with a variety of programming languages such as Fortran, C++, Powerbuilder, and so on. The user interface of the old software may be under traditional database system or in previous versions. The choice in reusing or rewriting them under the new environment, mainly depends on the quantity, complexity and quality of the existing software as well as on the availability of time and resources. Furthermore, the programs must meet a minimum standard of quality as far as reliability, efficiency and maintainability are concerned. We chose to reengineer and redevelop all existing systems in order to satisfy the common rules and to meet the requirements of reliability, efficiency and maintainability as far as possible. To speed up the development procedure, the functions of old systems are refereed and made some translation from one language to another.

Selection of prototype system

In China, there are more than 5,000 rivers with area over 100km^2. There are about 86,000 reservoirs, and among them, more than 3,000 have storage capacity over 100 million cubic meters. These reservoirs are classified as medium to large types that are the essential objects of development for the national software project of reservoir flood control. 20 reservoirs were chosen as prototype systems in the first trial project from the whole country in 1998. 40 reservoirs were chosen in the second batch in 1999 while 60 reservoirs were selected in the third batch in 2000. Among them, the developing groups of DUT chose 10 reservoirs as prototype systems in 1998, 14 ones in 1999, and 20 ones in 2000. From these prototype systems, we aim to find the common features and to distinguish the differences among them. Furthermore, we are planning to develop a general software system of reservoir flood control. On the other hand, the calibration and validation of these common rules are also one of main objectives.

Structural framework of system

IMSFCR adopts client/server structure based on large-scale database. The databases are divided into network databases and special databases. Network databases consist of real-time data library, history records library and results library. Special databases include flood forecast library and flood operation library. Network databases are shared resources involving original records and public information. On the other hand, special databases are kept private to facilitate simulation and analysis of flood forecasting and flood control operation by both technical and non-technical personnel before formal or official results have been generated. Most data are temporary in nature and are only valid in user's machines. For non-technical users, it is especially important that they can operate and learn from the system, without the threat that their inadvertent action may erase some important and raw data. For technical users, they can simulate any alternatives in an efficient way. This layout of databases enhances data security as well as improves flexibility of the system application. The structural framework of the reservoir flood control system is shown in Figure 1.

Custom designed functions

The reservoir flood control system includes six custom designed functions, i.e, "information query", "data processing", "flood forecast", "flood operation", "result post-processing" and "help". Figure 2 shows the main function tree of the reservoir flood control system.

"Information query" provides several basic information inquiry for brief introduction of reservoirs, dynamic real-time flood situation, flood forecasting results, flood operation alternative results, historical records, operation rules, law and policy related to flood control operation, and so on. Query can be activated through access to the databases via internet/intranet. The query results may be shown in various formats such as tables, graphic, maps, videos, and text.

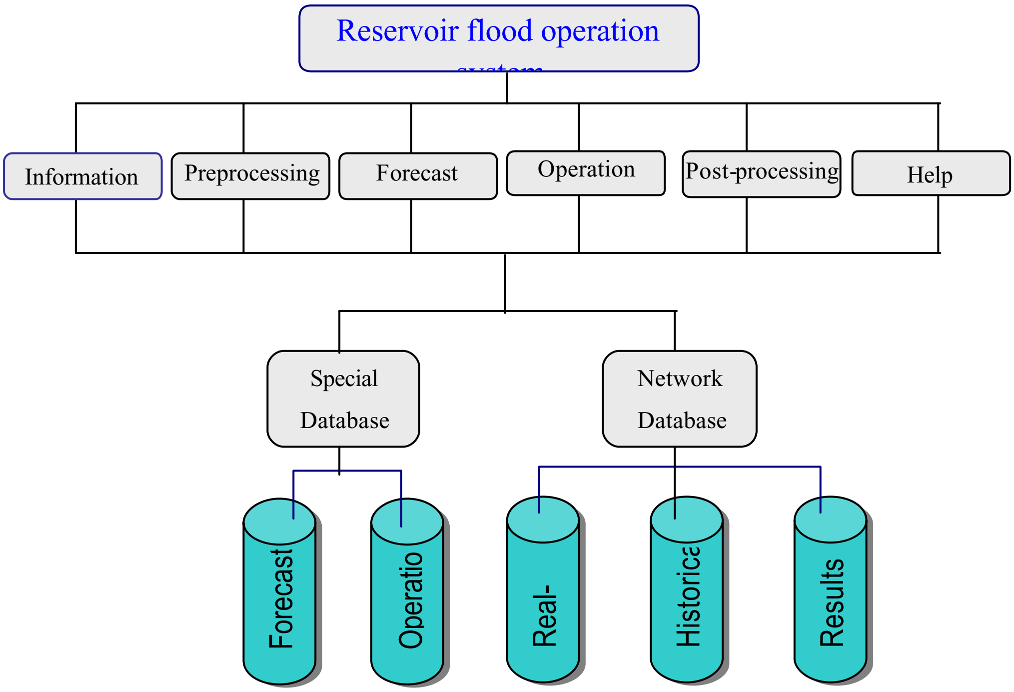

Figure 1. Structural framework of the reservoir flood control operation system

Flood Control System of Reservoirs					
Information	**Preprocessing**	**Forecast**	**Operation**	**Post-processing**	**Help**
Introduction	Data input	Model choice	Initial condition	Results project	About system
Real-time	Data processing	Initial condition	Automatic manner	Graphic result	Multimedia
Historical	Real-time monitoring	Real-time forecast	Interactive manner	Table result	
Policy		Simulation forecast	Evaluation	Report forms	
Rules		Revised forecast	Selection		
		Historical analysis			
		Parameter calibration			

Figure 2. Main function tree of the system

"Data preprocessing" provides the data input and modification requirements on historical records, real-time flood data processing, and real-time flood monitoring. Large amounts of historical flood records are very valuable to flood forecast and flood control operations. Since data input is a time consuming task, various choices are allowed in the manner of input, such as electronic formats developed for special tables, database translation connections from a database into another, and special file formats similar to "excel". General index and guidance are established to facilitate the data input. All imported data, such as historical records, historical files, and model parameters, can be reviewed and checked through "information query". Constrained by the time interval stipulated in the flood forecast model, some of the original data about rainfall, level and discharge must be processed in order to satisfy the requirements of the real-time system. In addition, employing the real-time monitoring of flood event, the user can dynamically perceive rainfall spatial-temporal distribution of the whole basin as well as level process of some control sections. When alarming accumulated rainfalls or water levels arise, the system will prompt the user to perform flood forecast and flood control operations.

"Flood forecast" includes the choice of flood forecasting models, initial condition set and modification on antecedent soil moisture, real-time forecast, simulation forecast, revised forecast, historical flood analysis, and model parameter calibration and validation. The system has integrated most of the commonly used flood forecasting models in China, such as the famous Xinanjiang model developed by Zhao(1992), typical rainfall-runoff models, unit hydrograph model(Linsley et al.,1975; Hoggan, 1997).When a model is chosen, the system will set it as the default in the next time. Flood forecast is classified into "real-time" and "simulation" depending on the situation when real-time and simulation data are used respectively. Forecast results are dynamically analyzed and shown with tables and graphics. Some characteristic values of the flood , including total rainfall, total runoff, pure precipitation rate, peak inflow, peak time, the largest flood inflow volume , occurrence time and corresponding frequency during the given time interval, are displayed. When there is a large discrepancy between real data and prediction, revised methods can be evoked. Historical flood analysis can be performed from the similar historical floods based on pattern recognition. With the accumulation of more hydrological data, the user can recalibrate and revalidate the model parameters, and choose another appropriate model.

"Flood control operation" can deal with both single reservoir and multi-reservoirs system. Reservoir flood control operation is operated in real time, which often differs very much from other operations for planning purposes. The crucial difference between them is that decision making of flood control is usually effective only for the current period or for the following periods. Constrained by the updating forecasting inflow information at the current period, decisions need to be made on a daily or even hourly basis during flood events. Multi-criteria decision analysis has been shifting from optimization methods to more interactive decision support tools (Bender and Simonovic, 2000). This system unitizes the recent fuzzy optimal model for the flood control system developed by Cheng (1999) and Cheng and Chau(2001). The main features are the ability to quickly generate, select and evaluate alternatives and the flexibility of these models to allow for the transient change of practical flood conditions and to mimic the intuitions and experience of operators. "Automatically generated alternatives" uses knowledge-based rules gleaned from flood control authorities (experts) and from analyzing a mass of recorded historical data (Cheng and Chau, 2001). After these automatically generated alternatives are evaluated, "interactively produced alternatives" may be activated to produce more alternatives. Through fuzzy optimal model, one of the satisfied solutions is obtained.

“Results post-processing” completes the task management for real-time information, flood forecast, flood control operation, and report outputs. Tables and graphics are direct and distinct demonstrations for problem and are easy to be understood by users and decision-makers. The numerous tables and graphics are designed for the special tasks and can be printed as report outputs. In addition, the formal results of flood forecast and flood control operation are only accessible by the authorized users and institutions.

“Help” provides support and guide for users. The user can learn to use the system through multimedia tutorials.

Database development

The database system is the basis of IMSFCR. Sybase and SQLServer are adopted as the DBMS of reservoir flood control system. The two DBMS can ensure high data integrity, recovery, and concurrency control. They support the high-level query language SQL and enable users to perform sophisticated data retrievals. Most of the structural definitions of Sybase about data properties is the same as those of SQLServer. One of the two DBMS can be chosen according to the scale of the application system and the economic condition of the user. It is not necessary to modify the programming source codes.

The design of the relational tables has a significant effect on the programming source codes and the operation efficiency of the flood control system. The software system based on the database is completely different from traditional files such as in HEC1-HEC5 packages(Hoggan, 1997). All preprocessing, calculation, query and post-processing are based on database and necessitates the access to the data in the related tables. An optimized database design can render the system easier to expand and minimize adjustment to the programming source codes, as well as improve the efficiency.
The main works to achieve database optimization are to define the types of data queries and requests, and to normalize the database relationships. The optimization products are table structures where the table names, the name and data types of its fields, and the integrity constraints are defined. More than 400 tables have been designed for the reservoir flood control system. These tables form parts of the common rules for the national flood control system. The database can be utilized to generate all the standard reports required by the user. Another major objective is to provide the public with flood control information. The increasing use of the Internet makes the World Wide Web an attractive vehicle for the dissemination of such information. The flood control information about reservoirs can be accessed using Internet/Intranet.

Design of object-oriented system

During recent years, object-oriented framework has become popular technology as effected by object-oriented software development(Whitten et al., 2001). The technology has been applied to water resources system development (Beclkhouche et al., 1999), as well as in other fields (Cheng, 2000; Mattsson and Bosch, 2000). Object-oriented technology bears the promise of reduced development effort through large-scale reuse and increased quality (Moser and Nierstrasz, 1996). For the national flood control system, reliability, efficiency, maintainability and reuse are the important objectives of the normalized and standardized flood control system for reservoirs. The fourth generation languages (4GL), such as PowerBuilder 6.0, VC6.0 and VB6.0, are object-oriented software development and are easier to be used. Most of components in IMSFCR are developed by using PowerBuilder 6.0, some by VC6.0 and integrated by ActiveX.

Good quality object-oriented software system depends on the workflow analysis. The detailed design of object involves layout of conceptual design, logical design, physical design and implementation (Bekhouche et al, 2000). In other words, the whole system will be divided into a mass of single objects. The attributes and behaviors of each object will be analyzed and defined. A series of object-oriented models capturing attributes and methods of objects are established based on the analysis of objects. The whole system is in fact the implementation of object-oriented models based on the logical and physical relationships of objects. Figure 2 is the main function tree of the system, which also shows the logical and physical relationships of main objects. The main interface of flood control system for reservoirs is an integrated object consists of six integrated objects of second level function components. Each object of second level function components is also an integrated object consists of lower level objects. The lowest level component is a series of single object-oriented models. Figure 3 shows the framework of object-oriented models.

In Figure 3, rectangular boxes represent integrated objects; rectangular boxes with shadow represent single objects. Adopting these object-oriented models, the interrelations that exist among these components are established, specifying the behavior of the entire structure and each component. The object-oriented framework technology has the following appealing traits: (1) easy development by team groups thus speeding up the development, (2) large-scale reuse because of relatively independent encapsulation of the object, (3) improved quality such as reliability, efficiency and maintainability because of high portability.

Integration of mathematical models and methods

The two essential components are flood forecast and flood control operation. Numerous models related to these two parts are integrated into this system. Most of the common methods and models are coded with general functions through conversion from previously developed software as far as possible. Only small proportions of them are developed recently under the new environment. Interactive contents related to these functions such as initial conditions are provided and executed through graphic user interface. Most of the mathematical models and methods are embedded in methods of object through the call for mathematical model or method functions.

The forecasting component consists of precipitation-runoff model libraries and flood routing libraries. The precipitation-runoff model libraries have integrated five models up to now: rainfall-runoff relationships (including P+Pa~R and P~Pa~R, flow forecast using unit graph model), Xinanjiang model (Zhao,1992), Dahuofang Model(Liu 1985). The flood routing libraries provide for Muskingum methods (Muskingum and Muskingum-Cunge), coefficients methods and direct additional method after consideration of the time lag.

Real-time revised forecast results are useful in improving the forecasting quality. An effective method for all cases is still under development because the flow routing time is very short for most reservoirs. Two particular methods and technologies are used in this system. The first method is dynamically adjusting the model parameter through calibration and validation of model from those classified floods based on pattern recognition or from recent floods. Figure 4 represents a case application of the real-time revised forecast results through the above methods. Another method is interactively modifying the forecasting results by hand with reference to those similar historical floods. These two methods are effective for some reservoirs only.

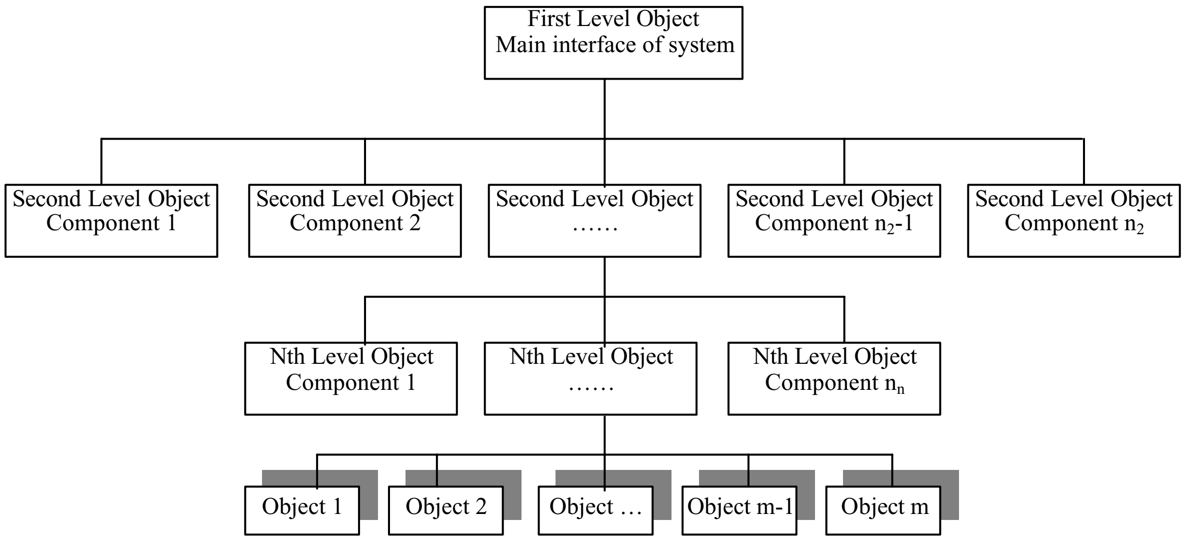

Figure 3 Framework of object-oriented models

Calibration and validation of model parameters are also a time consuming process. A new technology, i.e., genetic algorithms, is developed to automatically calibrate and validate model parameters. In recent years, genetic algorithms have become one of the most widely used techniques for solving a number of hydrology and water resources problems (Wang, 1991; Ritzel et al, 1994; McKinney and Lin, 1994; Dandy et al, 1994; Cieniawski et al, 1995; Franchini and Galeati, 1997;See and Openshaw, 1999; Wardlaw and Sharif, 1999) because of their advantages over classical optimization methods. They have been used successfully as an optimization tool in runoff model calibration (Wang,1991; Franchini and Galeati, 1997). A new genetic algorithm, which combines a fuzzy optimal model with a genetic algorithm, is developed to solve the multiple objective rainfall-runoff model parameters calibration problem (Cheng et al.,2001).

The parameter calibration includes optimization of multiple objectives: (1) peak discharge, (2) peak time and (3) total runoff volume.. Furthermore, the graphic user interfaces related to the genetic algorithm are designed and developed. Users can easily set the ranges of different parameters, choose real and binary codes, and decide the approaches of crossover and mutation.

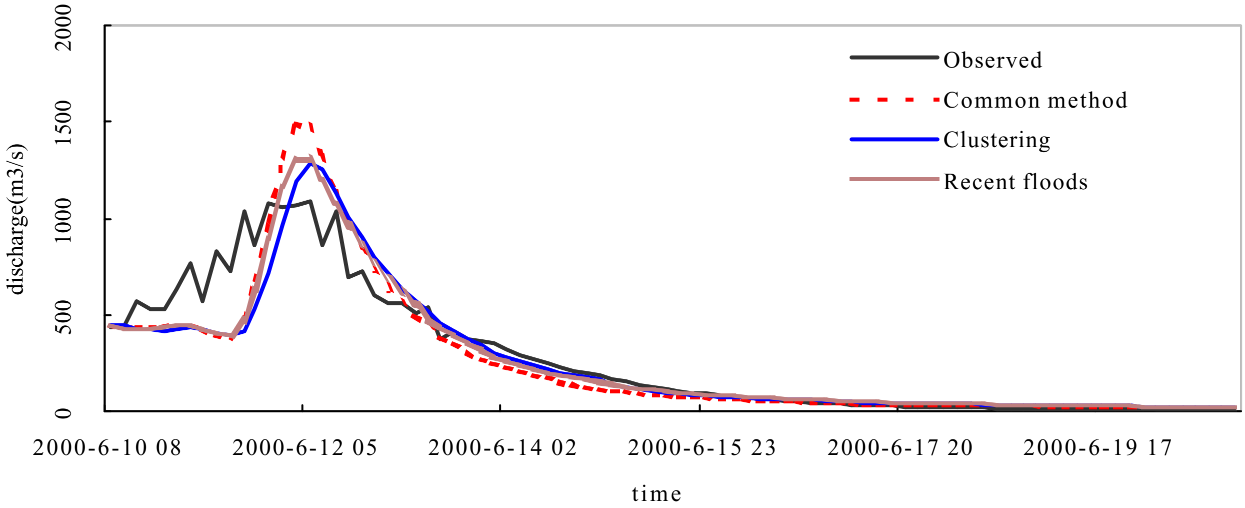

Figure 4. A case study about the real-time revised forecast

After entering the initial conditions and evoking the "calibrate" button, the model parameters will be automatically calibrated. The results will be shown in both graphics and tables. When a group of satisfied parameters is available, choosing the "replace" button will update the old parameters of the model. Figure 5 and Figure 6 show the part results of a case study about the parameter calibration and validation based on our genetic algorithm.

As mentioned above, flood control is operated in real-time. The decision making process is very complex and related to all the parties interested in the problem under consideration. Traditional techniques often simplify the problem by transforming the multi-objectives into a single-objective, which are difficult to be related to intuitions and experience of operators.

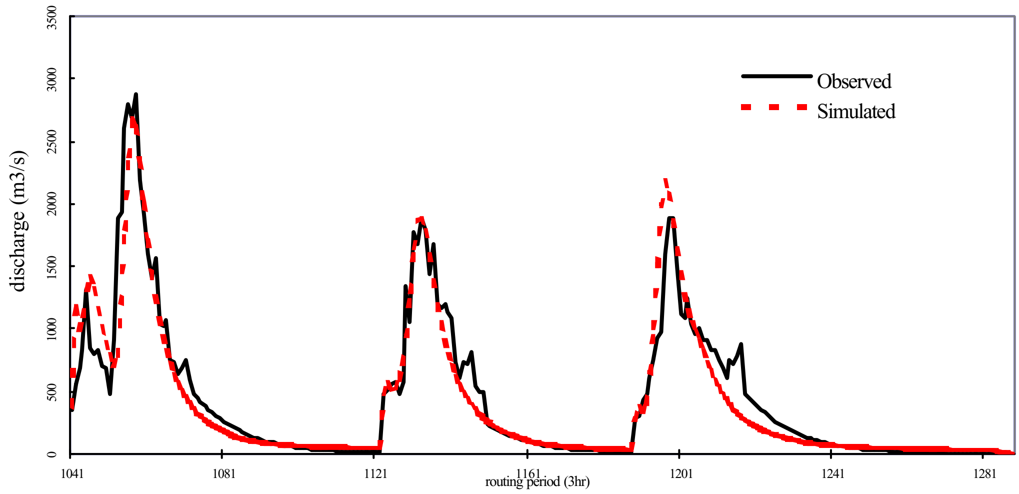

Figure 5 The simulated and observed hydrographs during calibration

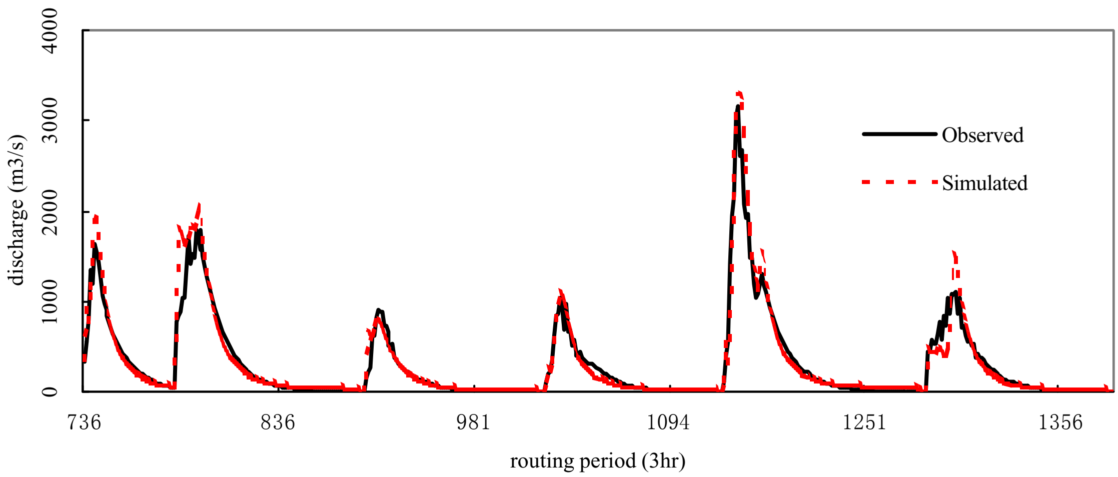

Figure 6 The simulated and observed hydrographs during validation

Fuzzy optimal models are easy to deal with the complexity of a typical system with uncertainty and to mimic intuitions and experience of operators (Cheng, 1999; Cheng and Chau, 2001).

Similar works can be found in Russell and Campbell (1996), Fontane et al.(1997), Despic and Simonovic(2000), and Bender and Simonovic(2000). These models (Cheng, 1999; Cheng and Chau, 2001) have been integrated into this system. When a new flooding event is imported, the system will automatically generate a series of alternatives based on the rules in the knowledge base and gives the evaluation of various alternatives (Cheng and Chau, 2001). Furthermore, users can interactively propose new alternatives and evaluate all alternatives. Finally, one alternative can be selected according to the evaluation.

Conclusion

The flood control management system for reservoirs has a significant role in alleviating flood losses. The establishment of IMSFCR will speed up the development of the national flood control system for reservoirs, make full use of the flood control capacity of existing reservoir projects and improve the national standard of the flood control operation for reservoirs. Large-scale database is the basis of IMFCR. IMFCR integrates descriptive knowledge (e.g., data and information), the procedure knowledge (methods and algorithms) and reasoning knowledge (rules), with robust and effective management capacity.

Acknowledgments

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Non-structural Control Measures for Municipal Stormwater Management

By

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Abstract: Urbanization alters the hydrologic characteristics of catchments, resulting in flooding, erosion, water quality degradation, and impairment of aquatic life and habitat. Stormwater management practices (SWMP) are typically employed at new developments to reduce these impacts. Among the various types of SWMP, non-structural control measures have become popular in Canadian municipalities. Non-structural control measures refer to operation and maintenance measures which aim at improving hydrologic characteristics and storm runoff quality. The objectives of this paper are to review a number of non-structural control measures and outline the development procedure of a pollution prevention plan. In order to implement these non-structural measures, a pollution prevention plan should be developed at municipal, industrial/commercial, and neighbourhood levels. A municipality can incorporate these non-structural measures in (1) municipal wide programs such as pollution prevention and control plans, environmental management systems, by-laws, best management practices; (2) local programs such as pollution prevention, by-law enforcement, public education; (3) watershed programs such as watershed and regional action plan studies. Industrial and commercial establishments can implement these non-structural measures at individual-site and industrial sector-based levels. Community-based groups can participate in the development of municipal, industrial and commercial pollution prevention plans, and encourage residents to implement non-structural control measures.

Keywords: stormwater. non-structural control measures, pollution prevention, urban drainage

Introduction

Land development for urbanization alters the hydrologic characteristics of watersheds resulting in a number of runoff impacts on the water ecosystem. Table 1 summarizes the major runoff problems due to urbanization.

Urban runoff problems are caused by the altered runoff characteristics after urbanization. The peak flow rate, volume, and timing of runoff are important characteristics in the planning and design of SWMP. Before urbanization, these characteristics are functions of watershed characteristics such as shape, soil types, topography, and vegetation covers and local precipitation patterns. Urbanization alters watershed features by changing the land cover and topography.

Table 1 Causes and impacts of urban runoff problems

Urban Runoff Problems	Causes	Impacts
Increased flooding	High runoff peak rates due to increased imperviousness.	Loss of life and property; economic hardship; non-tangible damages such as anxiety.
Reduced base flow	Reduced groundwater recharge due to increased imperviousness	Recharge is reduced; soil moisture is depleted; decreased exfiltration to rivers; reduced summer low flow in rivers.
Impaired water quality	Polluted runoff from urban areas	Reduced aquatic communities
Channel instability	Change in flow-duration characteristics and sediment loads.	Change in channel form by erosion and deposition.
Impaired habitat	Changes in flows, water quality, and channel form	Reduced terrestrial and aquatic species.
Loss of wetlands	Filling of wetlands for urbanization; altered drainage pathways	Loss of wetland habitats and species.

Runoff rate and volume generally increase after urbanization (Fig. 1). Watersheds are covered by asphalt and houses and runoff is conveyed by efficient drainage systems to the receiving waters. Flooding occurs when the downstream channel capacity is exceeded. Another related problem is channel erosion which depends on runoff rate and its duration. This brings out the frequency issue of runoff rate and volume. As indicated in Fig. 1, the percent of time that runoff rate exceeds a certain value generally increases after urban development. Thus, urbanization not only increases runoff rate and volume but also their frequency. The frequency of high runoff rates has a direct impact on erosion and sediment transport at the receiving river channels.

Runoff from non-urban areas carries eroded sediments, nutrients from natural and/or agricultural sources, bacteria from animal droppings, and pesticides and herbicides from agricultural and urban lawn maintenance practices. Its quality is a function of rainfall, soils, vegetation, and agriculture practices. After urbanization, runoff carries solids particles from automobile wear and tear, dust and dirt, and winter sand, nutrients from residential fertilizers, metals such zinc, copper, and lead, hydrocarbons leaching from asphalt pavement materials, spilled oils and chemicals, and bacteria from domestic animal droppings. This change of runoff quality causes a general degradation of water quality in the receiving waters (Table 2).

Stormwater Management Practices

In order to control urban runoff, a number of SWMP are normally employed. The term "practices" is commonly used in stormwater management (SWM) because their performances are difficult to verify universally. The random nature of rainfall and runoff makes field monitoring of SWMP difficult. Additionally, the performance of SWMP varies significantly during and between events and at different locations. Thus, the term "practices" has traditionally been used instead of "technology". All these practices can be categorized into:

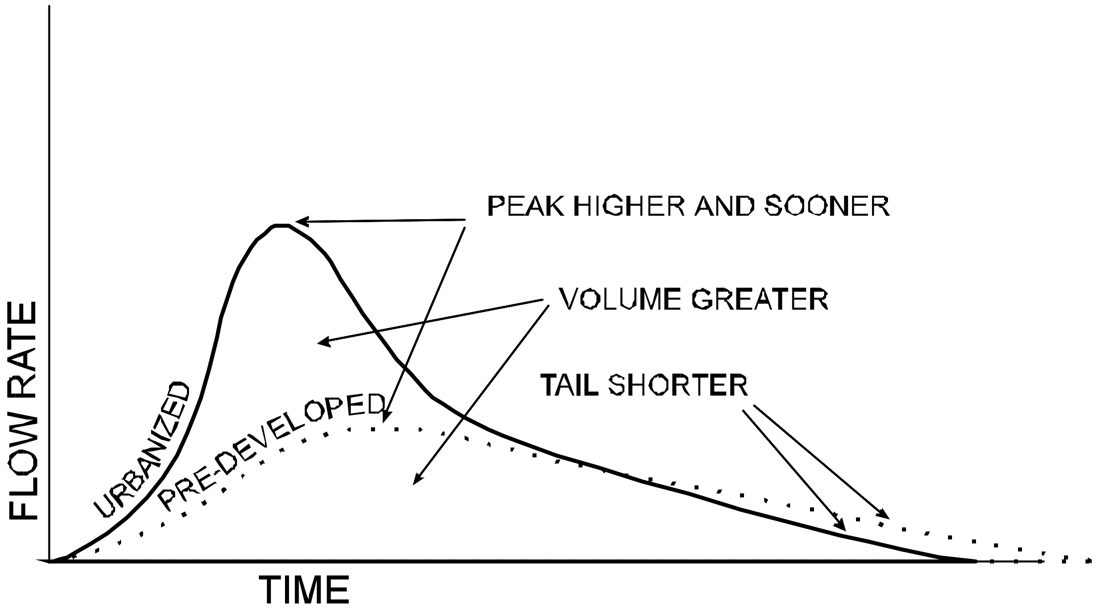

Fig. 1 Runoff hydrographs before and after development

Table 2 Typical runoff quality

Parameter	USEPA[1]	E.York[2]	St.Cat[3]	King[4]	Ont[5]
Total Suspended Solids (mg/L)	125	281	250	72	25
Biological Oxygen Demand(mg/L)	12	14	8.2	8.5	/
Chemical Oxygen Demand (mg/L)	80	138	/	/	/
Total Phosphorus (mg/L)	0.41	0.48	0.33	/	0.03
Soluble Phosphorus (mg/L)	0.15	0.06	0.084	0.118	/
Total Kjeldahl Nitrogen (mg/L)	2.00	2.20	0.89	/	/
Nitrate and Nitrite (mg/L)	0.90	0.46	0.65	0.25	/
Total Copper (mg/L)	0.040	0.050	0.021	0.009	0.005
Total Lead (mg/L)	0.165	0.570	0.084	0.013	0.025
Total Zinc (mg/L)	0.210	0.330	0.100	0.064	0.030
Fecal Coliform (No./100ml)	21,000	11,000	68,000	21,000	100

1. U.S. EPA - Mean concentration for median urban site Nationwide Urban Runoff Program (NURP) (U.S.A., 1990)
 - Fecal coliform, Median Event Mean Concentration (EMC), 11 sites (NURP, U.S. EPA, 1983)
2. East York - Arithmetic mean, 18 events, 1 site (Kronis, 1982)
3. St. Catharines - Geometric mean, 4 events, 1 site (CH2M Hill, 1990a)
4. Kingston - Geometric mean, 8 events, 1 site (CH2M Hill, 1990b)
5. Ontario - Provincial Objective or Guideline

- Source control measures which focus on lot-level non-structural and structural measures.
- Drainage system control measures which focus on measures along drainage systems.
- End-of-pipe control measures which focus on control measures at sewer outfalls.

Objectives

The objectives of this paper are to overview a series of non-structural measures for municipal SWM and discuss how to set up and implement these measures. The contents of this paper are based upon two projects conducted by the authors: (1) Stormwater Pollution Control Handbook (TSH, 2001); and (2) CSO and Stormwater Control Alternatives (Aquafor Beech, 2001). It is important to realize that non-structural measures are part of the overall municipal SWM and their effectiveness depends on the promotion and education provided by the municipality and public participation. Nevertheless, non-structural measures have become one of the important SWMP in Canada.

Non-Structural SWMP

Listed below are the non-structural measures which can achieve some of the SWM objectives.

1. Catch Basin Cleaning
2. **Street Cleaning**
3. **Control of Road De-Icers**
4. Control of Fertilizers and Pesticides
5. **Enforcement of Anti-Litter and Discharge By-Law**
6. Public Education
7. **Sewer Rehabilitation**
8. Water Conservation
9. Erosion and Sediment Control
10. Used Oil Recycling
11. Household Hazardous Waste Collection
12. **Safer Alternative Products**
13. **Business Education and Awareness**
14. Materials Storage Controls
15. Vehicle Use Reduction
16. Yellow Fish Road Program
17. **Pool Drainage**
18. **Spills Control**
19. Leaf Clearing and Removal
20. **Modifying Engineering Standards**
21. **Cross Connection Control Program**

Five measures **(highlighted)** are overviewed in this paper. Readers are encouraged to check the two studies described above for details on the remainder (TSH, 2001; Aquafor Beech, 2001).

Catch Basin Cleaning

Primary Mechanism: Catch basin and stormwater inlet maintenance is done on a regular basis to remove pollutants, reduce high pollutant concentrations during the first flush of storms, prevent clogging of the downstream conveyance system and restore the catch basin's sediment-trapping capacity. The maintenance program can reduce solid loadings to surface water and associated pollutants.

Description: Municipal staff should inspect public and private facilities on an annual basis to ensure compliance with the following:

- Catch basins should be cleaned regularly enough to reduce the possibility of sediment and pollutant loading from the flushing effect of stormwater inflow. Cleaning should occur before the sump is 40% full.
- Prioritize maintenance to clean catch basins and inlets in areas with the highest pollutant loading and in areas near sensitive water bodies. Ideally works should be scheduled just prior to the wet fall season to remove sediments and debris accumulated during the summer.
- Keep accurate operation logs of which catch basins were cleaned and how much waste was removed to track program.
- Catchbasins with "goss traps" also capture oil and other floatable materials.
- The metal content of decant and solids cleaned from a catch basin should be periodically tested to determine if the decant violates limits for disposal to the wastewater treatment plant or if the solids would be classified as a hazardous waste.

Application Requirements: Two-person teams are required to clean catch basins with vacuum trucks. Crews must be trained in proper maintenance, including record keeping, disposal and safety precautions. Arrangements must be made for the proper disposal of the collected wastes.

Equipment needed: Truck mounted vacuum excavators are normally used for this activity.

Proven Effectiveness/Experience Elsewhere: Basically, catch basins remove the largest particulates that are washed from the watershed during rains, preventing them from being deposited in downstream sewerage and in the receiving water. Cleaning catch basins twice a year was found to allow the catch basins to capture particulates for most rains. This cleaning schedule was found to reduce the annual discharges of total solids and lead by between 10 and 25 percent and chemical oxygen demand, total Kjeldahl nitrogen, total phosphorus, and zinc by between 5 to 10 percent (Pitt and Shawley, 1982). Butler and Karunaratne (1995) reported particle sizes trapped in sump to be between 300 and 3000 μm, with less than 10% of the particles smaller than 100 μm.

Cost Considerations: An aggressive catch basin cleaning program could require a significant capital and operating and maintenance budget because of the typically large number of catch basins in any given area and the high cost of labour and equipment required to do the work. Smaller municipalities may elect to contract this work out as an annual contract.

Measure addresses: healthy aquatic communities, reduction of fish consumption advisories, virtual elimination of toxic contaminants and sediments, improvement of body contact recreation, and elimination of aesthetic nuisances.

Street Cleaning

Primary Mechanism: Some reduction in the buildup of pollutants on street surfaces can be accomplished by conducting street cleaning on a regular basis. The primary and historical role of street cleaning is for sediment and litter control.

Description: The following approaches may be effective in implementing and maintaining the street cleaning SWMP:

- Prioritize cleaning to use the most technically advanced sweepers, at the greatest possible frequency, in areas with the highest pollutant loading.
- Cleaning frequency should be based upon inter-event times (the dry period between storms). To achieve 30% removal of street dirt, the sweeping interval must be no more than 2 times the average interval between storms. To reach 50% removal, sweeping must occur 1 or 2 times during the average interval between storms.
- Sweeping frequency should be increased just before the rainy season.
- Proper maintenance and operation of sweepers greatly increases their efficiency.
- Accurate operation logs should be kept of curb miles swept and amount of waste collected to track program.
- Climate, parked cars, street and curb conditions, traffic congestion, and construction projects may limit the effectiveness of this measure.

Application Requirements: The following considerations may apply to this measure:

- Sweeper operators and maintenance staff, supervisory and administrative personnel are required.
- Traffic control / bylaw officers may be required to enforce parking restrictions.
- Cleaning routes and the associated timings must be designed to optimize efficiencies.
- Collected wastes must be properly disposed.
- Operators require training in proper sweeper operation and technique.

Equipment needed:

- Mechanical broom sweepers (more effective at picking up large debris and cleaning wet streets, less costly to purchase but generate more dust).
- Vacuum sweepers (more effective at removing fine particles and associated heavy metals but ineffective at cleaning wet streets and heavy litter such as encountered in spring clean-up),
- Combination sweepers and street flushers.
- Speeds of 10-15 km per hour are optimal. In addition, brush adjustment, rotation rate and sweeping pattern also affect removal efficiencies.

Proven Effectiveness/Experience Elsewhere:
Normal street cleaning operations for aesthetics and traffic safety purposes are not very satisfactory from a stormwater quality perspective. These objectives are different and the removal efficiency for fine and highly polluted particles is very low. Unless the street cleaning operations can remove the fine particles, they will always be limited in their pollutant removal effectiveness.
Some efficient machines are now available to clean porous pavements and infiltration structures, and new tandem machines that incorporate both brooms and vacuums have recently been shown to be very efficient, even for the smaller particles. Conventional street cleaning operations preferentially remove the largest particles, while rain preferentially removes the smallest particles. In addition, street cleaners are very inefficient when the street dirt loadings are low, when the street texture is course, and when parked cars interfere. However, it should also be noted that streets are not the major source of stormwater pollutants for all rains in all areas.
Streets are the major source of pollutants for the smallest rains, but other areas contribute significant pollutants for moderate and large rains. Therefore, the ability of street cleaning to improve runoff quality is dependent on many issues, including the local rain patterns and other sources of runoff pollutants. More research is needed to investigate newer pavement cleaning

technologies in areas such as industrial storage areas and commercial parking areas, which are critical pollutant sources.

A study in Severn Sound found that use of vacuum sweeper technology would be an efficient and cost effective stormwater management practice. Potential phosphorus reductions from stormwater of approximately 5% are achievable at less cost than most other traditional stormwater management practices.

Cost Considerations:

A street cleaning program requires a significant capital and operating maintenance budget. Sweeper capital costs range from $85,000 to $140,000, with a useful life of about 4 years.

Measure addresses: healthy aquatic communities, reduction of fish consumption advisories, virtual elimination of toxic contaminants and sediments, improvement of body contact recreation, and elimination of aesthetic nuisances.

Public Education

Primary Mechanism: Inform the public about pollution prevention and stormwater management issues, solutions, regulations and related financing, using methods appropriate to the target audience and the specific issue. Involve the public in remedial action, cost saving through volunteerism, and to increase political support.

Description: A public education process involves the following steps:

1. Prepare the program.
   - Identify the problem and the solution;
   - Seek information and resources;
   - Identify and understand the target group;
   - Identify partners.
2. Design the Plan
   - Identify the product or desired result;
   - Consider costs and time limitations;
   - Consider roles and responsibilities of coordinator agency and partners;
   - Design promotion material and means of distribution.
3. Implement the Plan
   - Pretest the plan and make necessary changes;
   - Implement the plan and actions;
   - Monitor the effectiveness of the public education;
   - Monitor the effectiveness of the plan as a solution to the initial problem.
   -

Key public education messages include:

- Stormwater and urban runoff are not treated; therefore, as these surface flows reach local bodies of water, they contain all of the pollutants that accumulate from everyday living and commerce.
- By making changes in daily habits, individuals can protect the health of local creeks, streams, rivers, lakes, bays and oceans.

Messages addressing specific sources of stormwater pollution could include include:

- Educating the public that specific sources of stormwater pollution include automobile products, vehicle maintenance operations, litter, pet wastes, pesticides, fertilizer, erosion from construction sites and illegal sewer connections.
- These pollutants enter the storm drain as water from rainfall, overwatering or cleaning operations washes over outdoor surfaces.
- Specific outreach messages to business and/or groups typically revolve around encouraging the business to implement BMPs for their particular activity.
- One reference (WERF, 1998) noted that the three most commonly used messages related to wastewater pollution prevention inside homes and businesses are:
- To protect local bodies of water, it is important to avoid pouring toxic chemicals down drains leading to the sanitary sewer system.
- Most information materials emphasize alternatives that can readily replace household products that are toxic to the environment.

There are properly designed and controlled facilities to safely dispose of household hazardous waste in most areas of the country. The public is usually provided with telephone numbers and other information necessary to make arrangement to properly dispose of common toxic wastes.

Application Requirements: Public education programs are most successful when a coordinator or facilitator is employed or appointed. In a municipal setting, staff time may be needed to research potential solutions to the issues under consideration. Volunteer partnerships can take some of the load during the entire process.
The costs are dependent on the approach used and the desired result, and there may be costs for printed material, distribution or for any visual aids, devices or other material used during the public education program.

Proven Effectiveness/Experience Elsewhere:
Several municipalities in southern Ontario have undertaken public education programs related to pollution prevention. These include:

- City of Toronto Downspout Disconnection Program, City Works Service. Contact Ted Bowering at (905) 392-7705.
- Metro Toronto and Region Conservation Authority, Yellow Fish Road Program (ongoing). See the Website at www.trca.on.ca or call the Yellow Fish Road Coordinator at (905) 832-2289.
- City of St. Catharines, Downspout Disconnection Campaign; Stoop and Scoop Program. Contact Cindy Toth. Pollution Control Plan Coordinator, (416) 688-5600, ext. 693.

Cost Considerations: Costs will be entirely dependent on the type of public education and outreach needed and the desired results. Some desired actions could be promoted by provision of materials such as water saving devices, rain barrels, or other aids. Volunteer help and partnerships will reduce the costs in many cases.

Measure addresses: healthy aquatic communities; reduction of fish consumption advisories; reduction of erosion impacts; re-establishment of natural hydrologic process; re-establishment of natural features; virtual elimination of toxic contaminants and sediments; improvement of body contact recreation; elimination of aesthetics nuisances; elimination of sanitary discharges in sanitary sewer overflows (SSO), combined sewer overflows (CSO), bypasses, cross connections, and spill; reduction of basement flooding; reduction of sanitary inflow and infiltration; and protection of life and property from flooding.

Business Education and Awareness

Primary Mechanism: Promote education of the business and industrial community on the impact of pollution on the environment and the pathways of pollution in an industrialized watershed. Foster an environment where expertise and information can be shared on pollution prevention at source.

Description: Components of a business education program can include:
- Surveying area businesses to determine what potential presently exists for at-source pollution.
- Identification of key business individuals that may become involved in an "umbrella" association to review the needs of the business community education on pollution prevention and applicable BMPs. The focus of the group can include information sharing, networking and contacts that will assist small business by providing low cost expertise.
- Provision of seminars, fact sheets and information packages on BMPs related to area businesses, and also on environmental management systems covered by the ISO 14001 standard.
- Evaluation of the need and/or opportunities in a municipality to provide financial incentives to businesses to implement BMPs.

Application Requirements: A staff person is needed to coordinate surveys of area businesses, formation and support of any committees, and provision of educational materials, seminars, etc.

Proven Effectiveness/Experience Elsewhere:
Emery Creek Environmental Association. Emery Creek is a tributary of the Humber River draining a mixed industrial-commercial-residential area in Toronto. The industrial association was formed in 1993 to address watershed concerns.

- The Langstaff Ecopark in Toronto was officially opened in 1977 with a 2 km regeneration area through an industrial park along the upper West Don R. Local businesses along with volunteers have contributed towards creation of a new wetland and stormwater detention pond, tree plantings and construction of a trail system. Pollution prevention workshops have also resulted in some changes to more environmentally friendly industrial practices.
- Regional Municipality of Waterloo. A Water Resource Protection Liaison Committee was formed in 1994 and includes regional staff and business, environmental and agricultural interests. Working groups focus on promoting voluntary resource protection in urban business and industries.

Cost Considerations: Staff time will be needed for business outreach programs. Costs will vary according to educational materials, seminar expenses and other outreach projects.

Measure addresses: healthy aquatic communities; reduction of fish consumption advisories; reduction of erosion impacts; virtual elimination of toxic contaminants and sediments; improvement of body contact recreation; elimination of aesthetics nuisances; elimination of sanitary discharges in Sanitary sewer overflows (SSOs), combined sewer overflows (CSOs), bypasses, cross connections, and spills.

Modifying Engineering Standards

Primary Mechanism:
- Reduce pollutant sources near source through absorbing filtering of pollutants.
- Reduced runoff through encourging infiltration.

Description:
- Changes to engineering standards to promote the use of surface storage and drainage (through grassed areas).
- Using grading standards to promote surface ponding and / or increasing the detention time of surface water on grassed areas.
- Reduce the minimum and maximum surface slopes, provide retention areas.
- Change road design standards to promote roadside swales. These can and often require measures to promote infiltration such as rock or stone filled basis or trenches to storm water for infiltration.

Application Requirements:
- Will require the revision to engineering standards and site plan standards (and approval process).
- Will require public education for the acceptance of periodic surface ponding (and conveyance).

Proven Effectiveness / Experience Elsewhere: Roadside ditches used historically, and currently applied in some municipalities. Grassed swales have been evaluated for effectiveness.

Cost Consideration: Some research has concluded that capital and operating costs lower for roadside ditch applications (J.F. Sabourin, 2000).

Measure addresses: healthy aquatic communities; reduction of erosion impacts; re-establishment of natural hydrologic process; virtual elimination of toxic contaminants; improvement of body contact recreation; elimination of aesthetics nuisances.

Municipal Pollution Prevention Planning

Options that a municipality can consider for pollution prevention planning are summarized in Table 3. Types of action a municipality can take include: direct action, involvement of others, push for action, by-law adoption and modifications, official plan policies, and subdivision design policies and drainage standards.

Industrial / Commercial Pollution Prevention Planning

Industries and commercial establishments, and institutions can take action for their site or act collectively as shown in Table 4.

Community/Neighbourhood Swm Planning Level

Community-based groups such as neighbourhood rate payers, service clubs, or environmental interest groups can develop and apply stormwater pollution prevention programs as illustrated in Figure 2.

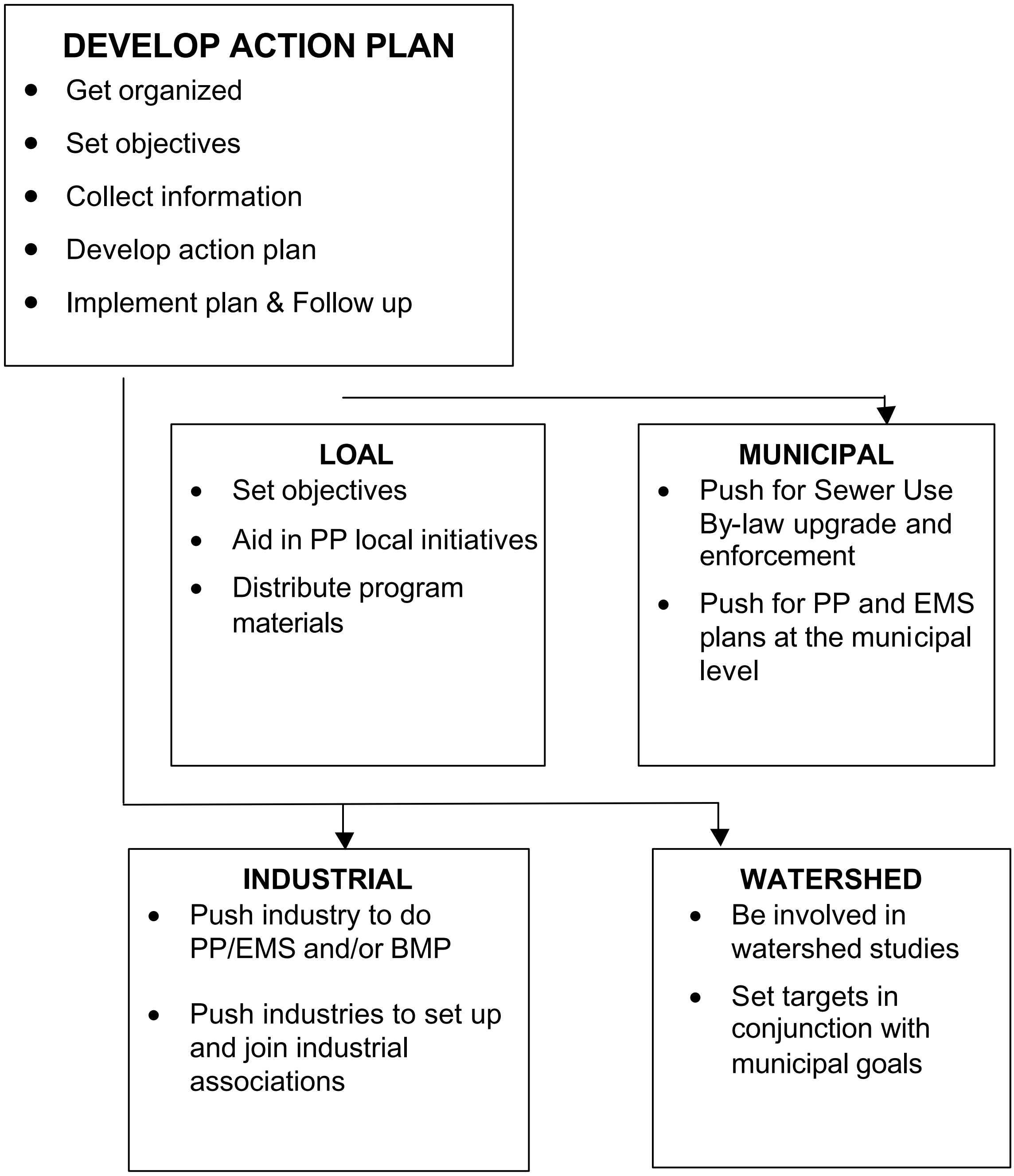

Figure 2 Community-based stormwater pollution prevention programs

Table 3. Options for Pollution Prevention Planning at the Municipal Level

Municipal Plans		
Municipal Wide	Local	Watershed
Pollution Prevention and Control Plan	Implement pollution prevention, flow reduction	Watershed Study
Environmental Management System	Enforce by-laws in residential areas	Regional Action Plan Study
By-law	Enforce sewer use by-law for industry	
Pollution Prevention Plan	Implement Public Education programs	
Best Management Practices		
Flow Reduction		
Programs – Air quality, Outfall and Monitoring		

Table 4. Industrial/Commercial Plans

Industrial/Commercial Plans	
Site Plans	Collective Action
Pollution Prevention Plan	Industrial Association
Environmental Management System	Community
Best Management Practices Plan	Watershed
Water Conservation	Sector

Conclusions

Storm management has become an important municipal service as urban runoff impacts intensify after urbanization. Among the various types of SWMP, non-structural SWMP are becoming popular in Canada. Although they may not be the most cost-effective measures in stormwater management, they can be implemented gradually. In fact, non-structural SWMP complement traditional structural measures such as stormwater management ponds. Successful implementation of non-structural SWMP rely on public education and participation, open-mindedness of municipal staff towards emerging technologies and practices, and innovative designs by engineering professionals. By their nature, the effectiveness of these measures in reducing pollution loadings and impacts is difficult to evaluate quantitatively.

Consequently, it is often difficult to justify additional expenditures for these measures in other than general terms. Monitoring programs targeted at measuring effectiveness need to be developed for each measure to address this deficiency. Last but not least, non-structural SWMP should be incorporated into municipal and industrial pollution prevention plans, based on their generally recognized effectiveness in contributing to reduction of pollution loadings

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Restoring Ice-Jam Floodwater to a Drying Delta Ecosystem

By

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Abstract: Overbank flooding is essential to the ecological health of riparian landscapes, particularly river-deltas. One of the world's largest freshwater deltas, the Peace-Athabasca Delta (PAD) in northern Canada, has experienced a series of wetting and drying cycles because of inter-annual variations in flooding. Recent research has found that most of the major floods affecting this system are produced by spring ice jams. For approximately two decades, however, the combination of climatic and flow-regulation effects precluded significant ice-jam flooding of the PAD. Resultant drying caused major changes to the ecology of the delta and led to the evaluation of a number of methods to restore water. Since most of delta is contained within a national park (Wood Buffalo National Park), a major goal was to employ non-structural measures. Hence, in an effort to manage the water problems of this delta, the final report of a multi-agency "Northern River Basins Study" made the recommendation that the spring flow-release strategy of the upstream hydro-electric reservoir be modified to increase the probability of ice-jam flooding near the PAD. This was to be conducted in years when downstream hydrometeorological conditions (snowpack magnitude and ice-cover strength) appeared conducive to ice-jam formation. Such favourable conditions developed in the spring of 1996, a natural ice jam began to develop, and regulated flows were increased to assist in potential flooding. As a result, the PAD experienced its first major flood in over 20 years. This paper reviews the hydrometeorological conditions that led to the ice-jam formation, compares the conditions to historical events, analyzes the spatial extent of the flood, and evaluates the effectiveness of the flow release.

Keywords: floods, wetlands, river restoration, river ice, ice jams, delta.

Introduction

Flooding is critical to the ecosystem health of river-delta environments, particularly to perched-ponds and lakes hydraulically separated from the open-water channel system. One of the world's largest deltas, the Peace-Athabasca Delta (PAD) in western Canada (Figure 1), has experienced two major periods of drying over the past three decades. The first drying trend was associated with construction and rapid initial filling of the W.A.C. Bennett hydroelectric dam in the headwaters of the Peace River from 1968 to 1971. The second drying trend began after 1974, the year of a major spring flood, and affected the elevated landscape of the delta region, especially an area of isolated perched-basins near the Peace River.

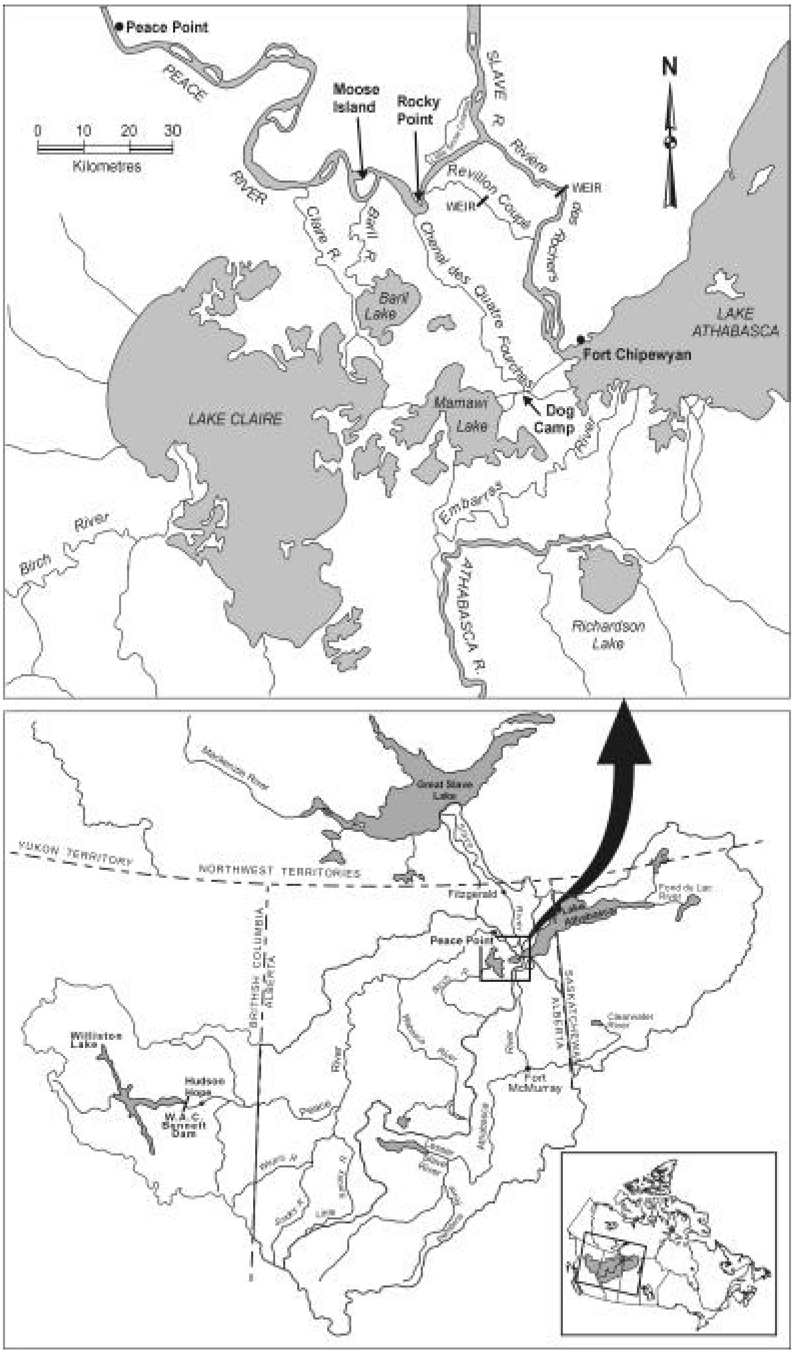

Figure 1. Peace-Athabasca Delta location maps

These events have produced a range of changes in the delta ecosystem varying from shifts in dominant vegetation types (Jaques, 1990) to dramatic declines in small-mammal habitat and population (e.g., Townsend, 1975). Although it was originally believed that decreased frequency of inundation of many of the high-elevation perched basins near the Peace River was due to reduced summer flows resulting from regulation, Prowse and Lalonde (1996) showed that ice-induced backwater was the historical source of annual high-water levels.

A number of structures were built or tested within the PAD in an attempt to restore water levels, but these were only successful for the large lakes and not for the extensive riparian wetland and grassland systems that surround them. In view of the PAD being largely located within a national park, non-permanent and/or non-structural methods were subsequently considered to restore water to the higher elevation zones. This paper analyzes the use of a flow-regulation structure located over a 1000 km upstream to enhance the formation of beneficial flood conditions within the PAD through the formation of a seasonal river-ice jam. Following this strategy meant that a structure would not be located in the park and flooding would result from a natural process that used to regularly affect this important delta ecosystem. In terms of the PAD, it can therefore be considered a non-structural adaptation strategy even though it employs a distant flow-regulation control structure to generate the correct conditions within the PAD.

This manuscript describes structural methods that had been previously attempted in the PAD and the research that led to the development of the flow-modification strategy. An assessment is then made of the success of this strategy that was applied in 1996 and methods to improve it are discussed.

Background

Study Site Hydro-ecology

The PAD (centred at approx. 59° N, 112° W) is located at the confluence of the Slave, Peace, Athabasca and Birch Rivers at the western end of Lake Athabasca, northern Alberta, Canada (Figure 1). It is one of the largest freshwater ecosystems in the world (6,070 km^2); accordingly, it was designated in 1982 as a wetland of international importance by the Ramsar Convention of 1971 (Frazier, 1999) and a World Heritage Site in 1984 by UNESCO (1972). Approximately 80% of it lies within the boundaries of Canada's Wood Buffalo National Park.

Three large shallow lakes (Claire, Mamawi and Baril; <1 to 3 m deep) occupy the PAD and are connected to Lake Athabasca and other small basins by a myriad of active and inactive channels. Other than relief produced by levees and a few islands of bedrock, land areas are rarely 1-2 m above the delta lakes. Three major channels, Rivière des Rochers, Revillon Coupé, and Chenal des Quatre Fourches, connect the delta to the northward-flowing Peace and Slave Rivers (Figure 1). Although flow is normally northward, it can reverse when the Peace River is higher than the level of Lake Athabasca. The Peace and Athabasca Rivers normally experience a peak during the spring breakup period (late April to early May) and a month later (June) during a period of sustained high flow produced by runoff from the Rocky Mountain headwaters. It is during these two periods that high water levels on the Peace River can obstruct northward drainage. As a result, delta-lake levels are typically highest in the mid-summer, and then recede during fall and winter months when outflow to the Slave River is greater than inflow to the PAD.

Depending on the elevation of lake and river levels, water can feed the riparian landscape of the PAD that is characterized by thousands of small lakes and wetlands. These are classified as having open, restricted or isolated drainage, depending on their level of connectivity with channels and lakes (PADPG, 1973). For the latter case, water can only enter the basin via overbank flooding and water level drawdown is almost exclusively the result of evaporation (Prowse et al., 1996a). Restricted and isolated basins are often referred to as 'perched basins'. When full, perched basins account for over 19,000 km of shoreline within the delta (Townsend, 1984).

The PAD provides the largest alluvial-wetland habitat in the region and its importance is accentuated by the low availability of wetland habitat elsewhere in the basin. Perched basins are generally the greatest source of muskrat habitat in northern delta areas because of their more stable water regime, extensive shorelines, and emergent vegetation. Muskrat has traditionally been the most important fur bearing mammal and source of trapping income for the local native people (Townsend, 1984). Similarly, moose are a valuable economic resource for settlements in the area and favour areas periodically subjected to ecological disturbances, such as flooding, where a mosaic of early seral vegetation and more mature climax stands are maintained (PADPG, 1973). Hybrid wood bison-plains bison are found throughout the lower Peace River area, although they concentrate in the open grasslands that are largely sustained by regular flooding (PADPG, 1973).

The PAD is also nationally and internationally significant because of its use by large numbers of migratory waterfowl. Most of the birds using the delta are from the Central and Mississippi Flyways, although all major migratory flyways pass through the Peace River Basin. When drought strikes the prairie regions to the south, the PAD provides a refuge for migrating duck populations (PADIC, 1987). The delta also provides major spawning and rearing habitat for Upper Slave River fish with large populations migrating between the delta lakes and major rivers.

Peace River Flows

The largest river affecting the PAD, the Peace River, begins in the Rocky Mountains of northern British Columbia. Since the spring of 1968, flow from its mountainous headwaters was captured in the Williston Lake reservoir behind the W.A.C. Bennett Dam, one of the world's ten largest dams (70×10^9 m^3; International Commission on Large Dams, 1988). About 70% of the annual runoff into the reservoir is derived from snowmelt during the months of May to August (Coulson, 1990). Flow releases are governed by power demand, which is greatest during the period October through April, resulting in a drastically altered runoff pattern immediately below the dam (Peters and Prowse, 2001). Along its 1,200 km course to the PAD, tributary streams (>20) dilute the effects of regulation. The largest of these tributaries, the Smoky River, is also the dominant source of spring (Prowse et al., 1996b) and summer (Warner and Thompson, 1974; Warner et al., 1988) runoff to the lower Peace River.

During the initial filling of the Williston Reservoir, significant concern developed about the altered hydrologic regime on the PAD ecology. Retention of ~ 41 km^3 of water over the period 1968 to 1972 (Muzik, 1985) reduced total shoreline length within the PAD by 36% and water-surface area by 38%, exposing 500 km^2 of mudflats. As summarized by Townsend (1975), this led to a rapid decline in muskrat and the replacement of productive sedge meadow vegetation by more invasive woody forms such as willow and poplar. Even after the filling, however, concern continued about potential ecological impacts related to the changing hydrologic regime (e.g., PADPG, 1973; PADIC, 1987; NRBS, 1996; Prowse and Conly, 2001). In an attempt to restore water levels, a number of structural controls were constructed and/or evaluated, as reviewed in the next section.

Structural Controls

Although located within a national park, two structural controls were constructed within the PAD in an attempt to restore high water levels. The first involved the use of rock weirs that were built soon after the effects of the reservoir filling were noticed in the delta (PADPG, 1972; 1973). The first rock-filled weir, established on the west arm of the Quatre Forches, was successful in raising lake water levels during a large spring-runoff event in 1972, but the crest of the weir was damaged by an ice push. Since the weir was believed to pose an impediment to the migration of fish between the large lakes, it was ultimately decommissioned by removing the top several metres of strata. New rock weirs, including a fish passageway, were subsequently constructed on the Revillon Coupé and the Rivière des Rochers. Assessments of the weirs performance indicated that they have been relatively successful in restoring water levels on the delta lakes and channels to their pre-regulation state (e.g., PADIC, 1987; Prowse et al., 1996c). Within many perched basins, however, a serious drying trend developed following the last major overbank flood in the spring of 1974.

Partly in recognition of the need to avoid permanent structures within Wood Buffalo National Park, an early assessment was also made of ice dams (Nuttall et al., 1973). The basic principle was to block completely a portion of the Rivière des Rochers with ice grown using cryophiles (thermal-syphons) until the early spring to mid-summer, when it would act as an obstruction to large open-water flows attempting to exit the lakes into the northward flowing Peace and Slave Rivers. Although only a partial testing of this strategy was completed, it did generate considerable ice-hydraulic information for a different ice-dam approach attempted after the importance of ice jamming was recognized.

Although major ice-jam events that produced wide-scale flooding of the PAD historically formed on the Peace and Slave Rivers, attention in the early 1990s again focussed on modifying the ice regime on smaller channels within the PAD. A trial experiment in 1993, using both surface flooding and spray-ice techniques, revealed that the latter was the superior method for producing large quantities of ice necessary to block the deep delta channels (Prowse et al., 1996c). In the winter of 1994/95, spray ice was used to construct a 60,000 m^3 ice dam overtop of the remnants of the original rock-filled weir on the west arm of the Quatre Fourches channel. Unfortunately, above-normal winter temperatures, a pronounced mid-winter decline in water levels due to upstream regulation, and abnormally low local spring runoff severely limited the amount of water available for storage behind the dam. Although only a partial success, the test demonstrated that localized flooding of some of the perched basins could be achieved (Prowse and Demuth, 1996).

Natural Ice Jams

Magnitude and Frequency

Although peak flow on the rivers through the PAD occur during the open-water period, it has been shown that, for at least the Peace River, peak water levels are regularly produced by ice-jam backwater (Prowse and Lalonde, 1996). Figure 2 illustrates the peak water levels that have occurred under ice breakup conditions from 1962 to 1996 at the closest hydrometric station to the PAD (i.e., Peace Point, Figure 1), located approximately 70 km upstream. Although the Peace Point gauge levels cannot be directly extrapolated to the main delta, they do indicate that much higher levels are produced by ice-induced backwater and at much lower flows. Also shown are the open-water rating curve for this site, the level and flow associated with the largest flow on record (i.e., 1990), bankfull stage, the expected stage in the presence of a sheet ice cover, and the maximum stage that would occur with formation of an equilibrium ice jam (e.g., see Beltaos, 1995). Bankfull stage is attained by an equilibrium jam at this site when flow is approximately 4000 m^3/s. A number of breakup induced water levels have exceeded the largest recorded open-water flood, often by as much as 2 m and at <1/2 the discharge. Three of these occurred biennially during the 6-year record preceding regulation and six within the 25-year period following filling of the reservoir. Note that two large events, in 1972 and 1974, occurred after regulation. Since 1974, however, no significant flooding of the PAD occurred until 1996, although some very high water levels (e.g., 1979, 1992 and 1994) were recorded at the Peace Point hydrometric station. Reasons why such years did not produce floods at the PAD are discussed later.

Hydrometeorological Controls of Ice-Jam Frequency

Reasons for the lack of major flooding of the PAD since 1974 were found to lie with the controlling hydrometeorological conditions. In general, river-ice breakup and the associated ice jamming are governed by a balancing of upstream forces and downstream resistance. Two major factors affect the downstream resistance, pre-breakup ice thickness (as determined by total winter ice growth and pre-breakup thinning) and ice strength. As summarized by Prowse and Conly (1998), these factors did not show any significant inter-annual variation. Upstream forces are primarily provided by the advancing breakup front that is driven largely by flow from upstream tributaries. Prowse and Conly (1998) did find that there had been a significant change in the magnitude of flows associated with breakup. Contrasting pre- and post-regulation periods, they found that more flow was carried by the Peace River at the time of breakup at Peace Point after regulation than before. For example, the mean pre- and post-regulation flows for April 15 were found to more than double from approximately 800 m^3/s to 1800 m^3/s. They also discovered that most major breakup floods were driven by flow from tributaries downstream of the point of regulation, particularly by the Smoky River. This one large tributary drains almost one quarter of the Peace River catchment between Hudson Hope and Peace Point, an area equivalent to 72% of that above the point of regulation.

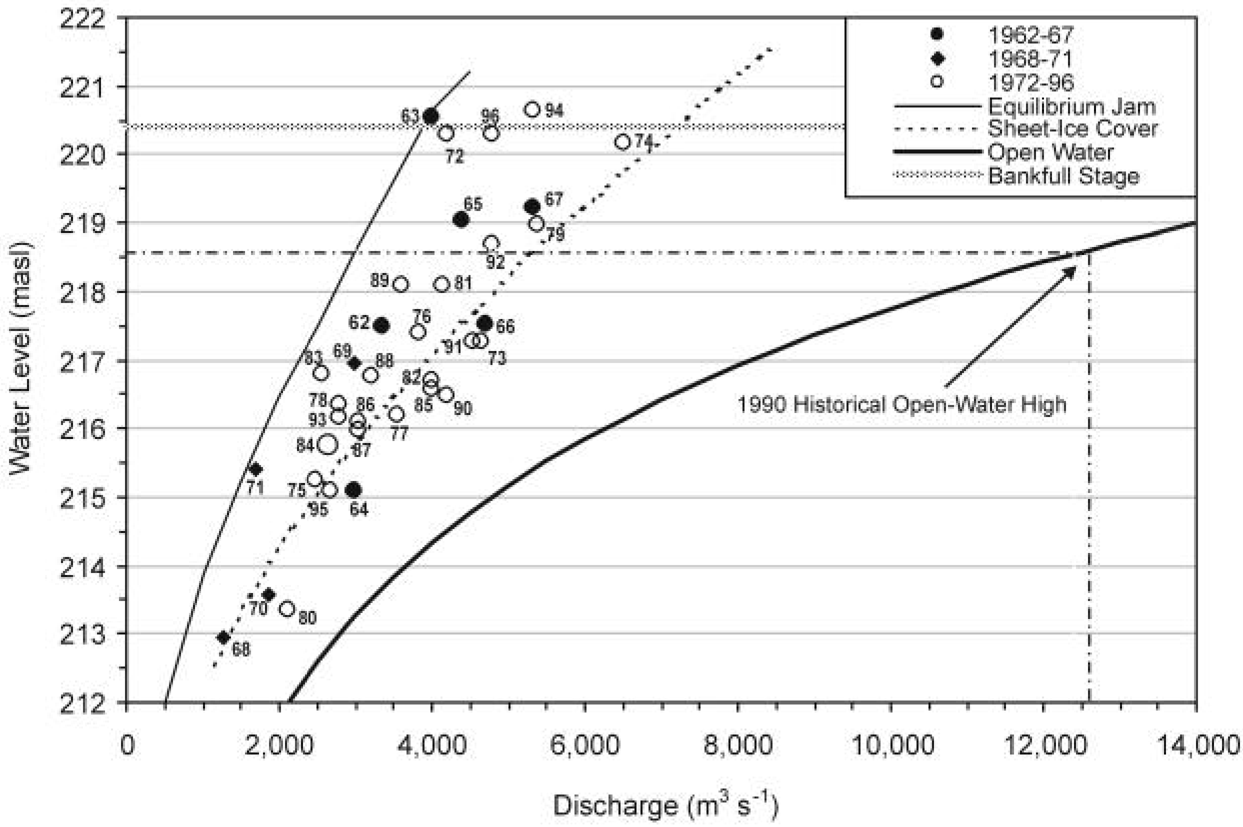

Figure 2. Rating curves for the Peace-Point hydrometric station showing water level/discharge relationships for different flow conditions and comparison with peak stages recorded during

breakup. Uppermost line: calculated maximum stage that would occur from an equilibrium ice jam (Beltaos, 1995). Intermediate line: sheet-ice cover just prior to breakup, assumed thickness of 0.6 m and Manning roughness coefficient of 0.03; lowermost line: open water condition. Breakup data updated from Prowse and Lalonde (1996).

Interesting, it was also found that since regulation the percentage of the flow upstream of Hudson Hope has become relatively more important to Peace Point breakup. This is largely the result of the winter increase in flows from the reservoir to produce hydroelectric power. By contrast, the relative importance of the Smoky River declined. While some of this was attributed to the increase in the upstream regulated, decreases in the size of the spring snowpack driving the tributary runoff were also identified as a contributing factor. A subsequent analysis of atmospheric circulation patterns by Keller et al. (1997) showed that a reduction in the frequency of snow-producing winter storms in the mid-1970s was responsible for the decline in the magnitude of the snowpack available for spring runoff.

Prowse and Conly (1998) also concluded that increases in freeze-up ice levels (stage at which the permanent winter ice cover is established) resulting from enhanced regulated flow (and related stage increase) during the winter has probably also affected the severity of ice jamming. This effect was believed not to preclude the formation of large-order floods driven by large snowmelt runoff from tributaries such as the Smoky, but thought to have the most pronounced effect on the middle-order ice-jam events.

Adaptation Strategy

Details regarding the importance of ice jamming on flooding of the PAD have been summarized in technical reports for the Northern River Basins Study (NRBS, 1996) and the Peace Athabasca Delta Technical Studies (PADTS, 1996). Based on this information, a primary recommendation of the final NRBS hydrology report (Prowse and Conly, 1996) was that the flow-regulation scheme employed at the Williston Reservoir should be modified to increase the chances of creating breakup ice jams near the PAD. Specifically, it was recommended that minor increases in flow be made in years where the downstream tributary flow was forecast to be large. It was on this recommendation that a trial of the strategy was attempted in 1996.

Analysis of 1996 Ice-jam Flood

The next major ice-jam flood event since 1974 to affect the PAD developed in late April of 1996. The next section details the snowpack, snowmelt, ice-cover, and breakup conditions that characterized this event, and compares them to historical trends. This is followed by a description and analysis of the additional flow provided to enhance flooding from this event.

Melt and Ice-Jam Conditions

As shown in Figure 3a, the accumulated winter precipitation (data for Grande Prairie in the Smoky River headwaters) leading up to the 1996 spring melt period was well above normal conditions for most years after 1974. Melt of this snowpack did not begin until approximately April 04 (Figure 3b: note concurrent rise in accumulated melting degree days and decline in snowpack), but once started was relatively intense compared to average conditions. This is evidenced by the steep slope in the 1996 accumulated melting degree days compared to the mean rate of rise. The effect on flow of the Smoky River is shown in Figure 3c where it far exceeds long-term mean conditions.

The relative significance of flow from the various tributaries (all flows have been lagged to account for travel times) to breakup at Peace Point are shown in Figure 4a. As for most years, particularly those of significant ice-jam flooding (see Prowse and Lalonde, 1996), the Smoky River was the major contributor. Above normal flows are also evident on the main stem of the Peace River (Figure 4b) as illustrated by the large magnitude of the 1996 Peace Point discharge compared to the mean pre- and post-regulation values.

On the same day as snowmelt initiation, the ice-cover thickness was measured at 0.87 m (WSC, 1997). This is within the range of the mean peak ice thickness noted by Prowse et al. (1996b) for the pre- and post-regulation periods. Based on estimates of pre-breakup thinning using a degree-day ice-ablation model (e.g., see Gray and Prowse, 1993), the final pre-breakup ice thickness was estimated to be approximately 0.56 m. A value close to the visual estimate of 0.60 m (max. 1.0 m) taken on the day following breakup (WSC, 1997).

Breakup of the ice cover occurred at the Peace Point hydrometric station on April 24, resulting in a maximum water level of 220.28 m on April 25. Over the following week, a breakup front progressed downstream such that on April 25, the ice cover was broken up to and jammed near the Baril River (Figure 1; Giroux, 1997). A fractured ice cover extended back upstream as far as Peace Point (WSC, 1997). At this time, flooding was restricted to low-lying areas adjacent to the river although the stage was sufficiently high to feed water into the mouth of the Claire River located at a high elevation point along the banks of the Peace River (Figure 5). By the next day, the downstream end of the ice jam (toe) had moved down to the confluence with the Slave River, blocking the Rivière des Quatre Fourches, and backwater flooding of inland portions of the delta commenced. As observed on April 27, the upstream end of the jam (head) was at Moose Island and the toe had remained stationary. Secondary jams were noted on the north arm of the Quatre Fourches on April 30, inducing additional overbank flooding in internal portions of the PAD (Figure 5). Breakup progressed along this channel and extended radially from Dog Camp (Figure 1) by the 1st of May. By May 3, the main ice jam on the Peace River had shortened by more than 20 km to so that the upstream end (head) of the jam was near Little Scow Channel (Figure 1). Sometime between the reconnaissance surveys of May 3 and May 4, the Peace River and smaller channels started to clear of ice and water levels rapidly declined.

As shown in Figure 5, large portions of the PAD were flooded by the 1996 spring ice jam although many basins surrounding the large lakes remained dry. It should also be noted that some flooding also originated in the southern portions of the PAD, probably related to ice jam conditions on the Athabasca River system.

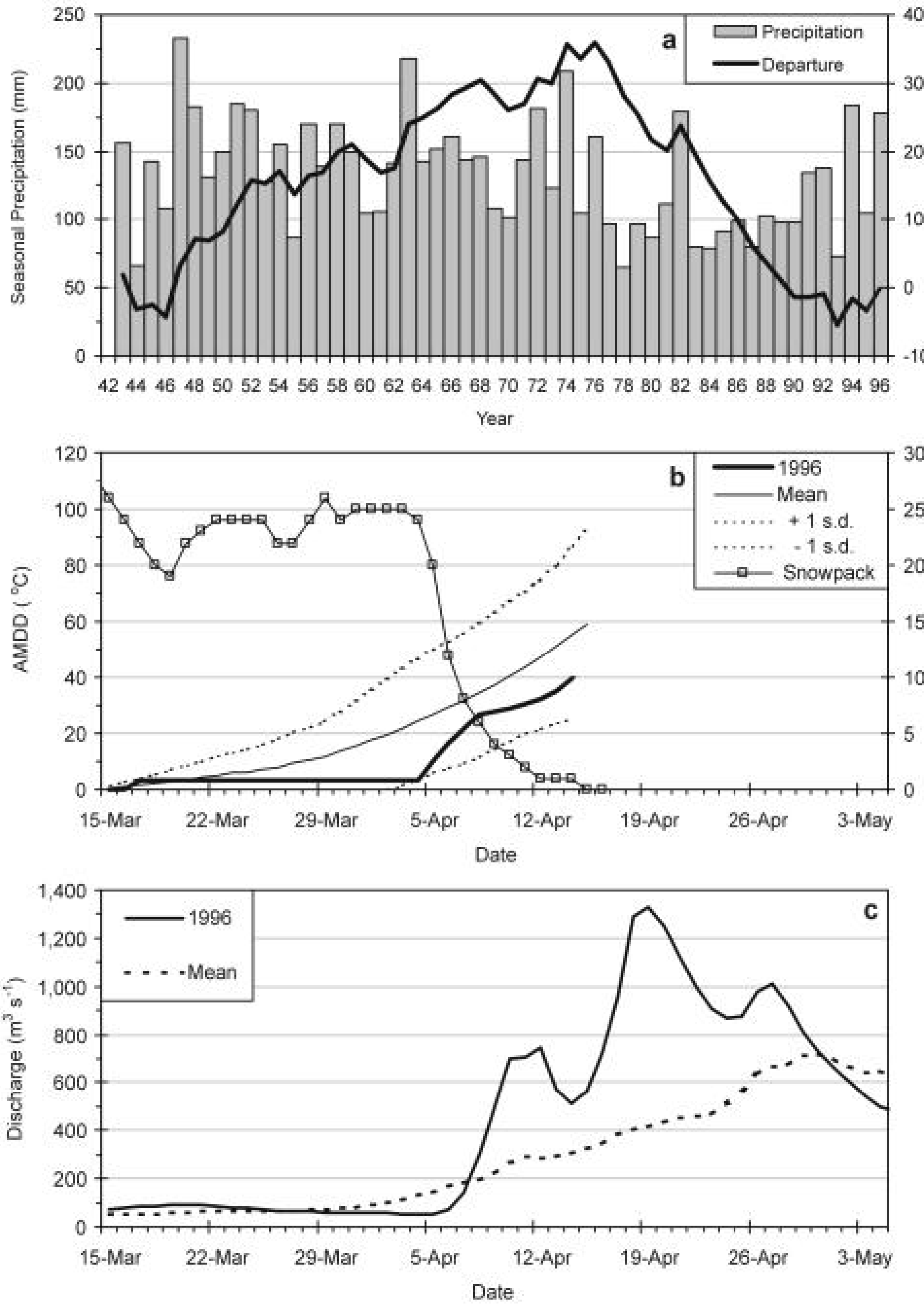

Figure 3. Hydro-climatic conditions in the Smoky River basin.

3a: Bars indicate annual accumulated winter precipitation reflecting size of spr ing snowpack; line is trend in annual cumulative departure from the mean for the period. Note decline beginning in mid-1970s.

3b: Melt conditions showing decline in 1996 spring snowpack (data from Beaverloge climate station; Environment Canada, 1998a) and intensity of melt as measured by accumulated melting degree days (>0ºC; AMDD; climate data from Grande Prairie climate station, Environment Canada, 1998a). Note delay and then rapid increase in 1996 melt when compared to long-term mean conditions.

3c. Spring discharge as recorded at Smoky River at Watino hydrometric station (Environment Canada, 1998b). Note rapid rise in 1996 flow matching, with a slight lag, the rise in melting degree-days.

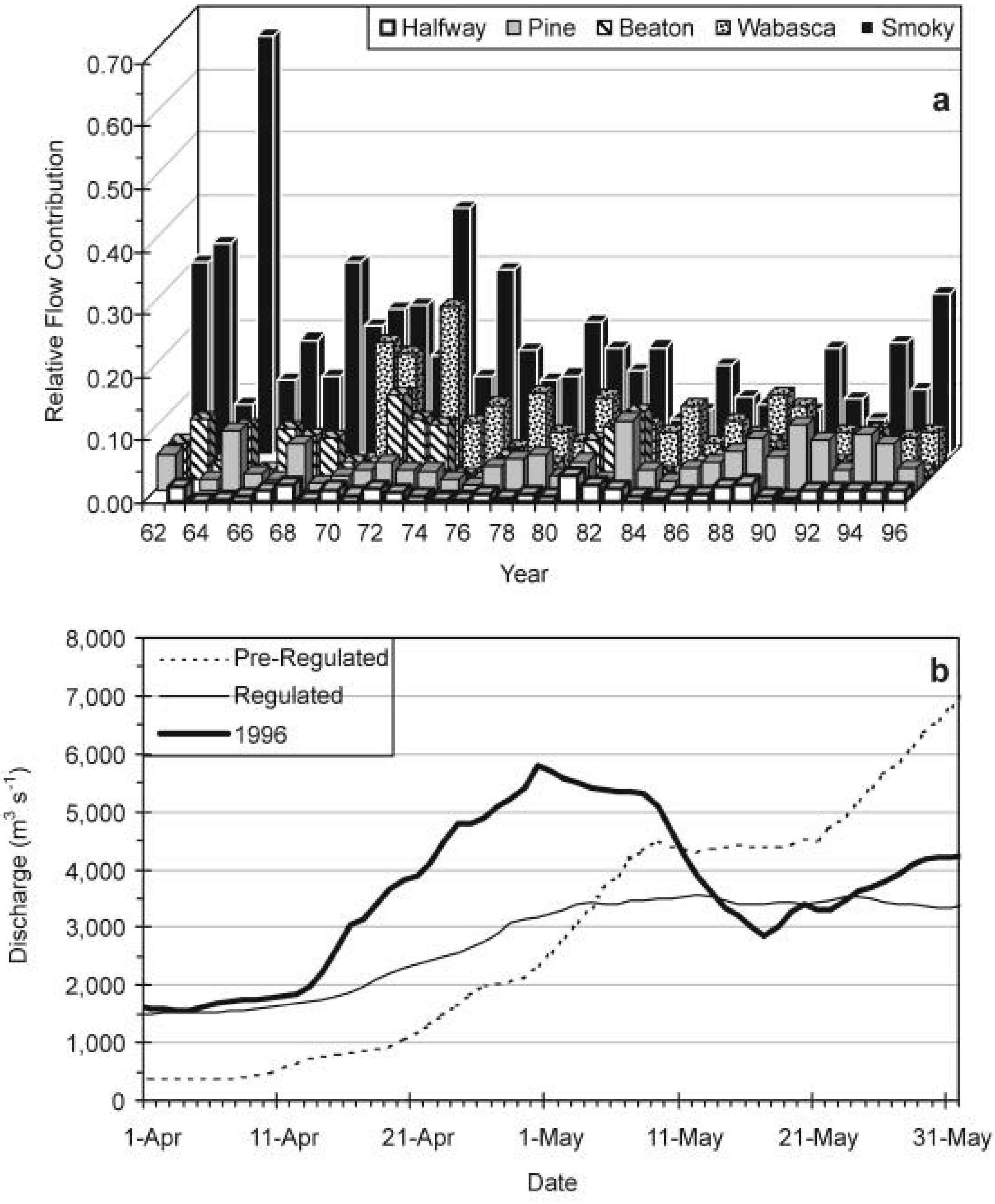

Figure 4. Flow conditions during spring breakup on the Peace River.
4a: Relative significance of flow contributed by major Peace River tributaries to the total flow recorded on the day of spring breakup at the Peace Point hydrometric station (updated from Prowse and Lalonde, 1996);
4b: Discharge recorded at Peace Point hydrometric station (Environment Canada, 1998b). As per Figure 3c, note rapid rise in 1996 conditions compared to long-term mean values for before and after regulation.

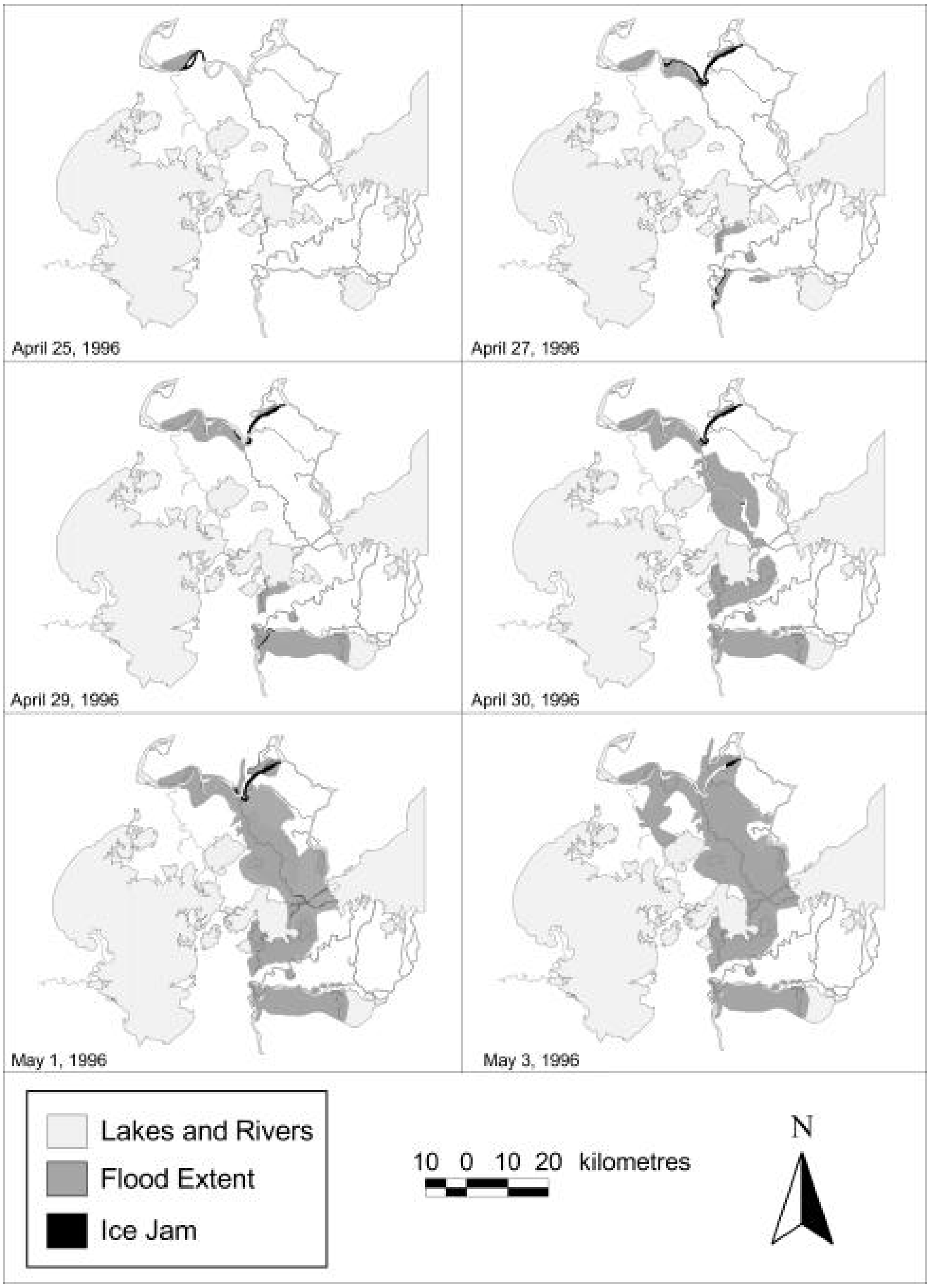

Figure 5. Development of 1996 ice-jam flood affecting the Peace-Athabasca Delta. Note twin sources of flooding via overbank conditions in the north from the Peace River and in the south from the Athabasca River (after Töyrä, 2000).

Flow Augmentation

Background

During the early portion of the 1996 spring, it was realized that conditions were conducive to the potential formation of an ice jam and that an opportunity existed to test the recommendation regarding the increase of regulated flow to assist ice jamming. The following is an excerpt from a personal communication from a representative of BC Hydro regarding the 1996 event (Chan-

McLeod, pers. comm.)

The ice management agreement between Alberta and British Columbia dictates that any requests for flow regulation during the ice season would have to come from Alberta Environmental Protection, River Engineering Branch, to the Power Systems Operation manager at BC Hydro. Safety considerations dictate that Alberta Environment hold off making a request until the Peace River ice front has passed the town of Fort Vermillion in Alberta to reduce the likelihood of ice-jam related flooding at Fort Vermillion and upstream. BC Hydro considers any request for modified releases, subject to a number of constraints including public safety, regulatory requirements, present and future power demand, economic and environmental trade-offs and operating efficiencies. Generally, following peak winter demands on the electric system, which is integrated province-wide, there is some flexibility to generate at alternative facilities and therefore accommodate such requests. Requests for increased flow (i.e. increased generation) from the Peace River plants can be accommodated if the Williston reservoir level is sufficient and non-power considerations allow decreased production at other facilities.

The request for increased Peace River flows, in spring 1996, similar in magnitude to those that formed the ice cover at the delta in early December, came as BC Hydro was recognizing a likelihood of spilling from some system reservoirs because of higher than average snowpacks in the watersheds. A system spill occurs when system inflows are high, all reservoirs are full (or soon will be) and electrical demand is not sufficient to run all turbines at maximum capacity. This situation provided maximum flexibility with respect to handling the request for increased flows at GM Shrum and Peace Canyon generating stations including transferring some of the impending spill at GM Shrum to another area of the system. At the time of Alberta's request, most of the smaller projects in the system were running at capacity because of the pending spill situation. Mica and GM Shrum, being the two largest projects in the system normally take the "swing" under such circumstances. In this particular instance production was curtailed at Mica so that generation could be increased on the Peace to accommodate Alberta's request for increased flows. Between April 25 and May 3, flow through the turbines at both Peace generating stations was increased from 1100cms to 1600cms.

Flow Routing

The extra release of flow to the Peace River is shown in Figure 6a for the Hudson Hope hydrometric station just downstream of the Williston Reservoir. To assess the effect of this release on flow conditions near the PAD during the ice-jam event, the Hudson Hope flow, minus the enhancement, was routed to the PAD using a hydraulic model of the Peace River. The model is based on modified St. Venant equations that are solved by the finite-element method using the characteristic dissipative Galerkin scheme (Hicks, 1996). A detailed description of the numerical model scheme and development of the geometric database is found in Hicks and McKay (1996), and the calibration and application of the model is presented in Peters and Prowse (2001). The simulated flow at Peace Point without the extra release is presented in Figure 6b, and the daily proportional contribution of the added flow to the total flow is shown in Figure 6c. Because of the lengthy flow travel time between the dam and the PAD, the first significant additions to flow (?Q) did not appear until May 2, but then steadily increased to 553 m^3/s or approximately 11% of the total flow by May 7. On May 3, prior to the release of the ice jam, ?Q = 307 m^3/s or about 6% of total flow.

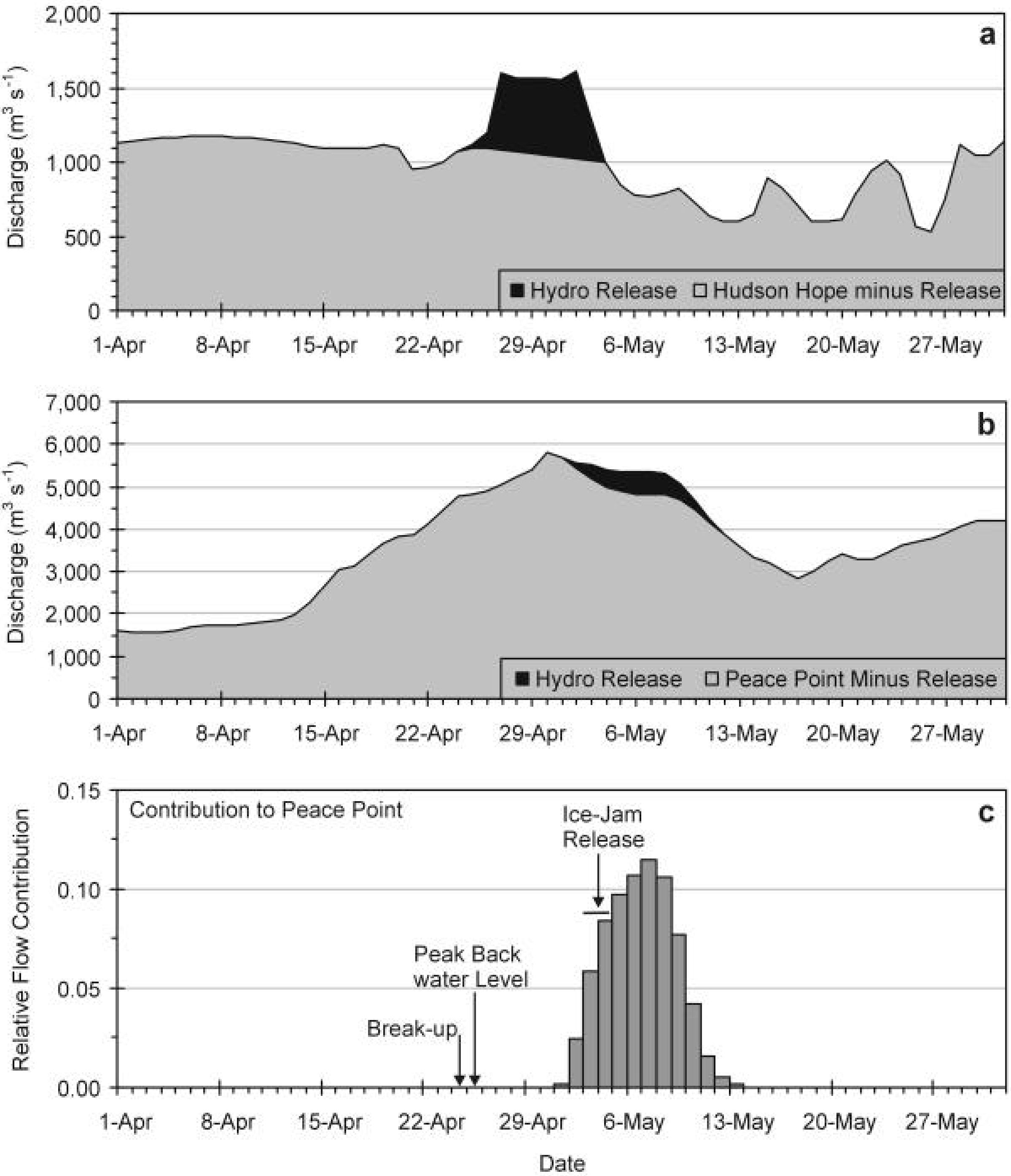

Figure 6. Augmentation to flow from release of water from the Williston Lake reservoir, 1996. 6a and 6b show Peace River flow with and without the release at the Hudson Hope (a) and Peace Point (b) hydrometric stations. 6c indicates the size of the flow release relative to the total flow at the Peace Point station. Dates of breakup refer to breakup progression shown in Figure 5.

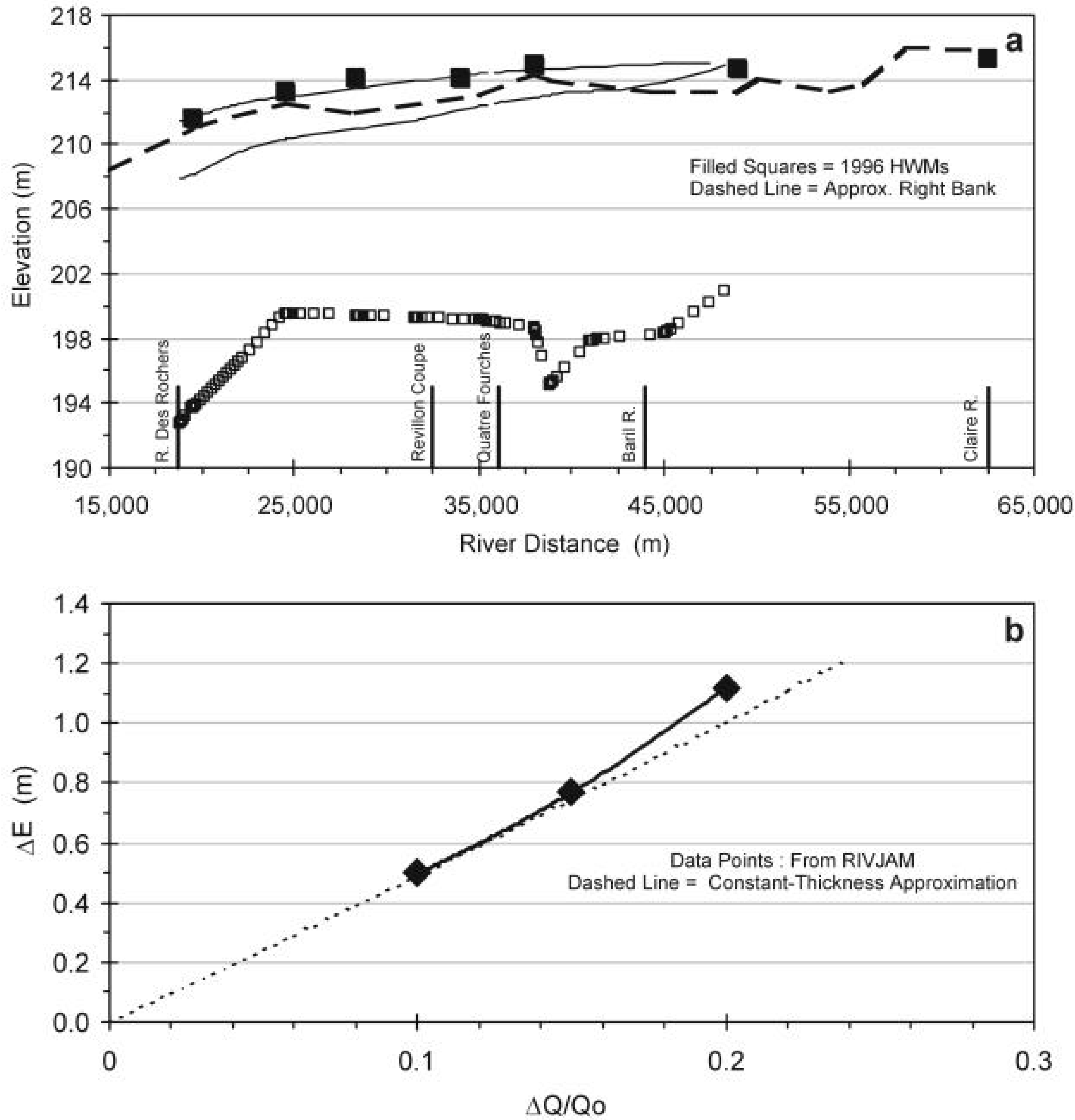

Figure 7. RIVJAM calculations.

7a: RIVJAM prediction for April 27, 1996 and comparison with observed 1996 high water marks. River distance is measured upstream from an arbitrarily selected datum in the Slave River. Solid lines: predicted water surface (uppermost); bottom of jam (intermediate); thalweg (lowermost).

7b: Reduction in water surface elevation (ΔE) near the jam head, as a function of relative flow reduction at Peace Point. Q_o = Peace Point flow affecting PAD reach on April 27, 1996 (travel time ~ one-half day) = 4985 m^3/s.

Ice-Jam Model and Calibration

Although the additional flow was < 6% of the total while the ice jam was in place, it had large potential to enhance flooding because water levels were already near bankfull stage due to backwater from the ice jam. A numerical ice-jam model, RIVJAM, was used to analyze the effect of the release on stage. The model computes water level and jam thickness along a river, given the location of the jam toe and channel hydraulic properties, including the discharge and river bathymetry in the study reach (Beltaos, 1993, 1996). In addition to flow under the ice accumulation, model input consists of (a) river bathymetry, specified as a set of surveyed cross-sections in the reach of interest; and (b) values of several coefficients that quantify the internal strength, porosity, and seepage characteristics of the rubble, and hydraulic resistance characteristics of the flow under the jam. Calibration of the model was based on the survey of high water marks (HWM) obtained after the ice jams of 1996 and 1997 and believed to represent conditions on April 27, 1996 and May 1, 1997. Examination of the 1997 event is ongoing and only the HWM data have been used to assist in the ice-jam model analysis of the 1996 event.

Calibration of the model also required estimates of the amount of flow that was diverted southward by the five main tributaries that feed into the PAD. Trying different plausible outflows and settling on the set that gave satisfactory ice-jam profiles and water level predictions resolved this question. These results indicate that the uppermost two tributaries (Claire and Baril Rivers) would have carried flows amounting to tens of m^3/s. Though highly significant for the replenishment of specific perched basins, such values are negligible relative to the thousands of m^3/s that are carried by the main river and used in RIVJAM. Consequently, the Claire and Baril River flows were set equal to zero. Flows in Revillon Coupé and Chenal des Quatre Fourches were respectively estimated as 200 and 300 m^3/s, while another 500 m^3/s was estimated to have been spilling over the banks between Peace Point and the head of the jam near the upstream end of Moose Island (Figure 1). The flow entering the jammed reach was thus estimated as 4500 m^3/s, using a one-half day travel time between Peace Point and the PAD reach. The flow near the jam toe, located just upstream of Rivière des Rochers would thus have been 4000 m^3/s. The end result of the RIVJAM application for the 1996 ice jam is depicted in Fig. 7a, where it is seen that the elevations of the HWMs and the upstream extent of the jam are closely matched by the model.

Significance of flow enhancement

Flow values used to calculate the profile in Figure 7a on April 27 are not affected by the reservoir flow release that only affected the site after May 1 (Figure 6c). The ice jam released sometime between the reconnaissance flights of May 3 and 4, therefore the maximum impact of the release on ice-jam water levels would have been on May 3 (?Q = 307 m^3/s). By that time, however, shortening of the jam would have meant that its effect on river stages would not extend as far upstream as it did on April 27.

By repeated applications of RIVJAM, a relationship was derived (Figure 7b) between ?Q and ?E (= corresponding drop in water surface elevation near the upstream end of the jam) to evaluate the effect of a range of flow releases. For this, the downstream end of the jam was assumed to be at the same location as it was on April 27, 1996 and that the volume of ice in the jam remained constant (calibration estimate = 15.7 x 10^6 m^3). Although ice thickness could vary under different flow conditions, model results indicate that it is rather insensitive to flow in the range under consideration, and only becomes so when ?Q > 500 m^3/s. Assuming that ice thickness is unchanged, ?E results solely from a reduction in the depth of flow under the jam, and is related to ?Q by:

$$\frac{\Delta E}{h_o} = 1 - (1 - \frac{\Delta Q}{Q_o})^{\frac{3}{5}} \qquad (1)$$

in which h_o = under-ice flow depth in reach of interest; i.e., near the head of the jam and = 8 m. Equation 1 is also plotted in Fig. 7b for comparison, and shown to provide very good estimates up to about ?Q/Q_o = 0.15 [In this range, Eq.1 simplifies further to a linear form, i.e. ?E/h_o ≈ (3/5)(?Q/Q_o)].
Using Figure 7b, it is now possible to determine the potential effects of the 1996 release under actual and other possible scenarios. The ideal situation would have occurred if the maximum flow addition of 553 m^3/s occurred on April 27 instead of on May 7. In this case, the increase in water stage near the head of the jam would have been approximately 0.55 m (i.e., $\Delta Q/Q_o$ = 553/4985 = 0.11, and from Fig. 7b, ?E = 0.55 m). Consider a case where the jam had not moved downstream and remain unchanged from April 27 to May 03, the effect of ?Q = 307 m^3/s on the latter day would have produced a stage increase of 0.27 m. In reality, the head of the jam on May 3 had significantly receded to near Little Scow Channel. Additional RIVJAM runs for this condition also resulted in a value of ? E = 0.27 m near the head of the jam. This effect on stage would persist for a considerable distance upstream, owing to the mild backwater profile above the jam, and the very low river slope (~0.04 m/km, Kellerhals et al, 1972; and surveys conducted in 1999 for this analysis).

Discussion

A 0.27 m increase in stage from the reservoir release is not appreciably large but it is significant to flooding potential considering that river stage was already at or above bankfull stage along portions of the Peace River adjacent to the PAD. This addition to the water head should have diverted significant amounts of additional flow into the perched basins of the delta. Although, it has been estimated that the stage could have been increased by over 0.5 m if the release had occurred several days earlier, the long flow time (~ 7 days) between the reservoir and the PAD make it difficult to know when to start a release so that it arrives when major ice jamming is ongoing and persists throughout the jamming period. From a hydro-climatic perspective, a release should only be contemplated when antecedent and concurrent conditions are conducive to ice-jam formation, including the size of the spring snowpack, thickness of the winter ice cover, and rapidity of spring warming (Beltaos and Prowse, 2001; Prowse and Beltaos, 2002). From a practical point of view, if such conditions are deemed favourable, a release should start as soon as it can be ascertained that the added flow will not lead to adverse flooding impacts on riverside property upstream of the PAD. Advanced modelling of breakup progression along the Peace River under varying hydroclimatic conditions is needed to help in identifying this critical window of opportunity.

Although the 1996 event was associated with a large snowpack, so were years such as 1976, 1982 and 1994 (Figure 3a). Other conditions, such as melt intensity or ice conditions, apparently precluded such heavy snow years from producing high breakup water levels at Peace Point, except in the case of 1994. As shown in Figure 2, the peak breakup water level recorded at Peace Point in 1994 was actually the highest on record. For some reason, either related to a change in the flows driving breakup or because of ice conditions in the reach between Peace Point and the PAD, an ice jam did not form adjacent to the delta and the breakup passed uneventfully into the Slave River. To increase the probability of such breakup years producing an ice-jam flood near the PAD, it might be possible to also affect the downstream resistance of the ice cover through manipulation of the freeze-up flow and the related formation of a thickened reach of ice rubble.

In general, breakup jamming occurs where moving ice floes encounter intact segments of the winter ice cover. Beltaos (1997) showed that the resistance of the winter ice cover to dislodgment depends on channel bathymetry, slope, and morphology, as well as on antecedent hydro-climatic factors. In the relatively flat reach of the Peace River near the PAD, ice covers would normally be expected to form by surface juxtaposition of ice floes (Andres, 1996; Prowse et al., 2002), and thermal growth at the ice-water interface. However, flow regulation involves higher-than-natural discharges during the fall and winter. On occasion, these discharges may be so high as to dislodge and break up the newly formed thermal ice cover. The broken ice accumulates in much thicker and rougher ice covers that consist of rubble and cause much higher water levels than those associated with thermal ice covers. This type of ice cover is known to have formed in November 2000, based on field observations carried out as part of a monitoring program initiated in 1999. The water surface elevation at Peace Point reached as high as 215.5 m while the average freeze-up stage was about 215.2 m. Such freeze-up elevations are among the highest in the post-regulation record (1972-2000).

Rubbling an ice cover at freeze-up can also lead to a greater end of season solid ice thickness. This is because downward freezing in ice rubble is accelerated since only the pore water needs to freeze (e.g. see Calkins, 1979; Timco and Goodrich, 1988). As already indicated, thicker ice and higher freeze-up levels render the winter ice cover more resistant to dislodgment when the spring runoff arrives, thus promoting formation of ice jams at the upstream end of the rubble-cover reach.

Flow release from the Williston Lake reservoir during the fall freeze-up period could be modified so as to produce an ice-jam or rubble ice cover near the PAD that would then enhance the probability of a breakup jam during the following spring. Caution would have to be exercised, however, to ensure that the breakup jam forms within the appropriate reach to cause flooding of the PAD. For instance, if a rubble cover forms within the PAD reach itself, the influence of the cover on water levels will extend tens of kilometres upstream owing to the low river slope. Ice jamming would then be initiated near the end of the rubble's influence, and may or may not advance into the PAD reach by the time the ice is cleared from the river by a combination of thermal decay and high flows. Thus there would be a risk that this strategy may prove ineffectual, or even detrimental by preventing PAD-reach jamming that might have happened otherwise. Considering also that the travel time between the dam and Peace Point is about a week, the use of this approach as a flood-enhancing strategy requires careful examination. Factors such as local weather conditions, rubble characteristics, and river morphology must be taken into account, and preferably quantified by means of freeze-up modelling. Again, possible impacts on riverside property would need to be considered, though the risk should not be as large as during breakup releases.

Conclusions

The 1996 flow release was a successful test of a remediation strategy designed to restore flooding to a major riparian ecosystem. The ice jam that precipitated the flooding was produced by hydrometeorological conditions favourable to ice jam formation, i.e., a large spring snowpack accompanied by intense melt. Moreover, such conditions were relatively uncommon over the last two decades, a period characterized by extensive drying of the delta environment because of the lack of flooding. The approximate week long release of an additional 500 m^3 of flow or approximate 50% increase from the upstream reservoir translated into a maximum daily increase of approximately 11% when it reached the downstream reaches of the Peace River near the PAD. During the actual residence of the jam, however, the maximum flow increase was only 307 m^3/s or 6% of total flow. This did, however, translate into an approximate maximum stage increase of 0.27 m, a significant rise in terms of additional flow available for flooding the delta considering that the river was already in a flood crest state. As such, this first test of this remediation strategy is considered a success.

Similar snowpack conditions characterized previous years, especially 1994 when peak breakup levels slightly upstream of the PAD were the highest on record, yet no significant ice jam flooding affected the delta. It is hypothesized that this may have been due to changes in flow as the breakup front moved passed the PAD or due to difference in ice conditions affecting the PAD-reach of the Peace River. In either case, it may be possible to further increase the probability of spring ice jamming along this critical reach by modifying ice conditions via flow manipulation during the fall freeze-up period. More research into exploring this possibility is recommended but the work must be guided by a need to minimize flood risks to other property along the Peace River.

Although this adaptation strategy has employed a structure to modify flooding conditions, it has done so by using a facility well away from the site of interest. To this end, the strategy could therefore be considered non-structural. The idea of using flow modification facilities on cold-regions rivers for addressing water-resource problems is relatively unexplored but could have large untapped benefits, particularly since no new structures would have to be constructed.

Acknowledgments

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Prediction as a Basis for Planning and Response

By

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Abstract: Enhanced management of water systems requires knowledge of the amounts of water availability on time scales of hours to decades. Managers of water systems can use the information from combined atmospheric-hydrologic prediction models to take appropriate actions in a real-time basis and also to plan the development of both structural and non-structural measures. Cooperation between the meteorological and hydrological communities is leading to improved models, for flash floods to climate change scenarios but there is a continuing need for dialogue to understand the needs and capabilities of each community. An important issue is the factoring in of the uncertainties of atmospheric predictions into a risk management approach to water systems management.

Introduction

Excess or lack of water both create havoc, with loss of life and property. Of the six most expensive (in dollar value) natural disasters in Canada, four were droughts and another a flood (Etkin, 2001). The costliest natural disaster in Canada was the Eastern Canadian ice storm of 1998, with over Canadian $4B in economic losses and 16 deaths. The droughts of 1979/80, 1988, 1984 and 1961 had costs in the range $0.6B to $2.5B. The Saguenay Flood of 1996 resulted from a few days of intense rain and caused 10 deaths, over 10,000 people displaced and over $1B in damage. The following year, the flooding of a Red River caused large damages on both sides of the Canada-United States border and was due to long series of meteorological and hydrological events. In Canada, four deaths resulted and the economic losses were over $0.5B. In both cases, the forecasts of precipitation were such that some action was possible but the timing for the Saguenay event, over a day or so, was so short as to prevent substantive action. In the case of the Red River, the predictions were sufficiently far in advance of the arrival of the high water that more preventive actions were possible. For droughts, the impacts are spread out over a longer period of time (usually a season or more). The economic costs of weather-related disasters around the globe has been steadily increasing, averaging close to US $80B over the last 5 years of the 20th century. The social (and economic) costs of the numerous deaths in many countries cannot be computed but the impacts are very high and should be considered unacceptable in a global context.

In view of the rising social and economic costs of natural disasters, it is appropriate for governments to review their approaches to disaster management, i.e., approaches to reduce the probability that a natural hazard will result in a natural disaster. Mileti (1999, p. 9) has reassessed natural hazards in the US and concludes that “the shift to a sustainable approach to hazard mitigation will require extraordinary actions.” Disaster management approaches can be grouped as:

1. Mitigation and adaptation.
2. Anticipate and withstand.
3. Recovery.

An important policy decision is the "right" balance of effort and expenditure of resources between disaster management approaches. Analyses indicate that investment in prevention (mitigation/adaptation and anticipate/withstand) are more effective in reducing overall costs than investing only in recovery.

Prediction as a component of disaster management strategies

Disaster management strategies need to built on information about the occurrence of natural hazards: when, where and what, the characteristics of events, including their statistics. For example, the adoption of standards and codes (building codes and flood mapping) to protect infrastructure, people, etc., from "reasonable" extremes needs to based on statistics of extremes. Forecasts and warnings to advise people about impending events and advise on response strategy is key to a "anticipate and withstand" components. In all cases, prevention or hazard mitigation is based on prediction: prediction of single events about to happen through to prediction of statistics or probabilities of events in the future. It should be noted that prediction of extremes is by its nature difficult. Models tend to be better at predicting more "normal" events and humans also tend to be somewhat skeptical of model predictions of an extreme event.

Environmental prediction has been defined as predicting future states of the environment as they will naturally occur, and as they will respond to human influence (McBean, 2000). Prediction in a broader context has been reviewed by Sarewitz et al. (2000). With predictions as part of the disaster prevention strategy, it is necessary to understand and optimize the use of predictions in each context. The traditional approach has been to use the record of the past to decide on the strategy (i.e., frequency of occurrence of events, their characteristics, etc.). However, with changing structures, river systems, human activities and habitat, as well as climate, it is appropriate to use more sophisticated prediction systems than just the record of the past. Hazard mitigation cannot be treated as a static situation (Mileti, 1999) since the earth's physical systems (e.g., climate), demographics and the built environment are changing, mostly in ways to increase sensitivity. We can consider the role of prediction, with respect to adaptation, schematically (Figure 1). Predictions provide information on the changing water levels or other characteristics and from that and related analysis, we can predict the impacts. Predictions need to be considered on several time scales and the disaster management strategy will depend on the period of time between when the prediction is made and the expected occurrence of the event. For example, for a prediction of a flash flood to occur in the next some tens of minutes, the appropriate response strategy is to issue a warning advising people to take immediate action of moving to less vulnerable locations, such as higher land. However, if the forecast is for river cresting in next a few days, then there is time to prepare for evacuation and implement emergency response procedures, such as emergency dikes or temporary levees.

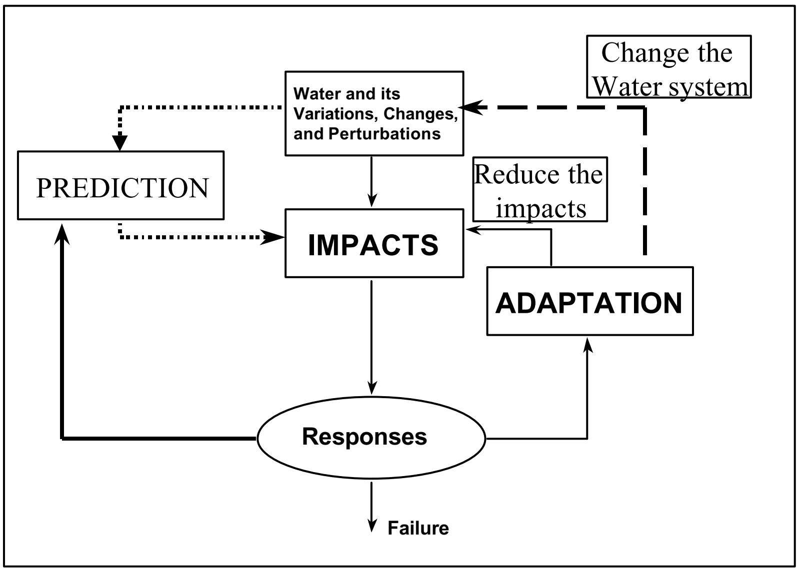

Figure 1. Schematic relationship between water hazards, their impacts and possible adaptation approaches, using prediction as part of the analysis and response strategy

On longer time scales, if there is a prediction of increased likelihood of floods, be they flash, riverine, or coastal floods, the appropriate approach would be to review and as appropriate modify building codes and to prepare response strategies. We can also, if there is time and resources, change the water system, such as building floodways or irrigation systems. Prediction should then be part of the response analysis to see how the modifications will affect the impacts.

When one considers the range of strategies of dealing with water management issues, there has been a tradition of structural approaches, i.e., building dams, waterways and irrigation systems. The Workshop on Non-Structural Measures for Water Management Problems provided a focus on the non-structural methods as attractive alternatives and additions to structural measures. There is a question in some peoples minds as to whether prediction is a non-structural method as they have viewed prediction as counter to non-structural approaches. For example, "Advocates of nonstructural approaches to the nation's flood problem, active since the 1950s, did not embrace flood prediction because they saw the public's belief that flood prediction equaled flood protection as counterproductive to achieving land-use changes in flood-prone areas." (White, 1994). Chagnon (2000) has reviewed the history of prediction as a component of US flood disaster management strategies.

Disaster management strategies are part of the fundamental, public good role of governments, defined as (Harris, 1995; McBean, 2000):

- To protect citizens from impending dangers (i.e., warnings about hazardous change);
- To maintain an archive or history of the nation; and
- To facilitate, by citizens, their mitigation and adaptation to hazardous events and to environmental and climate change.

A "public good" is something that is jointly useable so that public good services are those that all citizens receive more-or-less equally and share the benefit. In addition, it is not practicable to exclude the benefits of a public good service on a selective basis. Therefore, it makes sense to have prediction services, as part of a disaster management strategy, paid out of the tax base, rather than as a fee for service.

Predictions and predictability

The premise of prediction is that we have relationships of the form:

$$?W(\mathbf{x}, t)/?t = F(\mathbf{x}, t),$$

where W is a variable, such as water level, and **x** and t are the position vector and time. From this we use the finite difference approximation,

$$W(\mathbf{x}, t+?t) = W(\mathbf{x}, t) + F(\mathbf{x}, t)?t$$

to compute the W field at some time t+?t based on knowledge of the W field and the forcing field at an earlier time t. Deterministic predictions are defined to be those where a specific sequence of events during a period of time is forecast. Errors in the prediction will occur due to lack of understanding of the relationships (what exactly is F), errors in the initial state ($t=t_0$) of both W and F, and approximations in the numerical solution. For most variables, there is a limit to the length of the time period for which deterministic predictions can be made (Lorenz, 1963; Gleick, 1987) due to uncertainties in the initial state that amplify over time and eventually overwhelm the prediction. For atmospheric weather predictions, this theoretical limit is usually considered to be about two weeks. Over the past few decades there has been a steady improvement in the skill of atmospheric prediction models and this progress is expected to continue in the decades to come (Board of Atmospheric Sciences and Climate, 1998).

Prediction for water management will need to build upon weather-climate predictions plus water flow predictions so there is a cascading of uncertainties. We need to consider integrated water management prediction systems and look at their overall prediction capability. We can define (Figure 2) the limit of predictability as the time when the difference between the prediction and reality (the observations of what actually happened) exceeds some threshold. Further, for any time, there will be a measure of skill of the prediction (how right was it?). Although the limit and skill vary from case to case, what is most important are the averages for a large number of relevant and similar cases, so we can have some confidence in the statement of the skill as a function of time or prediction period (Figure 3). A climatological prediction, essentially the prediction for any given day is the mean value for that day over a long record of previous occurrences, has a skill that is essentially independent of the duration of the prediction. On the other hand, a persistence prediction, that the forecast for any day will be the same as the days before it (i.e., the system does not change), will have a skill that generally decreases fairly rapidly with time. A prediction system is "useful" only for that range of prediction period where its statistical skill is greater than both persistence (which may be better for very short periods of time) or climatology (which will be better for long prediction periods), beyond the limit of model predictability.

A major factor in limiting the range of useful predictions is uncertainties in the information on the initial state, which, as noted, amplify with time and eventually make the prediction useless.

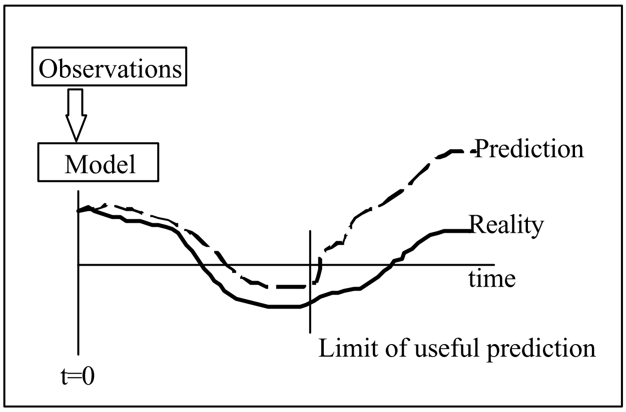

Figure 2. Deterministic prediction and the predictability limit.

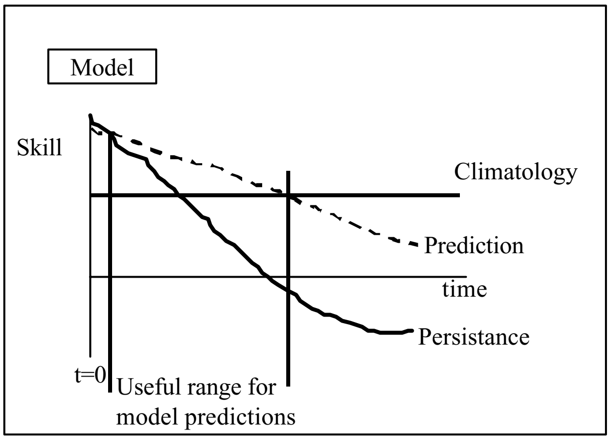

Figure 3. Skill of prediction system compared with the skill of predictions based on climatology and persistence.

One way of reducing the influence of uncertainty in the initial conditions is to use ensemble predictions. In this case, a series of simulations are done using different (but similar) starting times (Figure 4). By considering all the predictions from these initial states, one can obtain a statistically better estimate of the predicted values and extend the range of prediction. Ensemble prediction techniques also allow for better estimation of probabilities of events, such as heavy rain and a statement of confidence in the prediction. For limited forecast periods, these ensemble predictions will still be deterministic, in the sense that the prediction is of a sequence of events. For longer periods, they can be of a statistical nature that gives forecasts of probabilities, vulnerability and/or risk during a period, usually with no information on the sequence of events. Ensemble predictions were initially used to make seasonal or longer predictions, well beyond the deterministic limit of predictions from initial values. El Niño is a climate variation with significant impacts (Glantz, 2001) and ensemble approaches have been applied to its prediction. The Meteorological Service of Canada does a 12 run ensemble for its seasonal predictions (3 month periods). Two different models, with different characteristics are used and each is run from 6 different initial states. The products are predictions of whether the seasonal temperatures and precipitation will be above, near or below normal. In some cases, there is such a large divergence, in a region, of the results from the different simulations that the decision is made that there is insufficient confidence in the prediction to make a useful forecast and hence no forecast is issued. Now multi-forecast ensembles are being used for predictions of weather for periods up to 15 days, as well.

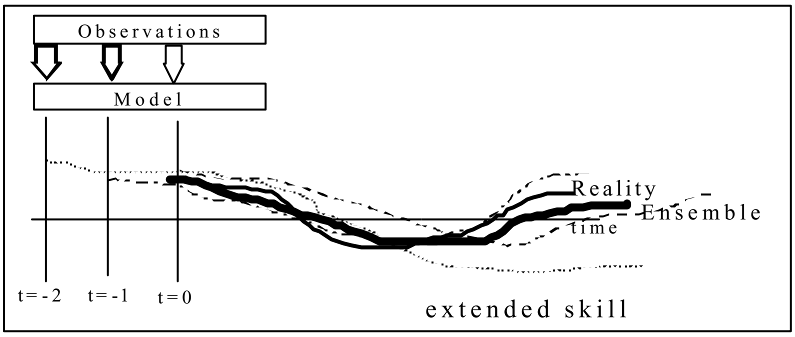

Figure 4. Ensemble predictions. In this case, three simulations are made from 3 different initial states. The resulting "best" prediction is the average of the three predictions. Research has shown that this approach does lead to extended skill, beyond the normal deterministic limit and can be used to improve the skill for shorter periods within the deterministic limit.

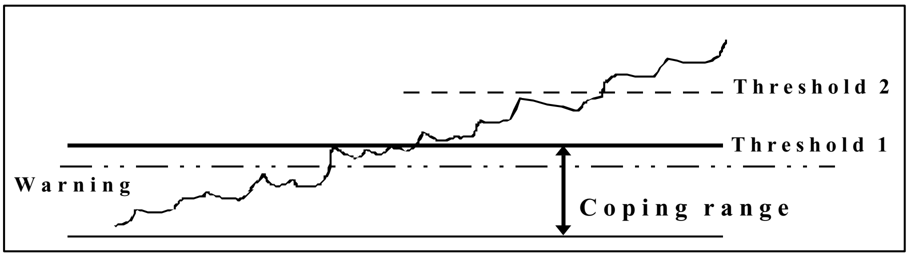

Figure 5. Schematic presentation of the concepts of a warning level compared to the threshold for a disastrous impact. The coping range includes those variations which the system can accept without significant impact. A strategy for disaster management would be to raise the threshold from 1 to 2.

For disaster management, the most important prediction is often when a certain condition will be reached that justifies a warning (Figure 5). The warning level is usually lower than the threshold for disaster (beyond the coping limit) because allowance needs to be made for response times and practices and for uncertainty in the prediction. When designing prediction systems, particular attention needs to be given to the warning and threshold levels since small errors there are more important than similar magnitude errors well away from these levels. One objective of disaster management should be to increase the coping range by making the threshold for disaster higher, i.e., the system less vulnerable.

Climate change and water management

Another use of predictions is more appropriately called scenarios for decision making, where predictions or simulations are done with and without changes in, for example, human influence. Climate change is an issue that is based on prediction, predictions that as the atmospheric concentrations of greenhouse gases continue to rise, the climate will change in significant ways. From a prediction point of view, climate change is an example of the "What if? Then" predictions. Based on scenarios of future greenhouse gas emissions, one conducts modeling studies that examine: what if the emissions are …, then the climate will change … For water managers, climate change is a huge issue. In his speech to the opening of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change, Dr. R. Watson (Chair of the Intergovernmental Panel on Climate Change) said:

"One of the major challenges facing humankind is to provide an equitable standard of living for this and future generations: adequate food, water and energy, safe shelter and a healthy environment (e.g., clean air and water). The overwhelming majority of scientific experts, whilst recognizing that scientific uncertainties exist, nonetheless believe that human-induced climate change is inevitable. Indeed, during the last few years, many parts of the world have suffered major heat waves, floods, droughts, fires and extreme weather events leading to significant economic losses and loss of life. While individual events cannot be directly linked to human-induced climate change, the frequency and magnitude of these types of events are predicted to increase in warmer world."

Climate change over the next century and beyond will certainly change the hydrological cycle and through those impacts may have its biggest impact on people and ecosystems. Climate models have been used to project the probable changes in precipitation, evaporation, soil moisture and river runoff. Specifically with respect to the hydrological cycle, the IPCC in its Third Assessment Report (IPCC, 2001) concluded that increased summer continental drying and associated risk of drought was likely, over most mid-latitude continental interiors, but there was a lack of consistent projections in other areas. Further they concluded that more intense precipitation events were very likely over many areas. Trends in extreme weather events and model projections have been considered in two papers by Meehl et al (2000a,b). Traditionally, the analysis of extreme events has been done in terms of the likelihood over a given period of time, the concept of a return period. Within a changing climate, the time series is non-stationary so that computation of statistical values, that pertain to stationary series, is difficult. An advantage of climate model simulations is that the modeler can hold time constant, i.e., fix the atmospheric concentration at some level (which corresponds to stopping the clock in the sense of climate change driven by increasing greenhouse gas concentrations) and run a multi-year simulation to derive appropriate statistics.

An example of the changing statistics of extreme precipitation events is is given in Figure 6 (from Zwiers, based on Zwiers and Kharin, 1998, and Kharin and Zwiers, 2000). Averaged over Canada, the event recurrence for a 80 mm of precipitation event, which is now about 80 years, will reduce to about 50 years when the greenhouse gas concentrations are about double pre-industrial values and about 25 years by the end of the century. The figure also shows the reduction from 40 years to 25 to 15 years for a less intense event (70mm). These kinds of predictions will allow water managers to factor climate change into their planning for the future.

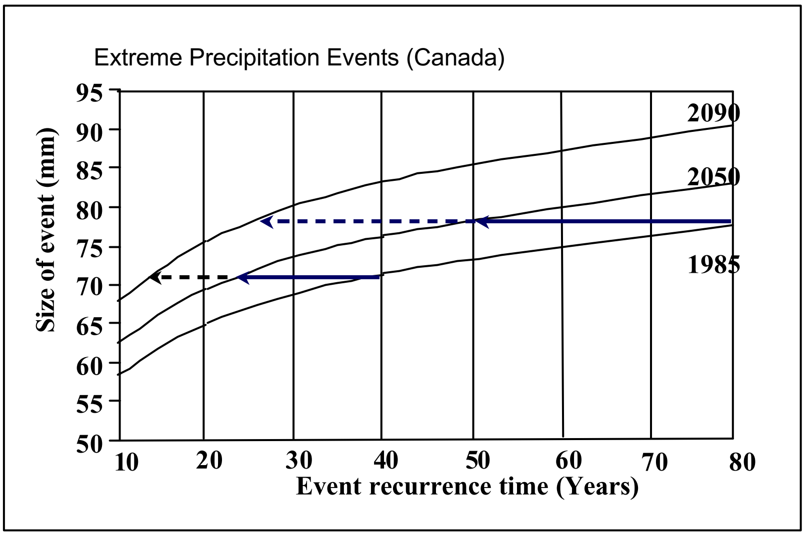

Figure 6. Example of the change in event recurrence time due to climate change, assuming that the greenhouse gas concentrations increase to about twice pre-industrial values about 2050 and to triple by 2090. This is the average for precipitation events for all of Canada. (from Zwiers, based on Zwiers and Kharin, 1998, and Kharin and Zwiers, 2000).

Climate change provides a challenge for the use of prediction in water and disaster management practices. As yet the spatial scale of predictions is often to coarse for detailed analysis of water systems but this should not be an excuse for not using the availability capabilities. Strategies for water management should be tested through scenarios of climate predictions to see how they are changed (Figure 7). For example, will there be enough water in a river system in the future, for irrigation or for hydroelectric power. How will climate change affect the frequency of high water levels that will determine the characteristics of dikes? With sea level rise, will the outflow from rivers be changed so as to alter strategies for flood control in coastal cities?

Conclusions

Prediction needs to be seen as a part of, in fact the basis of, both structural and non-structural measures of water management. Prediction for water management purposes should be done within the context of broader physical environmental prediction (Figure 8) where the predictions of flash floods, watershed levels and drought, for example, are part of an overall prediction strategy. Prediction will be used for the warn and inform aspects on short time scale periods and for mitigation/adaptation on longer time scales. Since predictions will always have some uncertainties, it is appropriate that they be factored in as part of a risk management approach.

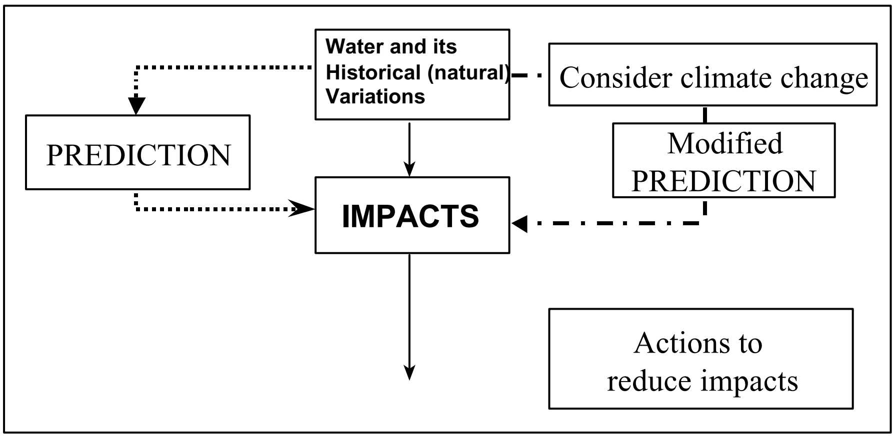

Figure 7. Schematic of using prediction to factor in the changing climate on the impacts of water hazards. Actions to reduce impacts can be tested through model simulations in the climate change context.

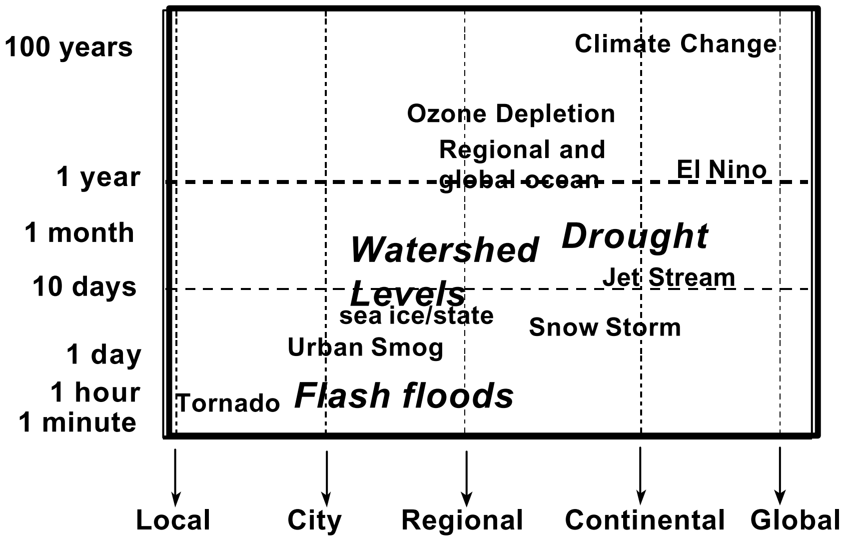

Figure 8. Predictions of water hazards (floods, drought) should be seen in the context of an integrated environmental prediction system, where forecasts on all scales and for time periods of from minutes to centuries are included. Disaster management strategies need to work across this spectrum of time and space.

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On Modelling of Extreme Hydrologic Processes

By

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Abstract: This paper reviews some recent progress in modelling of extreme hydrologic processes. Certain aspects of traditional methods based on annual maximum and partial duration series for analysing extreme hydrologic events are reviewed from both theoretical and practical viewpoints. In particular, methods based on the recently developed "scale-invariance" (or "scaling") theory for estimating extreme rainfalls and floods at ungaged and partially gaged sites are presented. The scaling concept implies that statistical properties of the extreme hydrologic processes for different spatial or temporal scales are related to each other by a scale-changing operator involving only the scale ratio. The suggested scaling approach has been applied to flood data from 109 watersheds in Ontario (Canada), and to extreme rainfall data from 14 raingages located in Quebec (Canada). The Generalized Extreme Value (GEV) distribution was used to estimate the quantiles of the hydrologic variables considered. Results of these illustrative applications have indicated that the proposed scaling method could provide more accurate estimates of extreme rainfalls and floods for partially gaged or ungaged sites than those given by traditional regionalization methods.

Keywords: Extreme rainfalls, floods, scaling method, annual maximum series, partial duration series, hydrologic frequency analyses, statistical modelling,

Introduction

For planning and design of various hydraulic structures, extreme hydrologic variable (e.g., maximum rainfall or maximum discharge) for a given return period is required. For a site for which sufficient data are available, a frequency analysis can be performed. A great deal of effort during the past two decades has been directed toward the search for the best statistical approach that could provide the best estimation of the extreme hydrologic variable considered (see, e.g., NERC, 1975; NRCC, 1989; WMO, 1989). However, in most cases, either extreme hydrologic record at the location of interest is unavailable (an ungauged site) or the data sample at the site is limited (a partially gaged site). Hence, "regionalization" methods (e.g., Dalrymple, 1960; Schaefer, 1990) are frequently used to transfer the hydrologic information from one location to the other where the data are needed but not available, or to improve the accuracy of the estimates where available records are too short. Nevertheless, traditional regionalization techniques are often criticized for the obvious subjectivity, in particular in the definition of hydrologically similar sites or regions, and the lack of theoretical justifications. Further, the accuracy of these techniques is often limited because they cannot take into account some observed "scale-independent" properties of the hydrologic series considered.

In this paper, a review on some recent progress in modelling of extreme hydrologic processes is presented. In particular, this review concerns mainly with the statistical estimation of extreme rainfalls and maximum flood discharges, the two most important hydrologic variables for engineering design applications. Certain aspects of traditional methods for analyzing extreme hydrologic events based on annual maximum series (AMS) and partial duration series (PDS) are discussed from both theoretical and practical viewpoints. Further, the present paper focuses on new methods for estimating extreme hydrologic variables at ungaged or partially gaged sites using the "scale-invariance" (or "scaling") concept, which is currently a popular tool in the modelling and analysis of various geophysical processes (see, e.g., Gupta and Waymire, 1990; Tessier et al., 1996).

In this study, the scale invariance implies that statistical properties of extreme hydrologic variables for different spatial and temporal scales are related to each other by a scale-changing operator involving only the scale ratio. Physiographic and hydrologic data from 109 watersheds in Ontario (Canada), and extreme rainfall data from a network of 14 raingages in Quebec (Canada) were used to illustrate the application of the proposed method. The Generalised Extreme-Value (GEV) distribution (Hosking et al., 1985) was used to estimate the flood and extreme rainfall quantiles at different locations. Results of this numerical application have indicated that the proposed scaling approach could provide more accurate flood and extreme rainfall estimates for ungaged sites than to those given by existing procedures.

The Annual Maximum Series Method

For a site for which sufficient extreme hydrologic data are available, a frequency analysis can be performed. Traditional hydrologic frequency analyses are based on annual maximum series (AMS) or partial duration series (PDS) methods. The AMS contain the largest event in each complete year of record, while the PDS consist of all large events above a certain threshold. Arguments in favor of either of these techniques are well described in the literature (see, e.g., NRCC, 1989; Stedinger et al., 1993). Due to its simpler structure, the AMS-based method is more popular in practice. However, the choice of an appropriate technique should depend on the purpose of the analysis and characteristics of available data (in terms of both quantity and quality). Briefly, the following general steps are followed to determine the frequency distribution of annual maximum series for a given site:

(1) Obtain a data sample, and perform an assessment of data quality based on hydrologic and statistical procedures.
(2) Select a candidate distribution model for the data, and estimate the model parameters.
(3) Evaluate the adequacy of the assumed model in terms of its ability to represent the parent distribution from which the data were drawn.

The assessment of data quality represents an important step in all statistical computations. For frequency analysis studies, it is necessary to check data for outliers and consistency. An outlier is an observation that departs significantly from the general trend of the remaining data. In the context of regional analysis of extreme hydrologic events, the outliers could provide critical information for describing the upper tail of the distribution. Hence, high outliers are considered as historical data if sufficient information is available to indicate that these outlying observations are not due to measurement errors. Procedures for treating outliers require however hydrologic and mathematical judgment (Stedinger et al., 1993; Ashkar et al., 1994). Regarding data inconsistency, there are many causes. Changes in gauging instruments or station environment may cause inhomogeneity in hydrologic time series. The basic assumption in hydrologic frequency analysis is that the data are independent and identically distributed. Hydrologic measurements could be subject to various sources of error, inconsistency, and non-homogeneity.

Detailed examination and verification of the raw data are needed to identify invalid data in the record due to instrument malfunction and/or human error. Standard statistical tests are available to verify serial independence, stationarity, and homogeneity of the data series (see, e.g., NRCC, 1989).

There is no general agreement as to which distribution, or distributions, should be used for hydrologic frequency analysis of extreme rainfalls or floods. Common distributions which have been applied to the analysis of these AMS include the Normal and Log-Normal, Pearson and Log-Pearson Type 3, Gumbel, Generalized Extreme Value (GEV), Generalized Gamma, Wakeby, and Two-Component Extreme Value distributions (see, e.g., NERC, 1975; NRCC, 1989; Stedinger et al., 1993). A practical method for selecting an appropriate distribution is relied upon examination of the data using probability plots. Probability plots, which require the use of a plotting-position formula, are an effective tool to display graphically the empirical frequency distribution of the data and to assess whether the fitted distribution appear consistent with the data. There are several plotting-position formulas available in practice (Nguyen et al., 1989), among which the Hazen, Weibull, and Cunnane formulas are the most popular. The differences between these three formulas are small for observations that are neither the largest nor the smallest, but they can be appreciable for the largest three or four values in the data series (Stedinger et al., 1993). An alternative method for making a good choice among different distributions is based on the L-moment diagram (Stedinger et al., 1993). However, it has been suggested by some investigators (Cunnane, 1987; Ashkar et al., 1994) that the choice of an appropriate distribution for fitting the AMS should be based on other considerations involving: (a) the selection of an adequate number of distribution parameters; (b) the specification of some desirable properties that the selected distribution should possess; and (b) the choice of criteria for assessing the descriptive and predictive abilities of the distributions considered.

While a number of distributions have been suggested, the choice of the distribution seems not to be as crucial as an adequate data sample. Hershfield (1962) for instance showed that some widely used distributions give generally similar estimates over the range of exceedance probabilities up to 1% (100-year return period) for annual maximum rainfall series. When the return periods associated with frequency-based estimates greatly exceed the length of record available, discrepancies between commonly used distributions tend to increase. In addition, some previous studies (Wilks, 1993; Ashkar et al., 1994) have found that a three-parameter distribution can provide sufficient flexibility to represent extreme hydrologic data. However, a two-parameter distribution could be preferable for prediction in order to reduce the sampling variance (Ashkar et al., 1994).

Many methods for estimating distribution parameters are available in the hydrologic and statistical literature. The simplest method is the method of moments, which provides parameter estimates such that the theoretical moments are equal to the computed sample moments. For a three-parameter distribution, the sample moments used in the computation are commonly the mean, variance, and skewness. However, to avoid the large variability of the sample skewness estimate, some studies have suggested to replace this third-order moment by the first and/or second order moments in log space (Rao, 1980; Phien and Hira, 1983) or the geometric and/or harmonic mean in real space (Ashkar et al., 1988). An alternative method for estimating parameters is based on the sample L-moments (Hosking, 1990). Sample L-moments are found less biased than traditional moment estimators, and thus are better suited for use with small sample sizes (Stedinger et al., 1993). Another method is the method of maximum likelihood. Maximum likelihood method provides estimators with very good statistical properties in large samples, but these estimators are often not available in closed form and thus must be computed using an iterative numerical method. It is important to stress that the choice of an appropriate parameter estimation method is related to the type of distribution under consideration.

The reliability of hydrologic frequency estimates depends on how well the fitted model represents the parent distribution. Several goodness-of-fit criteria can be used to test whether a selected distribution is consistent with a particular data sample (NRCC, 1989; Stedinger et al., 1993; ASCE, 1996). As mentioned above, probability plots are extremely useful in the assessment of the adequacy of fitted distributions. The assessment is performed by plotting observed data versus plotting-position estimates of exceedance probability on a specialized plotting paper. The estimated distribution is plotted on the same graph. Goodness-of-fit is judged by inspection. More rigorous statistical tests such as the Kolmogorov-Smirnov, probability plot correlation, and L-moment tests are available allowing quantitative judgement of goodness of fit (Stedinger et al., 1993). However, these statistical tests are not sufficiently powerful for making a suitable choice between distribution candidates when small samples are considered. In addition, the selection of the distribution that best fit each data set is not a recommended approach for frequency analysis (Stedinger et al., 1993; ASCE, 1996). The use of the best-fitting distribution for each data sample provides frequency estimates that are too sensitive to the sampling variations in the data, and the period of record available. Current distribution selection procedures adopted by many countries are based on a combination of regionalization of some parameters and split-sample Monte-Carlo evaluations of different estimation methods to find distribution-estimation procedure combinations that give reliable quantile and risk estimates (NERC, 1975; Stedinger et al., 1993; ASCE, 1996).

For sites where hydrologic records are limited or unavailable, regional frequency analysis, which uses data from many sites, has been shown to be able to reduce the uncertainties in quantile estimation of extreme events. Several regional estimation methods have been suggested (see, e.g., Cunnane, 1988), among which the index-flood procedure introduced by Dalrymple (1960) for use with AMS is the most popular. The index-flood method has been applied to flood frequency analyses (Hosking and Wallis, 1988; Potter and Lettenmaier; 1990; Stedinger and Lu, 1995) as well as to regional estimation of extreme precipitations (Schaefer, 1990). However, one of the main difficulties in the application of this technique is related to the definition of "homogeneous" regions, which assume that data at different sites in a homogeneous group follow the same distribution except for scale. Various methods have been proposed for determining homogeneous regions, but there is no generally accepted procedure in engineering practice (Wiltshire, 1985; Acreman and Sinclair, 1986; Burn, 1990; Cavadias, 1990; Pearson, 1991; Hosking and Wallis, 1993).

The Partial Duration Series Method

As mentioned above, an alternative approach to the AMS method in the modelling of hydrologic extreme processes is based on the use of PDS models. The PDS method can provide a more complete description of flood generating processes because it can include all extreme events above a certain threshold in the analysis, while the AMS procedure considers only the largest event in each year. Classical PDS models are based on the assumptions that the number of threshold exceedances follow a Poisson distribution and the exceedance magnitudes are independent, identically and exponentially distributed (Shane and Lynn, 1964; Todorovic and Zelenhasic, 1970). From the practical viewpoint, the Poisson assumption for the distribution of the number of exceedances is not as crucial as the assumption for the distribution of exceedance magnitudes since expressions for hydrologic quantile estimators involve the expected annual number of exceedance rather than their distribution (Rasmussen et al., 1994). More complex distributions which have been suggested for exceedance distribution include the gamma distribution (Zelenhasic, 1970), the Weibull distribution (Ekanayake and Cruise, 1993), the lognormal distribution (Rosbjerg et al., 1991), and the generalized Pareto (GP) distribution (Van Monfort and Witter, 1986; Fitzgerald, 1989; Wang, 1991, and Madsen et al., 1997). It has been found that complex distributions may be necessary for descriptive purposes, but for the prediction of extreme events, the simple one-parameter exponential is quite appropriate (Rosbjerg et al., 1991, 1992).

The choice of an appropriate threshold level represents one of the most difficult issues in the use of PDS models in practice. This difficulty has thus limited the popularity of the PDS method as compared to the AMS procedure. The threshold should be selected to ensure that relevant information on extreme hydrologic events is included in the analysis without violating basic statistical assumptions required in the PDS model. The problem of threshold selection has been discussed in a number of studies (US Water Resources Research Council, 1982; Cunnane, 1979; Rosbjerg and Madsen, 1992; Rasmussen et al., 1994; Madsen et al., 1994). However, no general accepted procedure is available. Therefore, more research on this issue is needed to develop guidelines for an optimal choice of threshold in consideration of both physical and statistical characteristics of extreme hydrologic processes.

In the context of regional frequency analysis, as mentioned above, several regional estimation methods have been proposed for AMS, but few studies have dealt with the regional estimation based on the PDS model (Rasmussen and Rosbjerg, 1991; Fitzgerald, 1989; Madsen and Rosbjerg, 1997). In particular, it has been found that the regional index-flood method based on the PDS model (with GP distribution for modelling threshold exceedances) is more efficient than the procedure based on the AMS/GEV model in terms of identification of homogeneous regions and on the basis of extreme event estimation accuracy (Madsen et al., 1997).

The Scale-Invariance Method

Recent works (Gupta and Waymire, 1990; Gupta et al., 1994; Tessier et al., 1996; Burlando and Rosso, 1996) have suggested some new concepts to frequency analyses based upon the scaling behaviour of hydrologic series. In particular, the popular index flood method for regional estimation of floods (see, e.g., Hosking et al. 1985) has been shown to imply the assumption that the regional flood series possess a simple scaling behaviour (Smith, 1992). These studies have therefore indicated the need to develop alternative methods for estimation of extreme hydrologic events which could preserve the scaling property of hydrologic processes and at the same time could provide accurate estimates of these events.

By definition (see, e.g., Fedder, 1988), a function $f(x)$ is scaling (or scale-invariant) if $f(x)$ is proportional to the scaled function $f(\lambda x)$ for all positive values of the scale factor λ. That is, if $f(x)$ is scaling then there exists a function $C(\lambda)$ such that

$$f(x) = C(\lambda)\, f(\lambda x) \qquad [1]$$

It can be readily shown that

$$C(\lambda) = \lambda^{-\beta} \qquad [2]$$

in which β is a constant, and that

Hence, the relationship between the non-central moment of order k (μ_k) and the variable x can be written in a general form as follows:

$$\mu_k = E\{f^k(x)\} = \alpha(k)\ x^{\beta(k)} \qquad [4]$$

in which $\alpha(k) = E\{f^k(1)\}$ and $\beta(k) = \beta\, k$. Notice that if the exponent $\beta(k)$ is not a linear function of k, in such cases the process is said to be "multiscaling" (Gupta and Waymire, 1990).

The Generalized Extreme Value Distribution

Application of the Generalized Extreme-Value (GEV) distribution to model the annual series of floods and extreme rainfalls has been advocated by several researchers (see, e.g., Hosking et al., 1985; Schaefer, 1990). The cumulative distribution function, $F(x)$, for the GEV distribution is given as

$$F(x) = \exp\left[-\left(1-\frac{\kappa(x-\xi)}{\alpha}\right)^{1/\kappa}\right] \qquad \kappa \neq 0 \qquad [5]$$

$$f(x) = x^{\beta}\ f(1) \qquad [3]$$

where ξ, α, and κ are respectively the location, scale and shape parameters. It can be readily shown that the k-th order non-central moments (NCM), μ_k, of the GEV distribution (for k? 0) can be expressed as (Pandey, 1995)

$$\mu_k = \left(\xi+\frac{\alpha}{\kappa}\right)^k + (-1)^k\left(\frac{\alpha}{\kappa}\right)^k \Gamma(1+k\kappa) + k\sum_{i=1}^{k-1}(-1)^i\left(\frac{\alpha}{\kappa}\right)^i\left(\xi+\frac{\alpha}{\kappa}\right)^{k-i}\Gamma(1+i\kappa) \qquad [6]$$

where ? (.) is the gamma function. Hence, on the basis of [6], it is possible to estimate the three parameters of the GEV distribution using the first three NCMs. Consequently, the quantiles (X_T) can be computed using the following relation:

$$X_T = \xi + \frac{\alpha}{\kappa}\left\{1-[-\ln(p)]^{\kappa}\right\} \qquad [7]$$

in which $p = 1/T$ is the probability of interest.

Numerical Application

In the following, to illustrate the application of the proposed scaling approach, two case studies were carried out. First, the suggested method will be used to estimate floods at sites where flow records are unavailable (ungaged sites). Second, the proposed procedure will be used to estimate rainfall extremes for short time intervals (e.g., 1 hour) at locations where rainfall data for longer time scales (e.g., 1 day) are available (partially gaged sites).

Regional Estimation of Floods at Ungaged Sites

In this application, annual peak flow series from 109 watersheds in Ontario are considered. The length of the flood series varies from 20 to 76 years and the size of the basin area ranges from 0.8 km^2 to 86,929 km^2. Since the majority of the floods in the region occur during the spring season (i.e., from May to September), only spring floods were considered in this study. The NCMs of order from one to six of the flood series were computed for each station in the region. Using [4], the regression estimates ($a(k)$ and $b(k)$) of the coefficients $\alpha(k)$ and $\beta(k)$ for the sample non-central moments (m_k for $k = 1,2,..., 6$) are given in Table 1. It can be seen that the exponent $\beta(k)$ is a linear function of the exponent $\beta(1)$ (i.e., $\beta(k) = k\beta(1)$). The linearity of the exponent $\beta(k)$ supports the assumption that the spring flood series in Ontario can be described by a simple scaling model (Gupta and Waymire, 1990).

In the present study, a homogeneous region is defined as a region in which all annual flood peak series must have similar scaling properties. More specifically, the power-law relation between the NCMs and the basin area (Eq.[4]) for various watersheds within a homogeneous region can be represented by a straight line on a log-log plot, giving a unique set of parameters $a(k)$ and $b(k)$.

For example, Figure 1 shows the log-log plot of the at-site sample mean (m_1) versus the basin area for 109 watersheds in Ontario. It can be seen that three groups of homogeneous basins can be identified based on the similar scaling behaviour of the statistical properties of the flood series.

The validity of any method of delineating homogeneous regions should be supported by some physical evidences, such as the proximity of geographical locations and similar climatic features. To this end, the geographical location of the stations for each homogeneous sub-groups are shown in Figure 2. It can be seen that, irrespective of the basin size, the newly delineated homogeneous groups are well defined within each geographical regions which have distinct climatic features. Notice that there are some basins which are on the boundary between two groups. Such basins may be considered as being members of either group. Further, since the basin area is the most significant variable in the estimation of floods (see, e.g., Thomas and Benson, 1970), the delineation of homogeneous groups based on the scaling of flood statistical moments with the basin area can be considered as acceptable.

In the present study, the Jacknife procedure is used to simulate the ungaged condition. That is, one basin was removed from the database and the model was developed using the data from the remaining stations. The model was in turn used to make prediction of the quantiles for the site which was not used in the model development. The process was repeated until every station was removed once. Further, for comparison purposes, estimation of the flood quantiles was made using the GEV/Index Flood Method (GEV/PWM) (Hosking et al., 1995). This method was selected because of its popularity and its superior performance in the regional estimation of floods (Hosking et al., 1985; Potter and Lettenmaier, 1990).

In the estimation of flood quantiles using the proposed scaling approach (GEV/NCM), only data belonging to a specific homogeneous group delineated earlier was used in the model development. For each homogeneous group, using [4], the first three non-central moments (m_k

for k=1,2, and 3) were estimated for an ungaged site (i.e., the site which was not included in the estimation of the parameters $a(k)$ and $b(k)$ of [4]). Those predicted moments were in turn equated with the first three non-central moments of the GEV distribution (Eq. [6] with k=1, 2, and 3) in order to determine the parameters ξ, α, and κ of the GEV distribution. Hence, the flood quantiles for the ungaged location can be estimated using [7]. For purposes of illustration, Figure 3 shows the Quantile-Quantile plot between the at-site (fitted) and regional (predicted) 100-year flood estimates based on the GEV/PWM and GEV/NCM methods. Notice that the results are presented in both real and log flow domains in order to assess the accuracy of the estimation of floods for small as well as for large basins. It can be seen that the quantile estimates obtained from the proposed GEV/NCM method are generally more accurate than those given by the standard GEV/PWM method for small and large floods.

Regional Estimation of Extreme Rainfalls at Partially Gaged Sites

In this illustrative example (see also Nguyen et al., 1998), the proposed scaling approach is applied to annual maximum rainfall (AM) series from a network of 14 raingages in Quebec (Canada). The rainfall record lengths vary from 15 to 48 years. To assess the scaling behaviour of these AM series, the log-log plots of rainfall NCMs against duration were prepared for all 14 stations. For purpose of illustration, Figure 4 show the plot for Dorval station. It can be seen that the rainfall statistical moments follow two different scaling regimes. The first one ranges from 5 minutes to 1 hour, and the second from 1 hour to 4 days. Hence, for a given location, it is possible to determine the distribution of rainfall extremes for short durations (e.g., 1 hour) using available rainfall data for longer time scales within the same scaling regime (e.g., 1 day). For illustrative purpose, Figure 5 shows the comparison between empirical (observed) and estimated distributions of 1-hour rainfall extremes at Dorval station for the case where hourly rainfall data are available (at-site curve), and for the case where hourly rainfall data are missing (regional curve). It can be seen that the regional estimate of hourly rainfall extreme distribution for partially gaged sites is comparable with the at-site estimate. Further, the good agreement between the estimated (both at-site and regional) and empirical distributions for 1-hour rainfall extremes as shown in this case study has indicated the feasibility of the proposed scaling method.

Table 1 Sample estimates of the parameters in the model representing the relation between noncentral moments of floods and basin area.

Ontario		
Order of the NCM	*a (k)*	*b (k)*
1	0.633	0.715
2	0.505	1.421
3	0.487	2.121
4	0.544	2.816
5	0.669	3.510
6	0.877	4.203

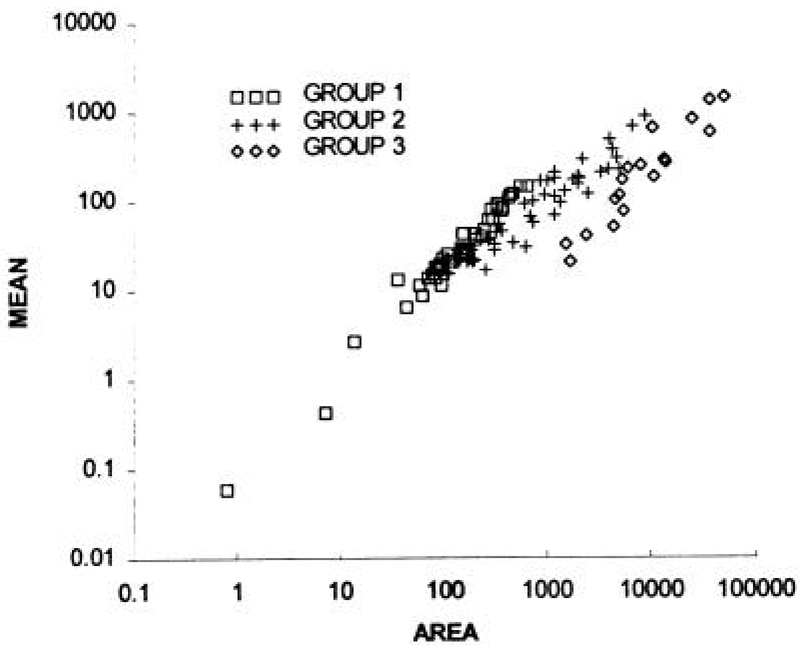
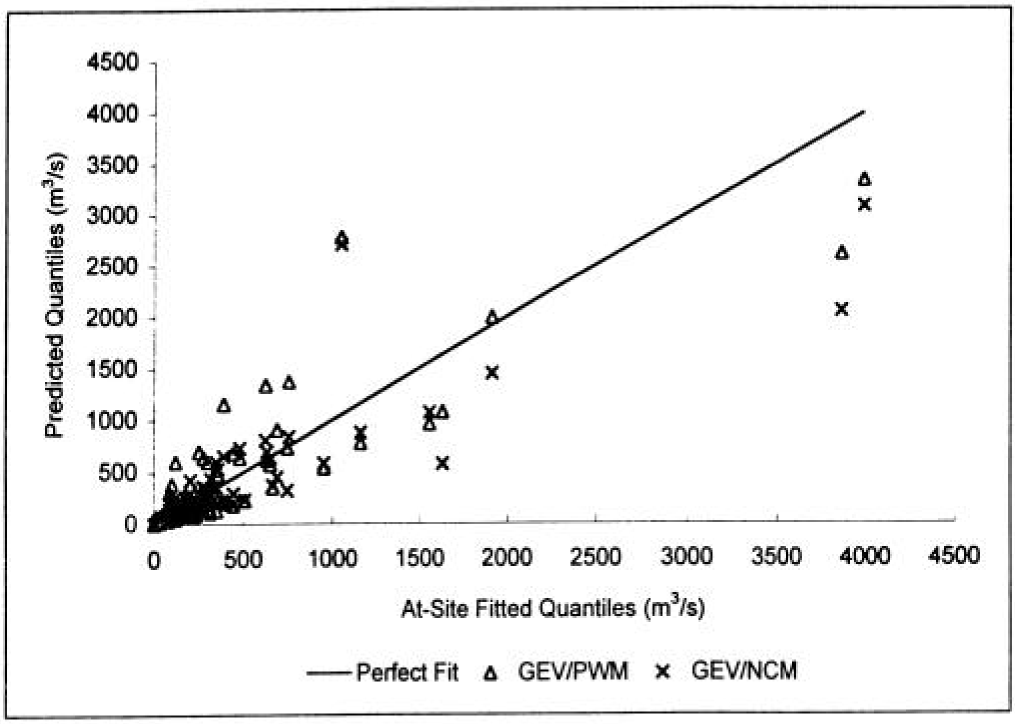
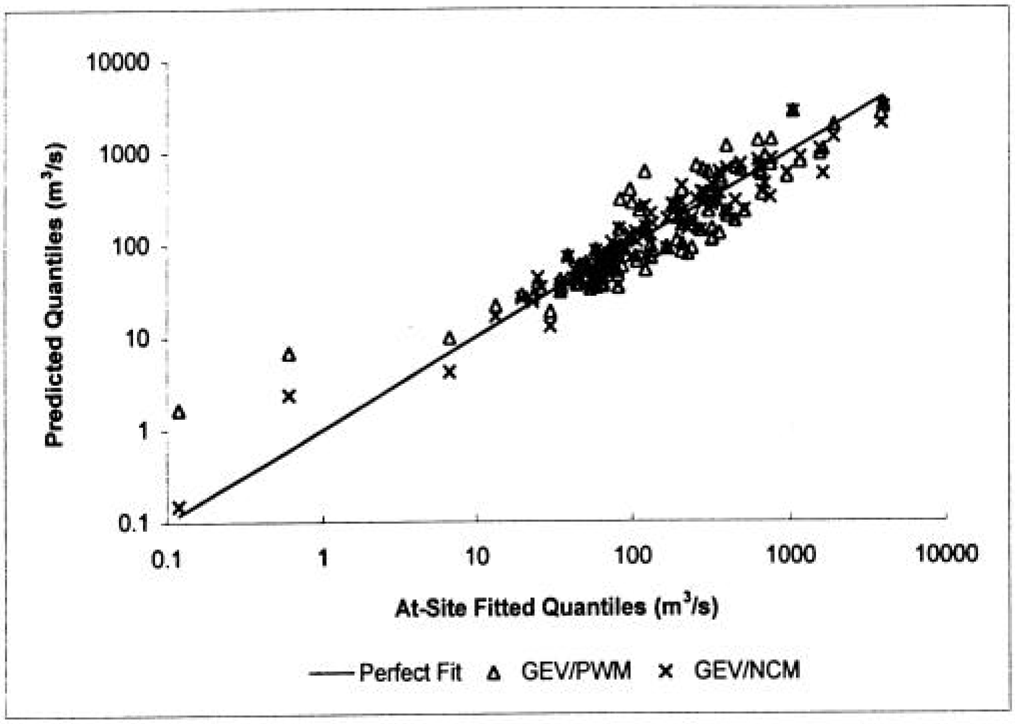


Figure 1. Area versus at-site mean for different homogeneous regions in Ontario



(a) Real space



(b) Log space

Figure 3. Quantile-quantile plots between at-site fitted and regional estimated flows using the Jacknife procedure (Ontario)

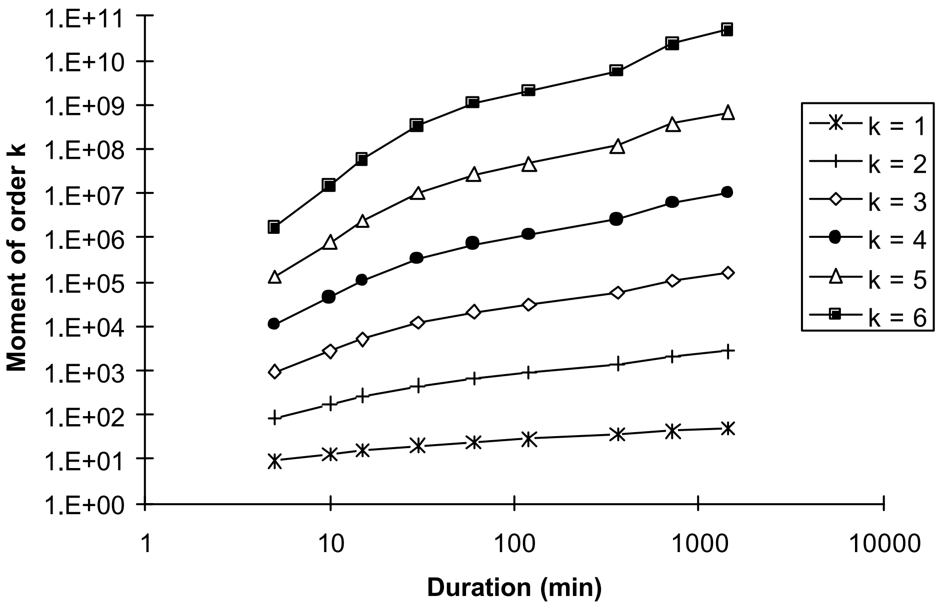


Figure 4. The log-log plot of maximum non-central moments versus rainfall duration for Dorval station.

Conclusions

Materials covered in this review demonstrated the importance of modelling of extreme hydrologic processes in engineering applications. Significant advancements have been made to improve the accuracy of traditional AMS and PDS methods in the estimation of extreme rainfalls and floods. Novel approaches based on the scale-invariance concept have also been proposed for the description and estimation of these processes. In particular, by considering the scaling of statistical properties of extreme hydrologic processes, new methods have been proposed for the estimation of extreme rainfalls and floods at partially gaged or ungaged sites. Results of an illustrative application have indicated that the proposed approach could provide more accurate estimates than those given by traditional regional estimation methods. Further, an important step in regional flood frequency analyses is the definition of hydrologically similar basins. To this end, instead of using an arbitrary criterion as in most previous investigations, it has been shown that similarity of basins can be defined based on the scaling behaviour of the statistical properties of the flood series. Further, it was observed that the grouping of similar basins into homogeneous groups as suggested in this study could form well-defined geographic regions with distinct climatic characteristics.

Nevertheless, most of the proposed methods have been heavily relied on statistical properties rather than on physical characteristics of the hydrologic phenomenon under consideration. Therefore, although progress has been made, practical problems and uncertainties associated with the estimation of extreme hydrologic events are still far from being solved. Indeed, much work remains to be done in this research area.

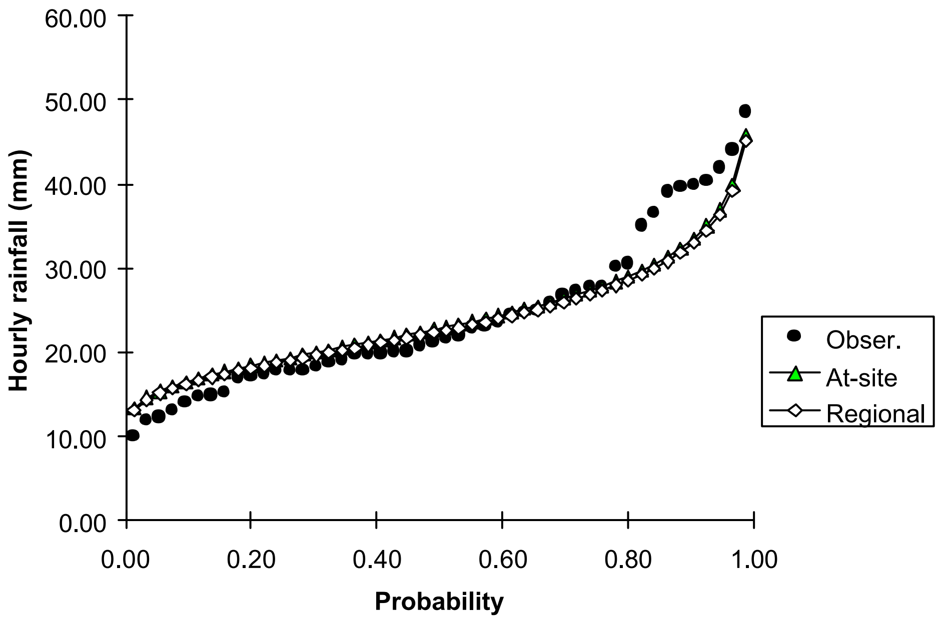


Figure 5. Empirical (observed) and estimated distributions of maximum hourly rainfalls using at-site and regional data.

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Estimation of Risk and Characteristics of Extreme Floods using Physically Based Models of Runoff Generation and Stochastic Meteorological Inputs

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ABSTRACT: Two main schools of estimation of extreme flood characteristics exist now in the world hydrological practice. The first approach is based on frequency analysis of observed peak runoff discharges, fitting a chosen statistical distribution of these values and extrapolating this distribution for determination of the high floods of small exceedance probabilities. The application of this approach can give reliable estimations of the magnitudes of maximum discharges only for the exceedance probabilities less 0.5-1.0%. The second approach based on the assumption that there are some physical limits of the values of precipitation for each region and each season and using these probable maximum precipitation for determination of probable maximum floods (PMF) with aid the unit hydrograph method or simple conceptual models of runoff generation. The techniques of estimating such precipitation values have insufficient scientific foundation and usually lead to significant overestimation of the possible maximum flood. Both mentioned approaches do not practically utilize available series of meteorological observations contained important information on possible variations of runoff generation factors. Another common shortcoming of these approaches is implicit use of assumptions that the physical mechanisms of runoff generation do not depend on the magnitudes of water inputs and basin characteristics are unchangeable. Achievements in development of physically based models of runoff generation and in stochastic analysis of meteorological time series as well as an immense increase of the computer speed allow us to implement for estimating the extreme flood characteristics a new technology in which the shortcomings of both above- mentioned approaches can, to significant degree, be overcome. This technology is based on coupling the monte carlo simulation of meteorological inputs with application of the detailed physically based models of runoff generation processes. The paper illustrates the implementation of these technology for estimation of risk and extreme flood characteristics for the Seim river basin (the catchment area is 7460 km^2).the model of runoff generation is based on the finite-element schematization of river basin and includes the description of the following hydrological processes: snow cover formation and snowmelt, freezing and thawing of soil, vertical soil moisture transfer and infiltration, overland and channel flow. The monte-carlo simulation is based on stochastic models of daily precipitation series, daily air temperature and daily air humidity deficit (for continuous modeling during autumn-winter-spring seasons) or distributions of snow water equivalent, depth of frozen soil, and soil moisture content before snowmelt (for modeling during only spring period). The 20-years hydrometeorological measurement series have been used for calibration and verification of the dynamic part of the model (5 parameters have been calibrated); the 34-years series have been used for construction of the stochastic part. The calculated exceedance probabilities of the peak discharge were compared with ones calculated using 61-years runoff data. The good correspondence of the measured and calculated values have been obtained.

Key words: Snowmelt flood, physically based modelling; stochastic modelling

Introduction

Estimation of extreme flood characteristics is a classic hydrological task associated with flood risk assessments, design of flow control constructions, and dam safety evaluation. Increasing of demands for criteria of the acceptable potential economic and environmental risk in water resources management has necessitated improving reliability of the existing methods of estimation of extreme flood characteristics and developing such methods for flood events of very low probabilities. At the same time, the solution of this task has been made more complicated because of intensification of human activity on the river watersheds and climate change.

In present-day hydrologic practice, there are two main types of approaches for estimation of extreme flood characteristics. The first approach is based on frequency analysis of measured flood peak discharges, fitting a chosen statistical distribution of these values and extrapolating this distribution for determination of the peak discharges of low exceedance probabilities. The methods using the first approach are well-developed and widely tested, however, as has been shown in many papers (for example, Swain et al, 1996), this approach yields reliable estimates of flood peak discharges if the recurrence intervals of these discharges do not significantly exceed the lengths of measured peak discharge series. It is also worth noting that for solution of many hydrological and environmental problems it is important to know not only the probable maximum flood peak discharges but also the probable maximum flood hydrographs.

The second approach is based on an assumption that there are some maximum values of precipitation for each region and for each season and these values can be utilized for calculation of the hydrographs of the probable maximum floods (PMF) with the aid of the unit hydrograph method or conceptual runoff generation models. The techniques for estimating the probable maximum precipitation values have inadequate scientific foundation and usually give maximum floods that have never reached up. Bowles et al (1994) have found a significant difference between the PMF estimates based on the different assumptions on centring, orientation, storm area, and position of the peak interval of the probable maximum storm. At the same time, the absence in this approach the estimation of the probabilities of the possible maximum discharges creates the difficulties for decision makers who prefer to have probabilistic estimates of the possible flood characteristics together with assessment of available uncertainty.

Neither of the aforementioned two approaches fully utilizes the available meteorological observations those contain important information on possible variations of runoff generating factors. Another common shortcoming of these approaches is implicit use of assumptions that the physical mechanisms of runoff generation do not depend on the magnitudes of water inputs and drainage basin characteristics do not change in time in spite of possible human activities in the drainage basin and climate change. However, many hydrological processes are essentially nonlinear, and the physical mechanisms of extreme flood generation are often quite different from such mechanisms for usual floods. In a number of regions, the extreme floods may be of snowmelt or mixed snowmelt-rainfall origin In many cases, the extreme floods can be a result of such unusual combinations of hydrometeorological factors which may be unobserved in the historical data. A significant influence on the generation of extreme floods may have the human activity (for example, deforestation, urbanization, change of land use).

Achievements in development of the physically based models of runoff generation and stochastic analysis of meteorological time series as well as an immense increase of the computer speed allow one to implement for estimating the extreme flood characteristics a new technology that provides possibility to overcome, to significant extent, the shortcomings of both mentioned above approaches. This technology is constructed on combining the Monte Carlo simulation of meteorological inputs with the simulation of runoff hydrographs with aid of the dynamic-stochastic models of runoff generation. Eagleson (1972) was probably the first who employed a dynamic-stochastic model of runoff generation for calculation of statistical characteristics of maximum runoff from the statistical characteristics of rainfall but trying to apply only analytical solutions of the underlying differential equations he implemented oversimplified models. The development of Eagleson's method and its application to practical tasks of calculating maximum discharges due to rainfall and snow melting are described by Wood and Harley (1975), Carlson and Fox (1976), Chan and Bras (1979), Hebson and Wood (1982), Diaz-Granados et al. (1984). Kuchment and Gelfan (1991) combined the simulation of meteorological inputs by the Monte-Carlo method with the numerical solution of the differential equations describing runoff generation processes. However, because of the limitations of the computer facilities, a relatively simple dynamic-stochastic model of rainfall and snowmelt runoff generation was applied. Calver and Lamb (1995) estimated flood frequencies using two conceptual semi-distributed models of runoff generation. Salmon et al. (1997) and Cattanach et al. (1997) tested the methodology for estimating frequencies of extreme floods on the basis a conceptual model of runoff generation, rainfall frequency curves, and probability distributions of snow melt and antecedent soil moisture.

Conceptual models of runoff generation those are commonly used in hydrological practice (SSARR, HEC1, Sacramento, NWSRFS, HSPF, etc) contain aggregated empirical parameters some of which have little physical meaning and exhibit a large range of variation. As a result, these models after calibration may give a satisfactory accuracy for conditions those are close to observed events and used for construction and calibration of the models. However, the reliability of these models in unusual hydrometeorological conditions or at changing basin characteristics can be very low. In contrast, physically based models include parameters with clear physical meaning and values of these parameters can, in principle, be determined from direct measurements in a given watershed or from *a priori* information gained from laboratory or field investigations in similar physiographic conditions. These models use more information available on drainage basin characteristics and simplify the prediction of runoff change caused by human activity on the drainage basin area. The coupling of the detailed physically based models of runoff generation with the Monte–Carlo procedure of simulation of meteorological inputs permits us to estimate of exceedance probabilities of peak discharges and volumes of floods for the most severe combinations of meteorological and hydrological conditions, taking into account the nonlinearity of hydrological processes and the change of drainage basin characteristics.
The input data for flood generation models include the time series of precipitation, air temperature, air humidity, as well as solar radiation and wind speed for the snowmelt period Consequently, for continuous Monte-Carlo simulation of these values during the whole year it is necessary to have their stochastic temporal models. Because of the strong and seasonally changed autocorrelation and crosscorrelations commonly existing in the meteorological time series, construction of such models is a complicated task and many such models may be too sophisticated and unreliable for application in the estimation of flood characteristics of small exceedance probabilities, especially extreme values. Each run of runoff simulation with the aid of the distributed physically based model requires a significant computer time and it is necessary to choose the models as simple as possible. Choice and construction of an optimum dynamic-stochastic model depend on climatic conditions, main hydrological processes, and available hydrometeorological information. As an example illustrating the proposed approach, we shall

consider the construction of dynamic-stochastic model of extreme snowmelt flood generation for the Seim River basin.

Choosing and Construction of the Physically Based Model of Snowmelt Flood Generation

The Seim River basin (the catchment area to Kursk is 7460 km^2) is a part of the Dnieper River basin. The relief of the basin is a rugged plain with many river valleys, ravines, gullies. The soils are mainly chernozem, gray forest soil, and meadow soil. The ground water level fluctuates at 15-20 m below the land surface. The most part of the basin (about 70%) is ploughed, the forest occupies about 10%, the pastures and urbanized land take up about 20%. The mean annual precipitation is 600-650 mm, the mean snow water equivalent before melt is 85mm. The mean snowmelt runoff is 55mm; the mean peak discharge is 592 m^3/s, their coefficients of variation are, respectively, 0.43 and 0.81. The mean snowmelt peak discharge is almost 20 times higher than the rainfall one.

To choose an optimum structure of the extreme flood generation in the chosen river basin, the system of the physically based models of hydrological processes developed in the Water Problems Institute (WPI) of the Russian Academy of Sciences was applied (Kuchment et al., 1983; 1986; 1990).The WPI system provides simulation of a wide diversity of runoff generation mechanisms for exploring different assumptions about runoff generation mechanisms for a given basin and choosing the optimum structure of the whole model of runoff generation for this basin. The WPI model system can simulate the following processes which can results in extreme floods and which the commonly used conceptual models do not or poorly describe:

- unsteady overland flow and river channel flow at the flow depths which had not been reached during the floods for the period of runoff measurements (overbank flow, flow at sharply changed hydraulic characteristics);
- formation of impermeable soil layer at different depths as results of thermophysical processes during winter and spring periods;
- formation of ice crust;
- runoff generation at the rainfall on the snow cover;
- interaction of subsurface and overland flow;
- change of the contributed area depending on the rainfall characteristics.
- change of the land use of the drainage area (urbanization, forest cutting, land treatment).

Most of the model constants can be determined from usually available measurements of the drainage basin characteristics (relief and river channel characteristics; soil constants, snow measurements) and special empirical dependencies those were derived and tested using mainly the Russian laboratory and field data. Part of the parameters can be calibrated using the available measurements of hydrological variables: runoff, snow cover, soil moisture, and evaporation.

As a result of an analysis of data of hydrometeorological measurements and numerical experiments, the following structure of the runoff generation model the Seim River basin was chosen.

Snow Cover Formation and Snowmelt

To calculate the characteristics of snow cover during snowmelt, the system of vertically averaged equations of snow processes in a point has been applied (Kuchment, Gelfan, 1996, Kuchment et al., 2000). The system includes the description of temporal change of the snow depth, content of ice and liquid water, snow density, snowmelt, sublimation, re-freezing melt water, snow metamorphism and is written as follows:

$$\frac{dH_s}{dt} = \rho_w\left[X_s\rho_0^{-1} - (S+E_s)(\rho_i I_s)^{-1}\right] - V \qquad (1a)$$

$$\frac{d}{dt}(\rho_s I_s H_s) = \rho_w(X_s - S - E_s) + S_i \qquad (1b)$$

$$\frac{d}{dt}(\rho_w w_s H_s) = \rho_w(X_l + S - R_s) - S_i \qquad (1c)$$

where H_s = snow depth

I_S and w_S = volumetric content of ice and liquid water, respectively

X_s and X_l = snowfall rate and the rainfall rate, respectively (it is assumed that if the temperature of air $T_a \geq 0^oC$ only rainfall occurs and if $T_a < 0^oC$ only snowfall occurs) S = snowmelt rate

ρ_s = density of snowpack calculated as $\rho_s = \rho_i I_S + \rho_w w_S$

ρ_w, ρ_i, and ρ_0 = density of water, ice, and new snow, respectively

E_s = rate of snow evaporation

S_i = rate of re-freezing melt water in snow

R_s = meltwater outflow from snowpack

V = compression rate.

The snowmelt rate S is determined as $S = \beta\rho_s T_a$ (2)

where β = empirical constant.

The meltwater outflow is determined as $R_w = \begin{cases} R_0 + S, & w_s = w_{\max} \\ 0, & w_s < w_{\max} \end{cases}$ (3)

where $R_0 = X_l + S - E_s - w_{\max}\frac{dH_s}{dt}$

$w_{\max}$ = maximum liquid water-retention capacity calculated as (Kuchment at al., 1983)

$$w_{\max} = \frac{0.11 - 0.11\rho_i I_s \rho_w^{-1}}{1.11 - 0.11\rho_w \rho_i^{-1} I_s^{-1}} \qquad (4)$$

It is assumed that the rate of re-freezing $S_i = K_i\sqrt{-T_a}$ (for $T_a < 0^\circ C$) while K_i=5.8×10^{-8} m s^{-1} ^{O}C^{-1} (Motovilov, 1993).

The compression rate V is determined as $V = 0.5\xi\rho_s \exp(0.08T_a - \zeta\rho_s)H_s^2$ (5)

where ξ=2.7×10^{-7} m^2 s^{-1} kg^{-1}; ζ=2.1×10^{-4} m^3 kg^{-1} (Anderson, 1976).

The snow evaporation E_s on snow cover formation was assumed to be negligible.

Soil Freezing

The soil freezing is described by the following equations (Kuchment, 1980; Kuchment, Gelfan, 1993):

$$C_f \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_f \frac{\partial T}{\partial z}\right), \; 0 < z < H(t) \qquad (6a)$$

$$C_{uf} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{uf} \frac{\partial T}{\partial z}\right), \; H(t) < z < L \qquad (6b)$$

$$T(0,t) = T_0(t); T(H,t) = 0; T(L,t) = T_L; T(z,0) = T(z) \qquad (6c)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D_f \frac{\partial \theta}{\partial z} - K\right), H(t) < z < L \qquad (6d)$$

$$\theta(L,t) = \theta_L; \theta(H) = \theta_0; \theta(\mathrm{z},0) = \theta(\mathrm{z}) \qquad (6e)$$

$$\lambda_f \frac{\partial T}{\partial z}\Big|_{z=H-0} = \lambda_{uf} \frac{\partial T}{\partial z}\Big|_{z=H+0} + \chi\rho_w(\theta_- - \theta_0)\frac{dH}{dt} \qquad (6f)$$

$$H(0) = 0 \qquad (6g)$$

where $H(t)$ = depth of frozen soil at time t
$T(z,t)$ = soil temperature at the depth z and time t
λ_f and λ_{uf} = thermal conductivities of frozen and unfrozen layers of soil, respectively C_f and C_{uf} = heat capacities of frozen and unfrozen layers of soil, respectively
χ = latent heat of ice fusion
$\theta(z,t)$ = volumetric liquid water content of unfrozen soil
θ_- = liquid water content just above the freezing front
θ_0 = liquid water content at a temperature near 0^oC (assumed to be equal to the wilting point)
D_f = diffusivity of soil moisture
K = hydraulic conductivity
L = depth of the ground where the ground temperature and the volumetric oisture content can be considered as constants equated T_L and θ_L, respectively (L was taken to be equal to 2 m).

The equation (6d) describes soil moisture transfer from the unfrozen layer of soil to the freezing front. According to experimental data (see Kuchment, Gelfan, 1993; and references therein), this process plays an important role in the vertical redistribution of soil moisture during the cold period for soils which are typical for forested-steppe zone.

The diffusivity, the hydraulic conductivity of unfrozen soil, the heat capacities and the thermal conductivities of frozen and unfrozen soil were calculated by the formulas from (Kuchment et al., 1983).

Soil thawing

Soil thawing was calculated for snow-free areas of the catchment area from the end of snowmelt.. The movement of the soil thawing front was described by the equations similar to ones used for soil freezing description excluding equation (6d). The description of soil thawing model has been presented in (Kuchment, et al., 2000).

Meltwater infiltration into frozen soil

It was assumed that melting water saturates the upper layers of soil just after the beginning of snow melting; so the intensity of infiltration into the frozen soil can be assumed to be equal to the saturated hydraulic conductivity of the frozen soil K_f calculated as (Kuchment, Gelfan, 1991):

$$K_f = K_{uf}\left(\frac{P - I - \theta_0}{P - \theta_0}\right)^4 \frac{1}{(1+8I)^2} \tag{7}$$

where K_s = saturated hydraulic conductivity of soil
P = volumetric porosity
I = volumetric ice content of the upper layer of soil.

Detention Of Melt Water By Basin Storage

It was assumed that the spatial distribution of the free storage capacity D before snow melting can be described by exponential probability function. In this case, the sum detention of water d_r by the basin storage up to time t after the beginning of melting was determined as (kuchment et al., 2000):

$$D_R = \int_0^R [1 - F(D)]dD = D_0\left[1 - \exp\left(-\frac{R}{D_0}\right)\right] \tag{8}$$

Where $F(D) = 1 - \exp\left(-\frac{D}{D_0}\right)$

D_0 = expected value of the free storage capacity (or the maximum possible detention)

R = sum melt and rainfall water yield on the basin area up to time t.

The vertical movement of water in the unfrozen soil

The changes of the unfrozen soil moisture content and infiltration into the soil during the warm period were calculated by the equation (6d).

The evaporation rate E calculated as

$$E = k_E d_a(t)\theta(0,t) \tag{9}$$

where d_a = air humidity deficit

k_E = empirical constant.

Overland and channel flow

Overland flow is the main mechanism of snowmelt runoff generation for the Seim River basin. Subsurface contribution into the total runoff during spring flood period is negligible. To model overland flow, the kinematic wave equations were applied in the following form:

$$\frac{\partial(h_s B_s)}{\partial t}+\frac{\partial(q_s B_s)}{\partial x}=R_e B_s \qquad q_s = i_s^{0.5} h_s^{1.67} B_s n_s^{-1} \tag{10}$$

where h_s , q_s , B_s , i_s , n_s = the depth, discharge, width, slope and Manning roughness coefficient for overland flow, respectively

R_e = snowmelt/rainfall excess.

To describe the channel flow, the equations were as follows:

$$\frac{\partial(h_c B_c)}{\partial t}+\frac{\partial(q_c B_c)}{\partial x}=R_c \qquad q_c = i_c^{0.5} h_c^{1.67} B_c n_c^{-1} \tag{11}$$

where h_c , q_c , B_c , i_c , n_c = the depth, discharge, width, slope and Manning roughness coefficient for river channel flow, respectively

R_c = lateral inflow of overland flow per unit length of the river channel.

For numerical integration of the overland and channel flow equations, the finite element method was used. The choice of finite elements for the river channel system was determined by the schematization of the drainage area and the structure of the river network (Figure 1).

The runoff measurements for ten years (1969-1978) were used for calibration of the snowmelt empirical coefficient β (Eq. 2), saturated hydraulic conductivity K_{uf} (Eq. 7), and the Manning roughness coefficients for overland flow and river channel flow (Eqs. 10,11). The empirical constant k_E (Eq. 9) was calibrated using soil moisture measurements. The rest of the parameters were measured or taken from the literature data. The same hydrometeorological data for another ten years (1979-1988) were used for verification of the model. The comparison of calculated and observed hydrographs are given in Figure 2 and observed snowmelt peaks are compared in Figure 3. It is shown from these Figs that the developed model of snowmelt runoff generation has allowed us to obtain satisfactory results of simulation of the Seim River hydrographs.

Construction of the Stochastic Input Model and Estimating the Exceedance Probabilities of Snowmelt Flood Peaks

As inputs, a precipitation model, a model of daily air temperature for cold season (from 1 November to 30 April), and the model of air humidity deficit for warm season (from 1 May to 31 October) were applied To choose the structure and to determine the parameters of the input models, the meteorological measurements at a station, located in the centre of the Seim River basin, for the period of 1955-1988 were used.

The precipitation model consists of a model of daily precipitation occurrence (a first-order Markov chain is applied) and a gamma distribution of daily precipitation amounts. The probabilities of the wet day after the dry day and after the wet day are determined as 0.3and 0.6, respectively. The mean daily precipitation amount and the corresponding coefficients of variation (1.4 and 1.5) were determined separately for the warm and cold seasons (4.7 mm/day and 2.5 mm/day).

Because of the strong autocorrelation in the air daily temperature series, for modeling the daily temperature the following approach was applied. First, the observed sequences of daily air temperature was divided by the average values to obtain the normalized series ("fragments") for a season, these "fragments" were separated into several groups taking into account the average values. Then the distribution of the average seasonal temperature was fitted by the normal distribution. For generation of synthetic temperature series, the random "fragments" are chosen with aid Monte-Carlo procedure and multiplied by random values of the average temperature determined from the fitted distribution. The mean value of the seasonal temperature for cold season was taken –4°C at the variance of 4°C.

The histogram of daily air humidity deficit values was fitted by lognormal distribution with the mean 7.5mb and coefficient of variation 0.23. It was assumed that in the wet days the humidity deficit is negligible. The Monte-Carlo simulation was applied to construct the meteorological

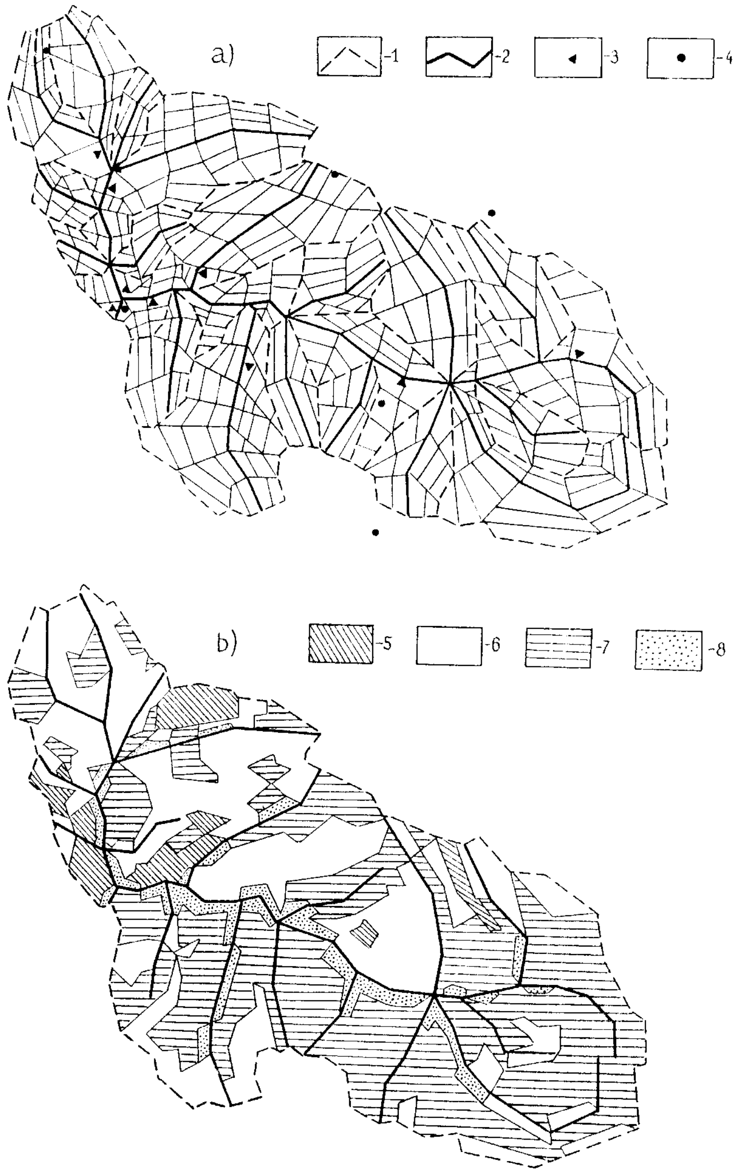

Figure 1. Finite element schematization of the Seim River basin:

(a) 1-subcatchment boundaries; 2-channel network; 3-runoff gauge stations; 4-agrometerological stations;

(b) distribution of soils in the basin: 5 - serozems, 6-podzolic chernozems, 7-typical chernozems, 8- meadow soils.

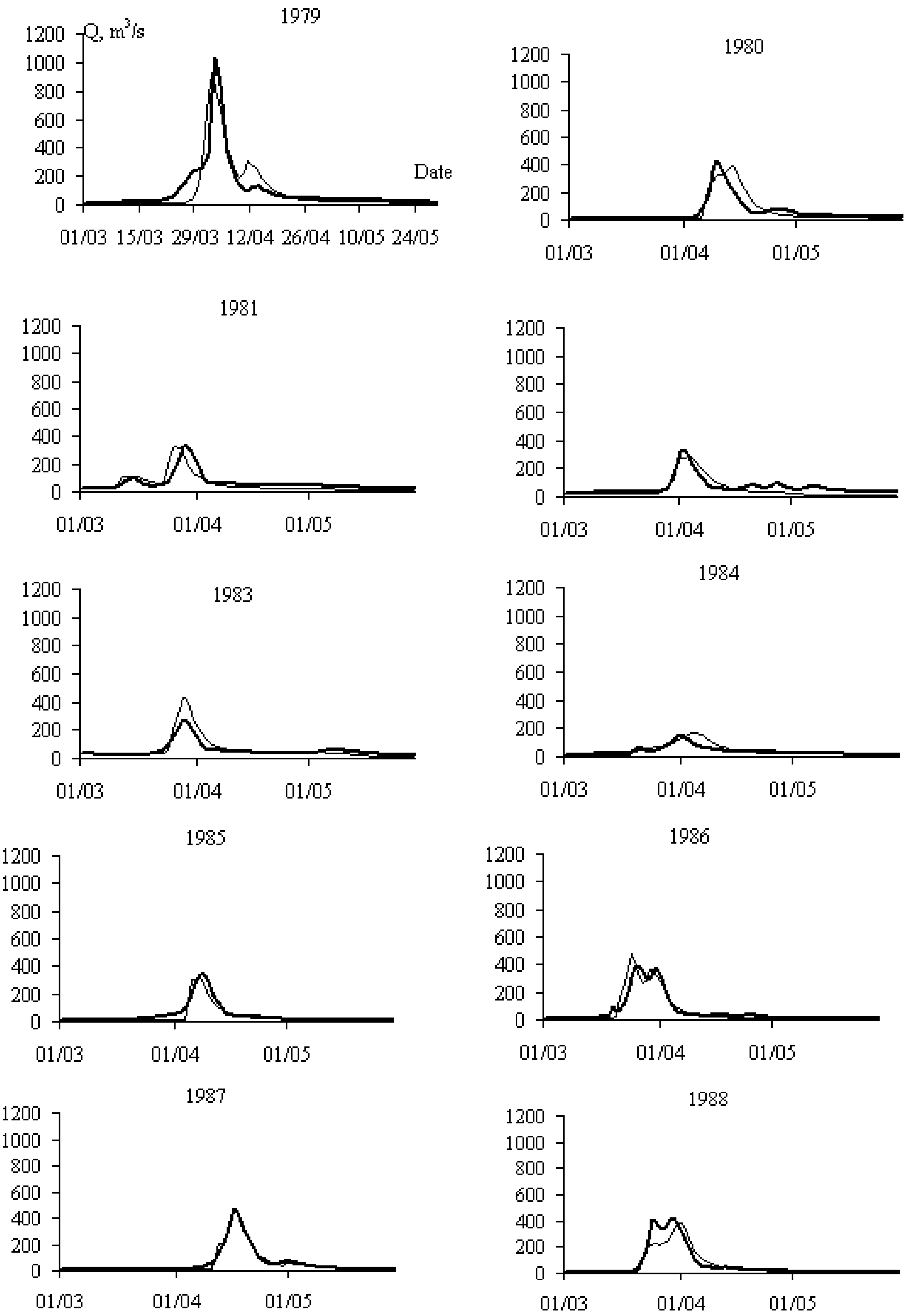

Figure 2 Observed (bold line) and calculated (fine line) hydrographs of the Seim River (verification phase)

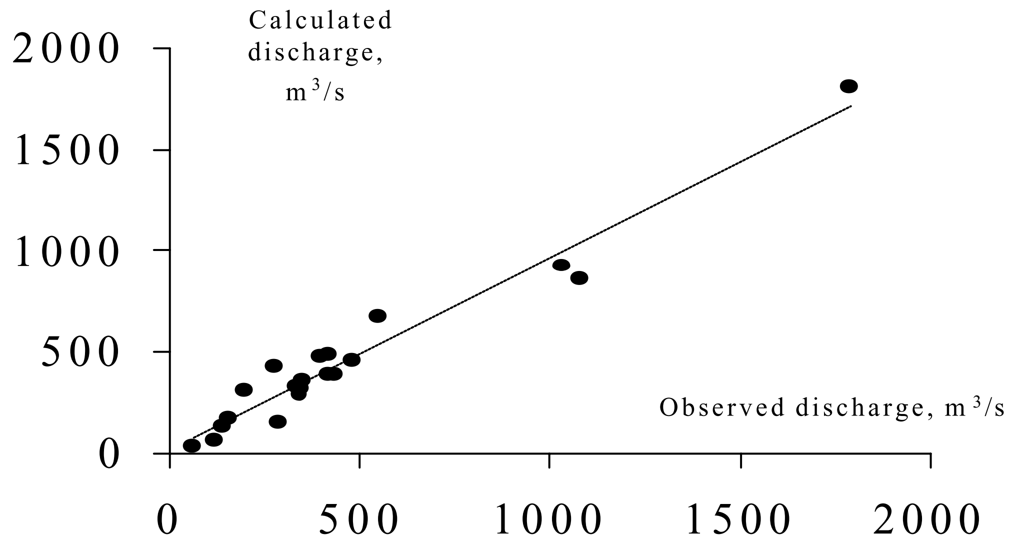

Figure 3. Observed vs. calculated snowmelt flood peaks (the Seim River; 1969 – 1988)

series and used to calculate the runoff hydrographs and the peak discharges with the aid the model runoff generation.

To avoid long-period stochastic modeling of air temperature, air humidity deficit, and precipitation, we also tested for simulation of the possible snowmelt floods the event generation procedure. In this case, we used the available daily series of air temperature, air humidity deficit, and precipitation for the previous summer, autumn and winter periods to calculate (on the basis of the equations (1) - (9)) the soil moisture, the depth of frozen soil, and the snow water equivalent before snowmelt and to construct the empirical statistical distributions of these values. These distributions were approximated by gamma distributions, extrapolated to the low exceedance probabilities, and used for assigning the initial conditions for the Monte-Carlo simulations of snowmelt runoff generation. The stochastic models of precipitation, air temperature, and air humidity deficit were applied for simulation after the beginning of snowmelt.

Figure 4 shows the comparison of the exceedance probabilities of snowmelt flood peaks calculated from 61-years measurement data and the exceedance probabilities determined from the 20,000 snowmelt hydrographs obtained on the basis of Monte-Carlo modeling of input data by the both procedures considered above.

Table 1 gives the comparison of the statistical characteristics of the peak discharges, calculated from the 61 years series of hydrological measurements the 20 years series of hydrological measurements (data used for calibration and verification of runoff generation model), and the 20,000 snowmelt hydrographs obtained on the basis of synthetic input data. As can be seen from Table 1 and from Figure 4, the correspondence between the observed statistical characteristics and calculated on basin of the Monte-Carlo simulation is quite satisfied.

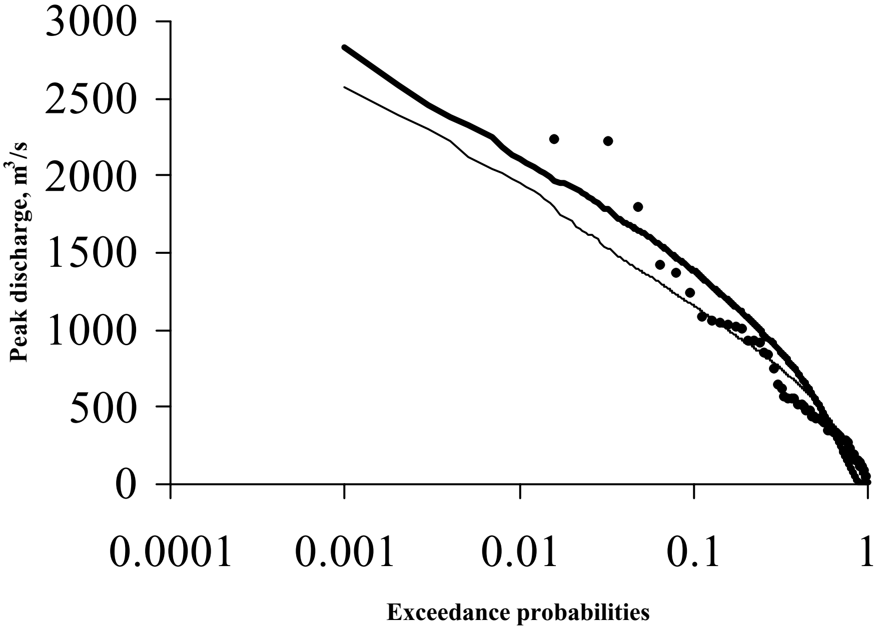

Figure 4. *Exceedance probabilities of the snowmelt peak discharges of the Seim River:*

Circles – 61-years series of the observed peaks;

Fine line – calculations by the dynamic-stochastic model with random meteorological inputs;

Bold line - calculations by the dynamic-stochastic model with random initial conditions.

The mean value of snowmelt peak discharge calculated by the first procedure appears to be closer to the observed mean, than one calculated by the second procedure. However, the coefficient of variation of peaks and the quantiles of low exceedance probabilities calculated by the second procedure are closer to the corresponding values obtained by 61-years observation series. It is possible to assume, that the first procedure allows us to reproduce better the averaged (climatic) conditions of snowmelt runoff generation, but not conditions of the extreme floods generation. Perhaps, using the second procedure, we can determine more reliable initial condition values of low exceedance probabilities.

Estimation of Exceedance Probabilities of Runoff Characteristics at Change of the Basin Land Use

The model is applied for estimation of exceedance probabilities of runoff characteristics at three scenarios of land use in the Seim river basin (for the beginning of the twentieth century, for the present time, for future). The main difference in these land use scenarios associated with change of area of agriculture land and agriculture land treatment. At the beginning of the last century, the all agriculture land used after harvesting as a pasture. At the present days, only about 20% of agricultural land is used for grazing after harvesting. The forest area during last century did not change. The same was also the virgin land area. However, it is supposed that in future the virgin land area will be used for agriculture and deep ploughing will be used for all agricultural area. The main change of soil characteristics are revealed in change of saturated hydraulic conductivity K_f and free storage capacity D_0. As can be seen from Table 2, changes of runoff characteristics range up 15-20% of estimated values.

Table 1. Statistics of the measured and calculated snowmelt peak discharges of the Seim River.

	Mean, m^3/s	Standard deviation, m^3/s	Coefficient of variation	Quantilies of different exceedance probabilities, m^3/s				
				0.001	0.005	0.02	0.05	0.1
Measurement data								
61 years (1928–1940; 1943-1990)	592	483	0.81		-	2230	1790	1240
20years (1969-1988)	458	409	0.89	-	-	-	1790	1080
Calculated data								
Model with the random meteorological inputs	594	429	0.72	2567	2123	1704	1381	1158
Model with the random initial conditions	637	531	0.83	2827	2325	1938	1633	1386

Results and Conclusions

The Monte-Carlo simulation of runoff hydrograph based on the physically based models of runoff generation and the stochastic models of meteorological inputs can ensure a more reliable determination of the statistical distributions of runoff characteristics than the statistical analysis of short observed runoff series. However, there are significant difficulties in assigning of parameters of the models of runoff generation and in constructing the stochastic models of meteorological models.

Table 2. Statistical parameters of the flood peak discharges (m^3 s) at different land use

Land use	***Soil constant*** values	***Mean, m^3/s***	Coefficient of variation	Quantilies of different exceedance probabilities, m^3/s		
				0.002	0.005	0.010
Autumn ploughing after grazing–20% Deep ploughing-50% Virgin land-20% Forest-10% (present)	K_{uf}=90 cm/day D_0 =12mm	637	0.83	2668	2325	2145
Autumn ploughing after grazing- 70% Virgin land -20% Forest-10% (beginning of XX century)	K_{uf}=50 cm/day D_0 =8mm	760	0.63	2866	2690	2204
Autumn deep ploughing -90% Forest-10%	K_{uf}=130 cm/day D_0 =18mm	535	0.84	2455	2122	1994

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A System Approach of Real-Time Hydrological Forecasting Applied to a Catchment Basin

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ABSTRACT: In non-engineering measurement for flood control, hydrological forecasting plays a very important role. Owing to the non-linearity and uncertainty of hydrological processes, real-time forecasting has become an efficient approach. This paper addresses the problems of how to use observed information to update parameters in hydrologic models to produce a real-time rainfall-runoff forecast. In this paper a simple nonlinear model with a variable gain parameter (VGPM) is developed. A separated calibration approach for updating parameters used in the runoff generation process and the response function in the flow routing is proposed. State space equations associated with updating model parameters in a real time scheme were developed. The VGPM approach is verified for three types of representative catchments.. The performance of different updating schemes in rainfall-runoff modeling and real-time forecasting were tested. The results indicate that significant improvement in the efficiency of hydrological modeling can be obtained from the VGPM approach, relative to simple linear models (SLM). For the catchments with a time–variant characteristic, however, significant improvement in the hydrologic forecasting efficiency can be obtained by adaptive schemes. The efficiency of real-time modeling by the self-adaptive Kalman Filtering algorithm was found to be very close to that of the Recursive Lease-Square method.

Key Words: river flow forecasting, updating, hydrological system approach

Introduction

Along with its economic development and population growth, many countries in the world are facing a series of challenges arising from water issues such as flooding and drought (Xia, 2001, Chen and Xia, 1999). In the past decade, for instance, a number of disastrous flooding events occurred in China, leading to approximately US$ 100 billion of economic losses (Zhang et al., 1997). In 1998, the direct economic losses from several flooding disasters on the Yangtze river and in other regions were over US$ 31 billion, accounting for 50% of the China's yearly GNP growth in that year.

In order to reduce flooding disasters, river flow forecasting, as one of most important non-engineering measurements, plays a very important role in flood control decision and management. Because of non-linearity and uncertainty in hydrological processes and incomplete catchment scale information, particularly in developing countries (see Xia 2000, Xia 2001), real-time forecasting as a hydrological system approach has been seen as a promising methodology, since observations of evapo-transpiration and rainfall-runoff processes in different space scales are not sufficient. For the methods of rainfall-runoff modeling and real time forecasting in an on-line operational model and updating methodology, such as recursive least-square algorithm or the Kalman filtering approach (Amorocho, 1963; Amorocho and Brandstetter, 1971; Hino, 1971; Diskin and Boneh, 1972, 1973; Amorocho, 1973; Papazafiriou, 1976; Natale and Todini, 1977; Liu and Brutsaert, 1978; Quimpo and Yuan, 1979; Diskin, 1982; Nash and Barsi, 1983; Hughes and Murrell, 1986; Xia, 1991; Kachroo and Natale, 1992; Ahsan and O'Connor, 1994; Kothyari & Singh, 1999)there are two updating approaches applied to real-time forecasting of flood discharge.

The first is to update flood discharge. For this approach, a deterministic, time-invariant hydrological model was firstly applied to provide a basic runoff forecast. The residual information was obtained using real time observations. The real-time flow-forecasting model is assumed to be an auto-regressive moving average (ARMA) model. The corresponding flow data are considered to be free of measurement errors. The minimum mean-square error forecasting method is obtained by using the 'conventional' Box and Jenkins-type time series forecasting method. However, there are some of arguments on the applications of the Kalman filtering method to discharge updating due to problems concerning application conditions (Ahsan and O'Connor, 1994).

Another way to applyreal-time hydrologic forecasting is to update the model parameter set that controls basic process of runoff generation associated with flood volume and discharge shape. Besides the application of real-time parameter evaluation to determine flow routing, a means to update the parameters controlling runoff volume from complex precipitation processes in a time-variant scheme has been an interesting problem.

The purpose of this paper is to develop an available hydrological system approach with a variable gain factor and real-time updating scheme. The developed model approach not only can be used to simulate the nonlinear relationship of the rainfall-runoff process in a simple and workable way, but also can be applied in a hydrological real-time forecast by updating model parameter sets to control both runoff volume and discharge shape.

The Variable Gain Parameter Model

The non-linearity of rainfall-runoff processes has long been recognized. The main non-linear effects on river flow forecasting may be contributed from the runoff generation process. This process is dependant on the volume of effective precipitation due to initial soil moisture deficit, infiltration loss and evapo-transpiration action. Moreover, flow velocity change in flow routing process is also nonlinear in most cases.

Using a system approach, a conceptual hydrologic model or a black system model could represent hydrologicly nonlinear processes. When catchment evapotranspiration or soil moisture data are too few, this system model approach will play an important role in river flow forecasting. The Volterra functional model may represent the general nonlinear system relationship, which is a non-linear extension of the unit hydrography approach (see, Amorocho, 1963, 1973; Napiorkowski and Strupczewski, 1979,1981; Singh, 1988; Xia, 1991,1995). For instance, the second-order Volterra non-linear model with a lumped, time-invariant assumption can be written as

$$Y(t) = \int_0^t h_1(\tau)X(t-\tau)d\tau + \int_0^t \int_0^{\tau} h_2(\sigma,\tau)X(t-\sigma)X(t-\tau)d\tau d\tau \tag{1}$$

where X is system input (e.g., rainfall), Y is output (e.g., runoff), h_i is the ith-order response function.

The above hydrological system representation is usually known as a " black box" approach that does not provide certain hydrological concepts or explanations. For instance, equation (1) simulates only a hydrological nonlinear relationship between the input X(t) and output Y(t) in the non-parameter formulation. The variable hi is a response function of a general, nonlinear system. However, there is a linkage between non-parameter formulation in hydrological systems and conceptual hydrological parameter models (see, Nash, 1966; Napiorkowski and Strupczewski, 1979,1981; Xia et al 1995). To study real-time forecasting of hydrological system by updating both parameter sets of runoff generation and response functions of flow routing, a Variable Gain Parameter Model (VGPM) approach was developed (Xia, 1989; Ahsan and O'Connor ,1994; Liang et al , 1994; Xia et al, 1995) . It can be proven that VGPM is a special formulation of the second orders Volterra non-linear functional series. Thus, the hydrological system representation is a nonlinear approach. On the other hand , the VGPM can be formulated by a rather simple way with a few runoff generation parameters and a set of response functions that characterize the flow routing process. It is easy to realize the operation of real-time hydrological forecasting by updating a model's parameters and response functions in real time. The basic concept and explanations of the VGPM are given in the following sections.

A framework of the VGPM applied to a lumped catchment system is shown in the Figure 1. This model consists of two sub-models. One is known as the runoff generation model which uses a few hydrological parameters. Another is the flow routing model which applies the unit hydrograph concept.

In the runoff generation sub-model, a variable gain factor is introduced when only precipitation and runoff data sets are available. The system gain, G_a, is an index of runoff generation amount (see O'Connor and Ahsan, 1991; Kachroo et al. 1992). In total runoff, linear system modeling, for instance, the gain factor, G_a, is approximately assumed as a constant, which is equivalent to the concept of an average runoff coefficient (Liang and Nash, 1988).

$$Ga = \frac{Y}{X} \tag{2}$$

where: Y is runoff volume during the calibration period, X is correspondent precipitation amount. However, observation from many catchments shows that the system gain factor is by no means constant - it is significantly influenced by catchmen wetness. The Antecedent Precipitation Index (API) is one of workable wetness indices. In general, the gain factor is proportional to catchment wetness. Ahsan and O'Connor suggested a general exponential function with wetness index z(t). In application, the wetness index, z(t), was defined as the ratio of simulated runoff to mean flow in the calibration period (Ahsan and O'Connor, 1994; Liang, 1994).

The authors found in 1989 and 1995 that a simplified representation of non-linear runoff generation, which does not require evaporation data (and which does not therefore take into account the variation in evaporation rate over time), can be developed in terms of the time-varying runoff coefficient G(t) of equation (2), as

$$G(t) = g_1 + g_2 API(t) \tag{3}$$

where the API is the Antecedent Precipitation Index function, to be used as an index of the degree of catchment wetness, defined in the present context as the outflow from a linear reservoir having the total rainfall function, X(t), as input, i.e. as

$$API(t) = \int_{\tau=0}^{\tau=t} \frac{\exp(-\tau / K_e)}{K_e} X(t-\tau)\,\mathrm{d}\tau \tag{4}$$

the reservoir storage coefficient, K_e ,being a parameter that indicates the rate of recession of soil moisture. The hypothesis and evidence of the relationship between API(t) and X(t) in the equation (4) was given in the references (Xia 1989; Ahsan and O'Connor, 1994). If evaporation data were available, then the parameter K_e could be estimated by an analysis of these data. In the absence of such data, however, K_e must be estimated instead through an analysis of the rainfall-runoff relationship using the available daily rainfall and streamflow data.

Using a discrete analogy, equation (4) can be written as

$$\begin{aligned} &\mathrm{API(k)} = \sum_{j=1}^{k} \mathrm{U_0(j)X(k-j+1)} \\ &\mathrm{U_0(j)} = (1-e^{-\frac{1}{K_e}})e^{-\frac{j}{K_e}} \end{aligned} \tag{5}$$

where U_0 (t) is linear response function calculated for the API sub-models.

The effective rainfall calculation in the runoff generation component can be operated by a simple variable gain formulation shown in equation (2), where G(t) is defined by equation (4) . This runoff generation sub-model is also represented by the other two equivalent formulations when equation (4) and (5) are substituted into equation (2), i.e.,

$$\mathrm{R(t)} = g_1\mathrm{X(t)} + g_2\mathrm{API(t)X(t)} \tag{6}$$

or

$$\mathrm{R(t)} = g_1\mathrm{X(t)} + \int_0^t g_2 U_0(t-\sigma)X(\sigma)X(t)d\sigma \tag{7}$$

Evidently, equation (7) shows that the relationship between precipitation, X (t), and effective rainfall, R (t), is perfectly non-linear when the variable gain in equation (4), G(t), was introduced. Only if the gain factor in equation (4) is assumed constant, i.e., G(t)=g_1 , can the runoff generation calculation be generated as a linear hypothesis. In real application of hydrological forecasting, the effective rainfall, R (t), can be directly calculated by the equation (6) when parameter set (g_1, g_2) and K_e are evaluated. This procedure can be completed independent relative to flow routing simulation.

When volume of effective rainfall is calculated from the runoff generation sub-model, flow routing modeling will determine the shape of discharge hydrograph. In most cases, the linear system modeling applied to flow routing is enough when the amount of effective rainfall is evaluated correctly. Thus, the unit hydrograph model that is also known as a linear response function, was used as the sub-model of flow routing in the VGPM. The system formulation has finite memory length, m, and can be expressed as

$$\mathrm{Y(t)} = \int_0^m \mathrm{U}(\tau)\mathrm{R}(t-\tau)d\tau \tag{8}$$

where U (t) is the unit hydrograph applied to a flow routing sub-system.

It should be mentioned that even though the mode of flow routing is assumed to be linear, the transfer behavior from rainfall to runoff is still non-linear due to variable gain contributions. An equivalent the Volterra non-linear model truncated after the second term could be derived from equation (7) to (8) as

$$\begin{aligned} Y(t) &= \int_0^m U(t-\tau)R(\tau)d\tau \\ &= \int_0^m U(t-\tau)[g_1X(\tau)+\int_0^\tau g_2U_0(t-\sigma)X(\sigma)X(\tau)d\sigma]d\tau \\ &= \int_0^m g_1U(t-\tau)X(\tau)d\tau + \int_0^m \int_0^\tau g_2U_0(t-\sigma)U(t-\tau)X(\sigma)X(\tau)d\sigma d\tau \\ &= \int_0^m H(t-\tau)X(\tau)d\tau + \int_0^m \int_0^\tau G\ (t-\sigma, t-\tau)X(\sigma)X(\tau)d\sigma d\tau \end{aligned} \tag{9}$$

where: $H(\tau) = g_1U(\tau)$, $G(\sigma,\tau) = g_2U_0(\sigma)U(\tau)$.

Evidently, it proves that the VGPM model is a nonlinear system, which could be characterized by a special formulation of the Volterra model. By introducing a variable gain into equation (2), a simple way can be used to deal with the complex nonlinear problem in the equation (9). It will be shown that parameters of the VGPM model could be directly estimated using the least-square method in both off-line and on-line ways.

On-line Identification of the VGPM Model and Real-Time Forecast

In most cases, particularly in semi-arid or monsoon catchments, determination of the amount or volume of effective precipitation, also known as runoff generation in a sub-model of the total hydrological system, plays a very important role in rainfall-runoff forecasting. The parameters of both the runoff generation sub-model and the flow routing sub-model are significantly time-variant due to time and space variability in hydrological the cycle and some hypothesis of runoff generation models to consideration of catchment soil moisture, precipitation, infiltration, evaporation and transpiration. Improvement in updating of both flow routing parameters and runoff generation, in real-time, may significantly increase the precision of hydrological forecasting. As a rather complex nonlinear relationship is used in evaluating the amount or volume of effective precipitation, most studies in the pass only focused on updating parameter sets for flow routing or discharge. It would be interesting to assess the results of updating both runoff generation parameters and flowing routing in real time.

On-line identification allows for updating of a model in real-time whenever data is received. One of the advantages of identifying model recursively is that it is possible to identify slowly varying parameters or the response function of the system. To use some of the available updating algorithms, it may be necessary to express the VGPM as a state space equations.

The Problem of State-Space Equation Formulation

For on-line parameter identification and real-time forecasting, the simplest approach that can be used is when the parameters vary over time in a random variable model (Hsia, 1977, Sage & Husa, 1980; Beven, 2000). The model consists of a state equation with model parameters and an observed equation. The simplest formulation could be written as follows:

$$\theta_{n\times1}(k+1) = \theta_{n\times1}(k) + \omega_{n\times1}(k) \tag{10}$$

$$Y_{1\times 1}(k) = h_{1\times n}{}^{T}(k)\theta_{n\times 1}(k) + e_{1\times 1}(k) \tag{11}$$

where θ is the nx1 state vector (i.e. parameter vector), Y is the discharge (scalar), h is a function of the hydrological model with the nx1 vector(e.g., it can be expressed by the VGPM) , $\omega(k)$ and e (k) are vectors of Gaussian independent random variables with zero means and covariance matrices Q and R, respectively.

The first problem in rainfall-runoff forecasting using the adaptive VGPM model is that of how to express it in state-space equation formulation. According to the purpose of this study, two-phase schemes were suggested. One is to update the parameters of runoff generation sub-model in terms of observed volume information for rainfall and runoff. Another is to update the response function of the flow routing sub-model using observed discharge. These two phases of operation can be completed interactively.

Real-time Updating of Parameter Set for Runoff Generation Component

By sensitivity analysis of the VGPM, it was found that the parameter K_e in the API model could be properly determined in an on-line identification manor (Xia, 1995). Then, real-time updating of the runoff generation component in the VGPM consists of either evaluating parameter g_1 or g_2. To estimate parameters reasonably using information on runoff generation volume, a water balance relationship was derived in terms of the convolution integral equation (8). The idea is that for a long enough period, T, the total water balance of input and output in terms of system equation (8) can be expressed as

$$\int_0^T Y(t)dt = \int_0^T R(t)dt \tag{12}$$

Moreover, we look for the water balance corresponding to different runoff generation events. The formulation of the volume relationship might be separated as a series of sub-equations relative to water volumes of different input events influencing the length of runoff generation period. The influencing length, here, is defined as variable T_m. It might be taken as n times memory length, i.e., $T_m = n\times m$. In fact, by integrating equation (8) over the period $[t-T_m, t]$ and taking the maximum input volume when integral variable changed in the interval [1, m], a shift water volume equation can be approximately derived as

$$\int_{t-T_m}^{t} Y(s)ds \approx \int_{t-T_m}^{t} R(s)ds \tag{13}$$

Substituting equation (6) into (13), a variable volume equation can be written as

$$\begin{aligned}\int_{t-T_m}^{t} Y(s)ds &= \int_{t-T_m}^{t} [g_1 X(s) + g_2\ API(s)X(s)]\, ds \\ &= g_1 \int_{t-T_m}^{t} X(s)\, ds + g_2 \int_{t-T_m}^{t} API(s)X(s)\, ds\end{aligned} \tag{14}$$

Let

$$V_Y(t) = \int_{t-T_m}^{t} Y(s)ds\,,\ \ V_X(t) = \int_{t-T_m}^{t} X(s)ds\ \ ,\ \ V_{AX}(t) = \int_{t-T_m}^{t} API(s)X(s)ds$$

The equation (14) can be re-written as

$$V_Y(t) = g_1 \ V_X(t) + g_2 \ V_{AX}(t) \tag{15}$$

The distinguish feature of the equation (15) is that volume relationship between rainfall and runoff can be directly linked to runoff generation parameters for the time t. Thus, equation (15) could be used as the observed equation of state-space model for the purpose of real-time parameter set updating for the runoff generation component of the VGPM.

For the discrete sample data, the state-space equations corresponding to (10) and (11) could be expressed as

$$\begin{aligned} \theta(k+1) &= \theta(k) + \omega(k) \\ V_Y(k) &= h^T(k)\theta(k) + e(k) \end{aligned} \tag{16}$$

where:

$$\theta(k) = \begin{pmatrix} g_1(k) \\ g_2(k) \end{pmatrix} , \qquad h\ (k) = \begin{pmatrix} V_X(k) \\ V_{AX}(k) \end{pmatrix}$$

Real-time forecasting for discharge is given by

$$R(k+1/k) = g_1(k+1/k)X(k+1) + g_2(k+1/k)API(k+1)X(k+1)$$

$$Y(k+1/k) = \sum_{j=1}^{m} U(j)R(k-j+2/k-j+1) \tag{17}$$

where the response function, U (j), could be determined by off-line identification(Xia, 1995).

Real-time Updating Response Function of Flow Routing Component

In the same way, we could provide a scheme to update the response function in the VGPM by real-time collection of observed discharge information. The parameters of the runoff generation sub-model were provided by the "Off-line" estimation.

Using linear convoluted equation (8), a set of state equations corresponding to (10) and (11) could be expressed as

$$\begin{aligned} \theta(k+1) &= \theta(k) + \psi(k) \\ Y(k) &= h^T(k)\theta(k) + \zeta(k) \end{aligned} \tag{18}$$

where: The updated parameter vector,$\theta(k)$, consists of each response function? ordinations U(k,j). The system observed value, Y (k), is discharge. The observed matrix, h (k), is formulated by effective rainfall calculated by the runoff yield model, i.e.,

$$\theta(k) = \begin{pmatrix} U(k,1) \\ U(k,2) \\ \vdots \\ U(k,m) \end{pmatrix}, \qquad h\ (k) = \begin{pmatrix} R(k) \\ R(k-1) \\ \vdots \\ R(k-m+1) \end{pmatrix}$$

Real-time updating of both Components of Runoff Generation and Flow Routing

If we wish to update both components of runoff generation and flow routing, then an extended real-time updating framework for the VGPM needs to be developed. A simple way is to couple the state equation set (16) with equation set (18).

Define a mixed parameter vector as Θ(k), and a mixed observed vector as Z (k), then extend state-space equations for updating both runoff generation parameters and response functions as:

$$\begin{aligned} &\Theta\ (k+1) = \Theta(k) + \Sigma\ (k) \\ &Z(k) = H^T(k)\Theta(k) + E(k) \end{aligned} \tag{19}$$

where :

$$\Theta(k) = \begin{bmatrix} g_1(k) \\ g_2(k) \\ U(k,1) \\ \vdots \\ U(k,m) \end{bmatrix}, \quad \Sigma\ (k) = \begin{bmatrix} \omega_{12}(k) \\ \omega_2(k) \\ \psi(k) \\ \vdots \\ \psi(k) \end{bmatrix}, \quad Z(k) = \begin{bmatrix} V_Y(k) \\ Y(k) \end{bmatrix}$$

$$H(k) = \begin{bmatrix} V_X(k) \\ V_{AX}(k) \\ R(k) \\ \vdots \\ R(k-m+1) \end{bmatrix}, \quad E(k) = \begin{bmatrix} e(k) \\ \zeta\ (k) \end{bmatrix}$$

Kalman Filtering and Recursive Least-Squares Algorithms

A remarkable approach to solving the problem of extracting useful information from noise-corrupted data, otherwise known as the filtering problem, was developed by Kalman (1960) and Kalman and Bucy (1961). Thus, this was the first choice for application to the recursive parameter estimation of the VGPM model.

How is the Kalman filtering approach applied to system equation (10) and (11)? Let ω(t) and e (t) both be stationary random processes with constant covariance matrix Q and scalar R. It is also assumed that the noise processes are not correlated. This means that $E[\ \omega(K)\ , e(j)\ ] = 0$ for all k and j, and both processes are independent of the state with the initial statistics $\theta(o) = N(\ \hat{\theta}(o),\ P(0)\ )$. Let θ(k/k) denote the best linear unbiased estimator of θ(k) based on measurement Y (k). θ(K/k) is the filtered estimator of θ(k) since it is the estimate of the state vector at the current time based upon all measurements including the current one. The optimal filtering problem can be stated as follows:

Given a measurement sequence Y (k) observed by the measurement equation (11), estimate the state of the parameter model (10) such as the error of estimate, i.e.,

$$\tilde{\theta}(k/k) = \theta(k) - \hat{\theta}(k/k)$$

will minimize the quadratic performance function

$$J = E[\tilde{\theta}(k/k)\tilde{\theta}^T(k/k)] \tag{20}$$

Kalmam (1960) rigorously derived the form of a recursive filter for the above system. It was shown that the optimal estimator for the filtering problem will provide us with the optimal estimator for the prediction problems if these assumptions hold true. The optimal filter applied to parameter equation (10) and (11) is summarized as (see Hsia, 1977; Wood, 1976):

$$\begin{aligned}
&\hat{\theta}(k+1) = \hat{\theta}(k) + \gamma(k+1)P(k)h^T(k+1)\varepsilon(k+1) \\
&Y(k+1/k) = h^T(k+1)\hat{\theta}(k) \\
&\varepsilon(k+1) = Y(k+1) - Y(k+1/k) \\
&P(k+1) = P(k) - \gamma(k+1)P(k)h(k+1)h^T(k+1)P(k) + Q \\
&\gamma(k+1) = 1/[R + h^T(k+1)P(k)h(k+1)]
\end{aligned} \tag{21}$$

where Y (k+1/k) is the prediction output, P(k+1) is the covariance matrix of the prediction error, ε(k+1) is new residual information applied to updating, γ and (k+1) is a scalar.

On the other hand, based on a weighted error function

$$J_{k+1} = \sum_{i=1}^{k=1} \lambda^{k+1-i}\varepsilon^2(i)$$

The recursive equations in terms of a weighted least-squares (WRLS) algorithm is also obtained (Hsia, 1977), given by

$$\begin{aligned}
&\hat{\theta}(k+1) = \hat{\theta}(k) + \gamma(k+1)P(k)h^T(k+1)\varepsilon(k+1) \\
&Y(k+1/k) = h^T(k+1)\hat{\theta}(k) \\
&\varepsilon(k+1) = Y(k+1) - Y(k+1/k) \\
&P(k+1) = \frac{1}{\lambda}[\,P(k) - \gamma(k+1)P(k)h(k+1)h^T(k+1)P(k)\,] \\
&\gamma(k+1) = 1/[\lambda + h^T(k+1)P(k)h(k+1)]
\end{aligned} \tag{22}$$

where λ is a constant weight, λ∈[0, and 1.0].

It has been found that the Kalman Filtering (KF) approach shown in equation set (21) has a very close relationship to a weighted recursive least squares (WRLS) algorithm in equation (22). The

WRLS is a special formulation of the KF approach. When model noise covariance matrix Q is assumed as zero, the scalar R and weight λ are also taken as unity. Then, the KF approach is reduced to a simple recursive least-square (RLS). However, in real applications of the KF approach, the covariance matrix Q and scalar R must be known. Any approximation of Q and R would render the algorithm sub-optimal.

To deal with the problem of noise covariant matrixes and unknown Q and R values, someadaptive Kalman filter methods were developed using the fact that the innovation sequence $\varepsilon(k)$ in equation (21) contains all the information necessary for estimation of the steady-state Kalman gain and the noise covariance measurement R (see, Sage and Husa, 1969; Wood, 1976; O'Connell, 1980). However, one of the main problems is application of the divergence of noise covariance estimation. The reason is due to bad initial estimation or biases basic assumptions of Kalman filter. Thus, some empirical methods were applied to deal with these problems. In the reference (O'Connell, 1980), for example, estimation of noise covariance matrices is given as follows:

$$
\begin{aligned}
&\hat{R}(k) = \frac{(k-1)}{k}\hat{R}(k) + \frac{1}{k}[\varepsilon\ (k)\varepsilon^{T}(k) - h^{T}(k)P(k-1)h\ (k)] \\
&K(k) = \gamma(k)P(k-1)h^{T}(k) \\
&\hat{Q}(k) = \frac{(k-1)}{k}\hat{Q}(k) + \frac{1}{k}[K(k)\varepsilon\ (k)\varepsilon^{T}(k)K^{T}(k) + P(k) - P(k-1)]
\end{aligned}
\tag{23}
$$

The preliminary examinations applied to the VGPM updating model show that the problem of divergence of noise covariance estimation is not fully solved in real-time rainfall-runoff modeling. To decrease the degree of freedom, let $Q_1 = Q/R$, $P1 = P/R$ and $\gamma_1 = R\gamma$, and mixed noise covariance matrix, Q_1, is assumed as a weighted function with the covariance matrix of the prediction error, P_1. A scaled Kalman filtering algorithm corresponding to equation set (21) could be reduced as

$$
\begin{aligned}
&\hat{\theta}\ (k+1) = \hat{\theta}\ (k) + \gamma_1(k+1)P_1(k)h^{T}(k+1)\varepsilon\ (k+1) \\
&Y(k+1/k) = h^{T}(k+1)\hat{\theta}\ (k) \\
&\varepsilon\ (k+1) = Y(k+1) - Y(k+1/k) \\
&P_1(k+1) = P_1(k) - \gamma_1(k+1)P_1(k)h(k+1)h^{T}(k+1)P_1(k) + Q_1 \\
&Q_1(k) = Q/R \approx wP_1(k) \\
&\gamma_1(k+1) = 1/[1 + h^{T}(k+1)P_1(k)h\ (k+1)]
\end{aligned}
\tag{24}
$$

where: w is a weight of value from zero to unity. Evidently, if is taken as zero,the above Kalman Filtering approach is reduced to the RLS method.

Moreover, a self-adaptive weighted least-squares algorithm (SWRLS) was developed. The recursive formulation of variable weight corresponding to the equation set (22) could be derived as

$$
\lambda(k+1) = 1 - \frac{\varepsilon\ (k+1)}{[1 + h^{T}(k+1)P(k)h\ (k+1)]\Sigma_0}
\tag{25}
$$

where Σ_0 is a scalar.

In real-time forecast applications on the VGPM model, two types of updating approach were examined, i.e., the Kalman Filtering method and the recessive least-square methods.

Application and Examinations

To examine efficiency of the VGPM model application, three types of representative catchment data sets were used for daily rainfall-runoff modeling and forecasting. The Department of Engineering Hydrology, University College Galway, Ireland, collected these databases.

The first data set is chosen from arid, semi-arid or monsoon influenced catchments. For such catchments, the efficiency of rainfall-runoff modeling displayed significant inconsistency between the calibration period and the verification duration when the SLM is used. Owing to strong variations in the runoff generation process, it is quite possible to get a negative efficiency in the verification period. Perhaps this was one of the most significant features for catchments with inconsistent data. Thus, two representative catchment data sets, namely the Bird Creek catchment of the United States and the Wolombi Brook catchment of Australia, were used in the paper.

The second data set is from semi-arid or monsoon influenced catchments with consistent relationship in calibration and verification period. This means that for efficiencies simulated by the SLM showed no significant differences between calibration and verification regardless of efficiency. Five representative catchments, including the Kizu of Japan and the Beihe of China, were chosen.

The third data set collected from large areas or monsoon influenced catchments, which have rather consistent efficiency in both calibration and verification. They include the Nam Mune catchment of Thailand and the Qing Jiang of China. The main indices of this selected catchment data set are listed in the Table 1.

Table 1 Chosen set of the rainfall-runoff catchments collected by UCG, Ireland

Class	Catchment Nmae	Area (Km^2)	County	R-R data length(days)
A	Bird Creek	2,344	U.S.A	2,922
	Wolombi	1,580	Australia	1,826
B	Kizu	1,445	Japan	1,826
	Chu	2,090	Vietnam	3,652
	Chaiping	2,370	China	3,653
	Shiquan-3	3,092	China	2,922
	Sunkosi-3	4,920	Nepel	2,922
C	Nam Mune	104,000	Thailand	2,922
	Qing Jiang	15,300	China	2,922
	Beihe	61,780	China	2,922
	Shiquan-1	23,805	China	2,922
	Shiquan-2	14,192	China	2,922

A: Arid and semi-arid catchment with inconsistent data series in model calibration and verification;

B: Semi-arid or monsoon influenced mid-small catchment with consistent data set in model calibration and verification;

C: Monsoon influenced mid-large catchment with consistent data set in model calibration and verification.

Considering the purpose of comparative studies, we designed different testing schemes. They included: (a) the comparison of the VGPM with SLM on rainfall-runoff modeling, (b) the on-line identification and comparisons of contributions due to real-time updating or no updating schemes, and (c) comparisons of different updating algorithms.

The main assessment index chosen in this paper is the efficiency R^2 (Nash and Sutcliffe, 1970):

$$R = (1 - \frac{F}{F_0}) \times 100\% \tag{26}$$

$$F_0 = \frac{1}{D} \sum_{K \in D} [Y(k) - \overline{Y}]^2 \quad , \quad F = \frac{1}{D} \sum_{K \in D} [Y(k) - \hat{Y}(k)]^2$$

where : F is the mean-square error within a given time span of D-units, F_o is an initial variance, $\hat{Y}(k)$ is the model-simulated flow, $\overline{Y}$ is the mean flow.

Moreover, it is interested to check the volumetric agreement between the observed flows and the model-estimated flows in a given time period D. For this purpose, the index of volumetric fit (IVF), as defined below, is also used.

$$IVF = \frac{\sum_{i \in D} \hat{Y}(k)}{\sum_{i \in D} Y(k)} \tag{27}$$

For the rainfall-runoff simulation, the results of comparisons in efficiency and the IVF from the VGPM model with SLM model is listed in the Table 2. The comparison of different updating schemes with no updating case for the VGPM model is shown in the Table 3. The comparisons of efficiency of three updating algorithms, namely the self-adaptive Kalman filtering algorithm (KF), the weighted recursive least-square algorithm (WRLS) and the self-adaptive weighted recursive least-square algorithm (SWRLS), for the VGPM model are listed in the Table 4.

Examinations indicate that significant improvements in efficiency, R^2, were obtained with the VGPM in almost all tested catchments (see Table 2). The IVF index also shows that the estimation of runoff generation amount is more correct with variable gain type model than the linear system model (see Table 2). The reason, perhaps, is that the index of catchment wetness such as the API index on runoff generation is considered in the VGPM type models. It is known that the main difference between VGPM type models and SLM model is the gain factor. The gain factor in the SLM is assumed as constant, which means the effective rainfall would be calculated by an averaged runoff coefficient, Ga. However, in the VGPM type model runoff generation coefficient (i.e. gain factor) is taken as a variable function of the API index. Thus, from the concept of runoff generation, the variable gain model is more reasonable.

The results of comparing contributions between operations with updating and without updating schemes on real-time rainfall-runoff modeling show that the updating scheme for runoff generation parameters plays an important role in improvement of runoff volume estimation. Most IVF indexes for the updating scheme were better than that for the no updating case (see the Table 3). Moreover, for the arid and semi-arid catchments with inconsistent data series, such as the Bird Creek and Wolombi, improvement in efficiency is significant using the method of real-time updating runoff generation parameters (see the R^2 results in the verification period, Table 3).

Table 2. Comparison of Efficiency of the VGPM model with the SLM model

Catchment Name	Memory length(days)	Parameter K_e	Test period	Efficiency R^2		Volumetric Fit (IVF)	
				SLM	VGPM	SLM	VGPM
Bird Creek	10	20	Calib.	59.24	87.67	1.605	0.974
			Verif.	-52.70	43.29	2.483	0.873
Wolombi	10	20	Calib.	46.23	83.57	1.708	0.839
			Verif.	-13.37	36.70	3.248	1.453
Kizu	10	20	Calib.	80.00	87.96	1.056	0.934
			Verif.	67.41	75.17	1.160	1.008
Chu	10	20	Calib.	59.79	79.86	1.256	0.854
			Verif.	70.09	74.98	1.207	1.005
Chaiping	40	40	Calib.	56.68	75.12	1.178	0.882
			Verif.	61.63	77.37	0.991	0.800
Shiquan-3	10	20	Calib.	71.95	87.54	1.267	0.884
			Verif.	53.91	74.75	1.689	1.226
Sunkosi-3	20	100	Calib.	80.06	86.90	0.970	0.953
			Verif.	80.04	82.26	0.857	0.820
Nam Mune	30	100	Calib.	50.27	78.89	0.990	0.903
			Verif.	54.09	85.78	1.057	0.993
Qing Jiang	10	20	Calib.	79.28	84.34	1.079	0.999
			Verif.	82.96	88.60	1.035	1.066
Beihe	10	20	Calib.	70.12	83.96	1.059	0.896
			Verif.	70.62	78.31	1.351	1.179
Shiquan-1	15	30	Calib.	67.66	82.11	1.105	0.867
			Verif.	55.45	73.38	1.134	0.868
Shiquan-2	10	20	Calib.	72.44	87.11	1.133	0.864
			Verif.	61.26	80.04	1.195	0.945

SLM: Simple Linear system model

VGPM: Variable gain parameter model

If improvement of a model (say model 2) performance over that of another model (say model 1) is assessed by the index, r^2, i.e., $r^2\% = (\frac{R_2^2 - R_1^2}{1 - R_1^2}) \times 100\%$ (Ahsan and O'Connor, 1994), then a set of comparisons for the Bird Creek and the Wolombi in the verification period is shown in the Figure 2. It is also shown that contribution raised from updating runoff generation parameters is bigger than that from updating the response function. However, for the catchments with consistent data series, there is almost no improvement of efficiency due to less contribution from time-variant parameter scheme. Perhaps this is explained by the fact that it is enough to take model parameters as a set constant in such cases.

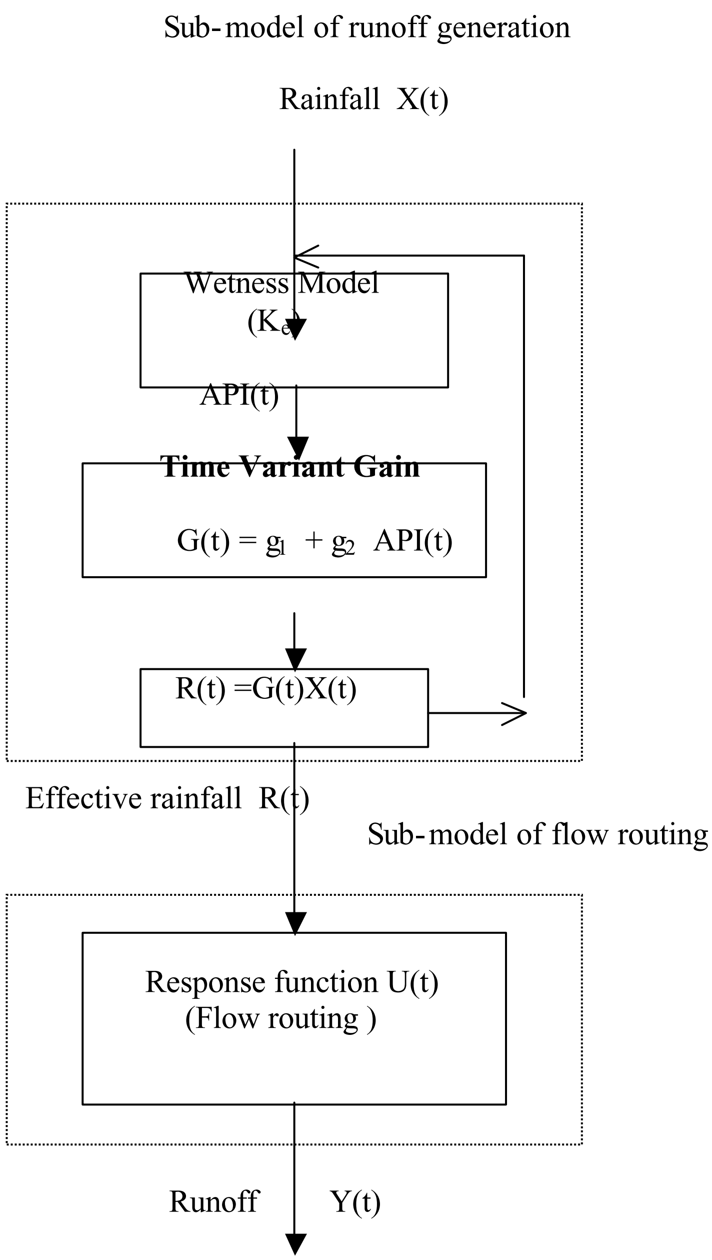

Figure 1 Schematic of a Variable Gain Parameter Model (VGPM) applied to rainfall-runoff modeling

The examination of efficiencies of three updating algorithms for the VGPM model indicate that the Kalman Filter approach can work on updating model parameter sets and response functions. Because the Kalman Filter approach has more flexibility in selection of matrix Q, R or weight w, it could provide higher efficiency on applications such as of the Nam Mune catchment. As far as flood peak forecasting is concerned, the Kalman filter approach provides a faster response on model updating than the recursive least-squares method (Xia, 1995). However, the efficiency of real-time updating by the Kalman Filter approach is very close to that of the recursive least-squares methods (see the Table 4). The reason is that in these cases the weight of the self-adaptive Kalman Filter approach was just taken as unity to obtain better efficiency. Thus, the contribution of the KF method is quite similar to the recursive least-squares methods. It seems to be enough to use the recursive least-squares method to update model parameters. The Kalman Filter approach has no significant advantages on application to real-time rainfall-runoff modeling over the recursive least-squares method.

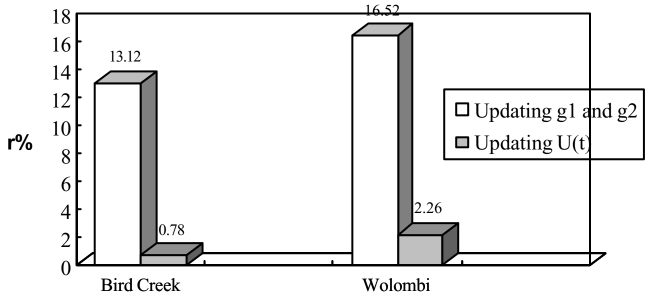

Figure 2

Conclusion Remarks

(a) For real-time rainfall-runoff modeling, the key problem is how to use observed information on runoff generation volume and discharges in an operational model. It is workable to use the variable gain parameter model (VGPM) due to its simple adaptability for use with separate real-time identification of the parameters used in the variable gain estimation and the unit pulse response function.
(b) The scheme of updating runoff generation parameters plays a role in forecasting runoff volume. Most index of volumetric fit (IVF) indicates improvement over the performance of the no updating case.
(c) The efficiency index , R^2, show that, for a catchment having consistent behavior, there is not yet much to be gained by adaptive parameter estimation; neither on the runoff generation component nor on the runoff routing component. For an inconsistent catchment, however, significant improvement can be obtained by adaptive schemes.
(d) Even though the Kalman filtering approach has more flexible on real-time rainfall runoff forecasting, no significant improvement in efficiency over the Recursive Least-Squares method was observed.

Table 3. Comparison of different updating schemes with no updating case for the VGPM model

Catchment Name	Test period	Efficiency R^2 No update	Efficiency R^2 Update (g1,g2)	Efficiency R^2 Update U(t)	Volumetric Fit (IVF) No update	Volumetric Fit (IVF) Update (g1,g2)	Volumetric Fit (IVF) Update U(t)
Bird Creek	Calib.	87.67	86.57	87.31	0.974	1.071	0.992
	Verif.	43.29	50.73	43.73	0.873	1.152	0.884
Wolombi	Calib.	83.57	82.57	81.93	0.839	0.971	0.911
	Verif.	36.70	47.16	38.13	1.453	0.945	0.601
Kizu	Calib.	87.96	84.77	87.11	0.934	0.966	0.936
	Verif.	75.17	75.64	79.56	1.008	1.003	0.932
Chu	Calib.	78.86	80.16	79.04	0.853	0.921	0.840
	Verif.	74.98	72.63	75.68	1.005	0.970	0.999
Chaiping	Calib.	75.12	74.84	73.36	0.882	1.023	0.867
	Verif.	77.37	78.58	78.31	0.800	1.004	0.804
Shiquan-3	Calib.	87.54	86.55	87.21	0.884	0.902	0.885
	Verif.	74.75	72.92	74.40	1.226	0.962	1.216
Sunkosi-3	Calib.	86.90	85.93	86.69	0.952	0.950	0.943
	Verif.	82.26	82.25	82.58	0.818	0.985	0.831
Nam Mune	Calib.	78.86	78.54	78.48	0.903	0.902	0.912
	Verif.	85.78	85.23	85.69	0.993	0.937	0.997
Qing Jiang	Calib.	83.34	84.04	84.13	0.999	1.002	1.003
	Verif.	88.60	88.01	88.85	1.066	0.995	1.057
Beihe	Calib.	83.96	87.88	83.68	0.896	0.989	0.887
	Verif.	78.31	81.29	79.29	1.179	0.956	1.155
Shiquan-1	Calib.	82.11	81.19	81.67	0.867	0.922	0.872
	Verif.	73.38	68.56	73.01	0.868	0.974	0.863
Shiquan-2	Calib.	87.11	86.36	86.86	0.864	0.924	0.860
	Verif.	80.04	76.25	80.54	0.945	1.001	0.936

* Updating result was taken from estimation of the KF or WRLS method,
No updating result was given by off-line identification of TVGPM model.

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Table 4. Comparison of efficiency of three updating algorithms for the VGPM model

Catchment Name	Calibration			Verification		
	KF	*WRLS*	*SWRLS*	*KF*	*WRLS*	*SWRLS*
Bird Creek	84.48	80.95	85.87	44.51	44.05	44.34
Wolombi	75.37	75.35	75.37	43.03	43.01	43.15
Kizu	90.62	89.91	89.89	83.02	83.29	83.29
Chu	77.03	77.03	77.03	77.39	77.39	77.42
Chaiping	73.53	73.52	73.70	78.73	78.33	78.86
Shiquan-3	87.79	87.76	87.74	74.85	74.86	78.80
Sunkosi-3	88.72	88.87	88.65	86.87	86.87	81.58
Nam Mune	90.51	82.80	83.09	94.25	90.00	89.32
Qing Jiang	87.09	87.09	87.01	90.08	90.08	90.25
Beihe	87.00	87.00	86.94	79.78	79.78	82.95
Shiquan-1	84.12	84.12	84.18	78.58	78.58	77.81
Shiquan-2	88.44	88.44	88.40	85.63	85.63	85.65

* KF - the Self-adaptive Kalman Filtering algorithm
WRLS - the Weighted Recursive Least-Square algorithm
SWRLS - the Self-adaptive Weighted Recursive Least-Square algorithm

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Water Pricing Under Joint Benefits: Perverse Subsidies Or Accounting For Positive Externalities

By

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Abstract: Water pricing, particularly for irrigation, has frequently been criticized on grounds that it is a subsidy to the water users, since the principle of full-cost recovery is not followed. Full-cost recovery based prices are considered economically efficient since they reduce waste by encouraging water conservation, and lead to optimal allocation of resources in the region. Much of these conclusions are arrived at by totally ignoring the joint private - public nature of benefits that result from such projects. Irrigation results in benefits to the region in terms of regional development and other activities that would not be possible without such irrigation and water supply development projects. Under the condition that such project provides joint private and public benefits, how should user fees be determined? This issue is raised in this paper using a case study of water supply projects in Southwest Saskatchewan. Major conclusion of the study is that ignoring public benefits would lead to user fees that could not be afforded by the water users. However, since economic logic suggests that under the presence of positive externalities, these external effects should be duly considered in determining user fees. Failure to ignore such externalities may result in water use being curtailed to the level that the projects would lose their original mandate for which they were created in the first place.

Keywords: User Fees, Joint Benefits, Externalities, Subsidies, Agricultural water use; Saskatchewan.

Introduction

It is now commonly accepted that the growing global water crisis threatens security, stability and environmental sustainability of many developing nations as well as regions within developed countries. Over the past few decades, there has been an increasing acceptance that the management of water resources must be undertaken by keeping value of this resource in mind. This information is of fundamental importance as the basis for rational decision-making and requires proper assessment of the resource. Management of water resources implicitly involves maximizing society's welfare through the proper allocation of the resource. Recognition of various goals of the society and attempting to fulfill them can be a challenge at times.

Water has value. This concept was recognized in the Dublin Statement (see WMO, 1992). It was stated that "Water has an economic value in all its competing uses and should be recognized as an economic good". Recognition of value of water by the Conference participants was a historical event. The value of water is perceived in terms of benefits to the society, and thus, can be very location and culture specific. Society benefits from water resource development in a variety of ways. Many of them are private benefits while others accrue to the society at large. Some of them are through the direct use of water – water for human needs, water for industrial production, water for aesthetics and recreational needs, and so on. Other roles of water may be somewhat elusive, yet tangible. Water management therefore, needs to look at all aspects of water use and its impact on the society.

In the wake of financial stringency in many developed and developing countries, cost recovery from private beneficiaries has been seen as an alternative way of sustaining current projects and / or financing future water resource development. User fees are tantamount to charging a price for water. One, however, should be cognizant of the fact that water prices (user fees) are primarily a reflection of the cost of services that are required in order to provide the water to various users; no explicit price is charged for the water itself.

Economists prefer the option of charging for water, since prices can bring forth a balance between its demand and availability (supply) at a given point in time and location or both. In addition, water pricing is seen to be desirable for another reason. According to OECD (2001), water pricing can perform two functions: (1) to insure that the service costs are completely borne by the users, allowing public water agencies to focus on actions and policies that reduce hydrologic risks and restore water bodies' environmental quality; and (2) to promote water use efficiency, narrowing the gap between private and social benefits and insuring that irrigators make appropriate use of their water resources.

In Canada, by most people, water is either seen as a free good or as a "priceless" commodity. Members of society hold different views on this resource. Some feel that water should be made available to all citizens, and should not be used for any monetary gain. Yet other groups feel that water is too valuable and should be protected at any cost. Even with abundant water in Canada, there are pockets of water shortages. Much of Canadian water resources are in regions of small demand (run-off to Arctic ocean). In developed areas, which happen to be heavily populated, pollution has significantly impaired the natural quality of the resource (Pearse and Tate, 1990). Under these conditions, two aspects of water resources are important: quality and quantity. Both are intimately intertwined and need to be considered in any water management decision. Furthermore, two other dimensions of water supply are related to the quantity issue. These are: time of availability, and degree of certainty. All these features make water management decisions complex.

Choice for Policy Instruments

Water resource management policies are developed for a variety of reasons. Most important motivations include economic, financial and social. With these motives, policy makers have a variety of choices, as listed in Table 1. At least seven types of management philosophies can be identified. These range from a total regulatory regime to an open market (with no intervention by the governments) approach. Then there are intermediate situations, including granting property rights, providing subsidies or disincentives such as taxes, either directly or indirectly. Each of these instruments has a different effect on economic efficiency and equity, therefore, different level of desirability on economic and social justice grounds. Similarly on financial grounds, the desirability of these instruments also varies widely. Two of these instruments – subsidies and water pricing, would be discussed in more details in a latter section of this paper.

Table 1. Smorgasbord of Economic Instruments for Water Resource Management and Water Projects Financing

Management Philosophy	Instrument(s)	Effectiveness for Economic Efficiency
Regulations	Controls or rationing with penalties for non-compliance	No incentive to improving economic efficiency. No incentive for suppliers to develop new technologies.
Property Rights	Contracts in perpetuity	Inappropriate for future changes in demand and supply
	License to use water	If rights are transferable, could increase economic efficiency Charge for water with no volume basis provides no incentive to conserve
Incentives: Subsidies	Government supported water works, or financial assistance to water supply agencies	Promotes waste of water through excessive use
	Low interest loans	Creates distortions in capital markets
	Payment for adoption of irrigation	May lead to mis-allocation of resources
Disincentives: Direct Taxation	Extraction charges	Appropriate for groundwater extraction; Efficiency improvements depend upon format of charges
	Betterment levies	Applied in regions such as irrigated area. Typically land based or volume of production based.
Disincentives: Indirect Taxation	Export Tax	Taxing products of irrigated agriculture results in
Privatization	Public utilities with power to price water	Effectiveness depends nature of pricing scheme
Market Approach	Pricing for water used / discharged	Flat rate: No incentive Increasing Block Rate Pricing: Encourages efficiency through enhance conservation Decreasing Block Rate Pricing: Discourages water conservation

The Prairie Farm Rehabilitation Administration (PFRA) has been instrumental in developing programs to bring stability to the southern region of the three prairie provinces during the post-depression period. Among other instruments selected by the agency, water resource development was the key measure. Many of these projects were built during the period extending from 1936 to 1960s. Although the initial objective of the water supply projects was to provide safe and stable water supply for forage and livestock, since then other uses of water have emerged. These projects have become a source of stable water supply to many farms, rural communities and urban centers, in addition to improving the quality of life in the project region(s).

In Canada, in order to reduce federal deficit and develop a balance budget, emphasis at many levels of the governments (particularly the federal government) has been on cost recovery. The

Treasury Board (see Government of Canada, undated) has raised issue of cost recovery at the federal government level. To quote:

> "Until the mid-1979s, the growth in expenditure at the federal level was financed relatively painlessly by an increasing stream of tax revenues produced by economic expansion. As economic growth slowed, expenditure growth was financed partly by deficits. More recently, federal expenditure growth has not only halted but has been reversed. In the current economic and fiscal environment, there is little chance that any significant new expenditures can be financed out of general tax. … In these circumstances, it is important to carefully examine the rationale and structure of all federal expenditures and revenues, including user charge policy" (p.5)

In the context of PFRA, the issue of cost recovery (user charge system) has also been raised by the Office of the Auditor General (OAG) of Canada (see Government of Canada, 1997). To quote, "Departments must develop their own strategies on what should be charged for, how much will be charged, and who will pay" (p. 24-22). Need to identify the nature of benefits emanating from these projects, and developing a basis for cost recovery were among various concerns raised by the OAG. This leads to the issue of what should be the charge for water, and how should one establish user fees or price for water under these conditions.

Perverse Subsidies And Water Use Charges

In economics "subsidy" is a bad word. According to Myers and Kent (2001), a subsidy is a form of government support extended to an economic sector (or institution, business, or individual), generally with the aim of promoting an activity that the government considers beneficial to the economy overall and to society at large. Subsidies are desirable if they improve society's welfare otherwise they become undesirable or sometimes called as "perverse" subsidies. One of the main roles of the governments is to steer economic development projects in the direct of welfare maximization. Private sectors would, to a certain extent, move towards this goal, but might not always undertake projects unless their private objective function is maximized first. Governments often have to encourage activities that the private market would not undertake or if undertaken, would occur at an unfavorable level or in an unfavorable manner (a situation known in economics as "less than socially optimal"). A subsidy is applied frequently to correct for these market-based distortions in resource allocation, either through monetary payments, taxes or through other transfers.

Subsidies for water resources are very common in both developing and developed countries. In Mexico, for example, assumed cost recovery from users of public irrigation systems (created at a cost of $16 billion in 1981 prices) averages only around 11% of capital, operating and maintenance costs (Bhatia and Falkenmark, 1992). Other examples of subsidized water supply are shown in Table 2. Cost recovery in United States is estimated to be 17% of the marginal cost of water supply. In some developing countries, such as Nepal, Thailand, and Bangladesh, water is provided at less than 5% of the marginal cost of supply. In many situations this has been reported to have resulted in overdrafting of aquifers, and wasteful use of water. Subsidies have also given rise to a host of other problems: chronic excess demand for water, especially through grand-scale water projects; poor operation and maintenance of water systems; inattention to scope for water conservation; among others. Repetto (1986) notes that because of subsidies, neither farmers, local governments, irrigation agencies, nor international banks are financially at risk for the success of irrigation investments, so pressure for new capacity lead to a proliferation of projects, many of them being of dubious worth. When these subsidies result in environmental degradation, one must re-examine the rationale for such measures.

Table 2. Water Prices as a Share of Marginal Cost of Supply

Country	Percentage
Israel	60%
China	25%
Egypt	20%
United States	17%
Pakistan, Indonesia South Korea	13%
Philippines	10%
Nepal	4%
Thailand	3%
Bangladesh	1%

Source: Myers and Kent (2001), p. 124

Although subsidies can be criticized as "bad" measures for water resource management, there are at least six economic reasons that could be used to support subsidized irrigation rates. These include:

(1) Where increasing return to scale in construction (decreasing average costs) have encouraged installation of a high level of installed capacity, which for one reason or more reasons is underutilized, rates at, or close to, short-run marginal costs are optimal. When viewed in terms of average cost of providing the service, it may appear that the users are being subsidized.
(2) More generally, it can be argued that the beneficiaries of irrigation include not just the farmers but also, indirectly, many others. Similarly it is possible that the incidence of benefits will lie in part with consumers of the output.
(3) Often there are major distortions in the market prices for factors of production and outputs because of government interference (import duties, export taxes, minimum wage legislation). The overall effect of these distortions is to make the financial costs to water users higher than their real (economic) costs. A subsidy is designed for the purposes of compensating for these additional costs.
(4) Low irrigation rates may be found in countries with many old-established irrigation schemes. Costs of these schemes were initially low and, because they are now fully depreciated, only operations and maintenance costs have to be covered by rates. In terms of opportunity cost of the resources, this would appear to be a subsidy.
(5) Betterment levies are sometimes placed on the increase in capital value of irrigable land. In this case it would be double taxation to levy annual irrigation rates on a full cost recovery basis. (Carruthers and Clark, 1981).
(6) Often the public sector may design projects using very expensive technology in order to reduce damage to the environment. However, the water users may not possess enough ability to pay, forcing the water agency to lower rates.

Since some subsidies could be desirable, the question then is when do subsidies become perverse. According to Myers and Kent (2001), one has to look at both types of effects of the subsidy – economic costs and environmental degradation. A subsidy to be perverse must exert effects that are adverse on both counts.

Multiple Benefits of Water Resource Development Projects

Development of water supply projects leads to a variety of benefits to the regional and external society. Some of these accrue to the users of water. If, for example, the water users are irrigators, this results in higher net farm income from the use of water, over and above their respective cost of production. If the water is used for growing forages for cattle, this may also mean increased number of cattle on farms, and result in additional stockwatering needs. Similarly, for rural domestic water users, availability of low cost and good quality water results in higher consumer surplus (cost savings, which may result in expenditure elsewhere). However, benefits of water supply projects are not limited to direct water users.

Using the Southwest Saskatchewan Water Supply Projects as an example, various benefits from a water supply and irrigation system result from the provision of water to various users plus the associated benefits from these goods to external agencies, in addition to benefits from the existence of such projects in a region. A display of these benefits is provided in Figure 1 (adapted using information provided in Pearson, Kulshreshtha and Thompson, 2000).

Total benefits from a project could arise through three types of effects:

(1) Provision of water to various users and generation of benefits to them directly;
(2) Through the existence and operations of the system as a whole or the grand system in a given region; and
(3) Benefits emanating to external groups or individuals, not directly related to water use, through the direct water users.

The first type of benefits is direct benefits of the project. Example of these would include: irrigation, stockwater, rural domestic, municipal, and recreational water uses. These benefits are typically recognized in setting user fees for various types of water uses. However, there are other types of benefits from these projects that emanate not from the provision of water, but through indirect effects of the direct water users, or through the existence (and subsequent operations) of the system. The latter would include flood control and improvement in the aesthetics of the region. The third type of benefits is a result of indirect or spillover effects of water use, commonly called the externalities, and are discussed further in a latter section.

Various system beneficiaries could be classified at two levels: One, benefits enjoyed by individuals, and Two, those enjoyed by groups of individuals or society as a whole. The former types of benefits arise from the provision of private goods, while the latter is commonly called public (or collective) goods.

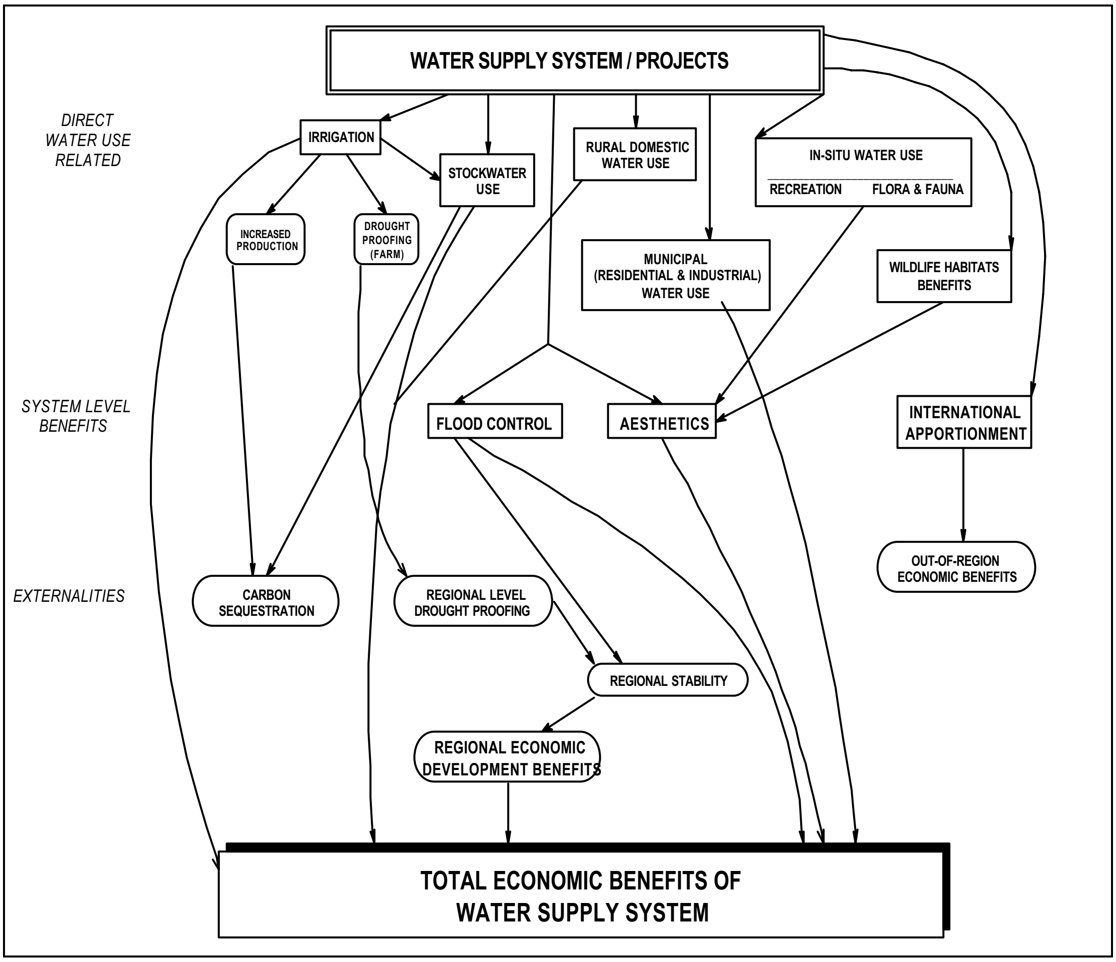

Figure 1. Benefits from Water Supply Projects

Public goods are associated with those services provided by the water supply system that have the characteristics of simultaneously providing benefits to more than one individual. Such goods are jointly (or collectively) consumed. Services of defence, law enforcement, radio and television, are common examples of public goods.
Public goods and private goods can be identified on the basis of their characteristics. According to Boadway and Wildasin (1984), public goods have two major characteristics: One, Non-excludability – where one individual user cannot exclude another user from receiving the benefit; and Two, Non-rivalry – where one individual user may enjoy any level of benefit without inflicting a reduction on the other users. Flood control and aesthetics are examples of public goods generated by water supply projects.

Based on the above two characteristics, various users / benefits of water supply projects can be divided into various categories depending upon types of goods being consumed. This classification is shown in Table 3. Some water users are high in terms of excludability as well as rivalry. Water allocated to one use is not available to other users. This is because it is possible to assign property rights to that water, and through that exclude other users. These goods are commonly called “Private Goods”, and are shown in the bottom right quadrangle of Table 3. In contrast, in the left top quadrangle, there are a number of users of water supply projects where beneficiaries cannot be excluded and there is low rivalry in terms of their use. These satisfy the characteristics of “Public Goods”.

Table 3. Classification of Benefits into Types of Goods

Level Of Excludability	Level Of Rivalry	
	Low	**High**
Low	• Regional Development • Regional Stability (through Drought Proofing) • Aesthetics • Flood Control • International Apportionment • Some In-Situ Water Uses	• Some Recreational Activities through Congestion • Some Flora and Fauna through Competition for Water • Some Wildlife through Congestion
High	• Some Recreational Activities • Some Flora and Fauna and Wildlife	• Irrigation Water Use • Livestock Water Use • Domestic Water Use • Industrial Water Use • Municipal Water Use

Externalities, Public Goods and Accounting Stance

Since water supply projects create many effects on parties beyond those that use the water provided from them, and since most of these effects are complimentary to the social welfare function of the society, positive (or negative) externalities are created. These effects, based on the above classification, are public goods, since no one can be excluded from enjoying the benefits, and one's benefit does not necessarily diminish the level of benefits enjoyed by other beneficiaries. Presence of public goods presents a problem for the private stakeholders. This is because of the fact that under these conditions it is not possible to exclude those individuals that are not willing to pay for the goods, and furthermore, they cannot be forced into paying for the benefits received. The result is that private entrepreneurs could not undertake such projects. Since some of the benefits are spilled over to other economic agents, and since there is no known way to internalize these benefits, public intervention in such projects is very commonly encountered.

In setting social desirability of a water supply project, one must choose an accounting stance. An accounting stance is merely a criterion used by the analyst to decide which costs and benefits are to be considered. Two basic accounting stances that are commonly employed are Private Accounting Stance, and Societal (or Social) Accounting Stance. In the first accounting stance, only those effects that are captured or borne by the private decision-maker (a firm or a consumer) are included. If the decision-maker is a firm, only the firm's profit level (plus any relevant non-economic factors related to the firm) is included. When the accounting stance changes to that of society as a whole, not only the effects on the private decision makers are taken into account, but impact on all other members of the society are included here as well. Thus, all externalities are captured in the societal accounting stance. However, this is subject to the scope of the society.

Selection of societal accounting stance raises another issue – which society? One has a choice of selecting anywhere from the local society to the global society. For example, in the context of

Southwest Saskatchewan Water Supply projects, one can take the accounting stance of: (1) Local region (irrigators, other farmers, rural communities, and other economic agents in Southwest Saskatchewan), (2) Province of Saskatchewan, (3) Canada as a whole, (4) Canada plus the United States River Basins connected to the projects; or (5) Global society. Each of these accounting stances would lead to a different scope of costs and benefits to be included. Thus, selection of the proper accounting stance is crucial for determination of any type of cost recovery level.

Distributional Equity and Financial Responsibility

Policy makers must decide whether or not some of the costs should be borne by people that are not directly affected by the project. Such decisions should be based on consideration of distributional equity. In other words, 'should income be shifted from others to irrigation farmers or not' is an issue that needs to be settled in political circles first. Consideration of regional development, depressed areas, chronic unemployment or underemployment, widespread poverty in a certain group, and other evidence of an undesirable distribution of income may affect the decision (Manning and Anderson, 1984).

Equity considerations also provide other avenues to the decision-makers for cost recovery. In Figure 2, revenues for water supply projects can be raised through direct or indirect financing methods. Direct financing methods can take various forms: these could be in the form of user charges, or through taxing the benefits directly. User charges can also take alternative forms – water pricing being one of the major one recommended on grounds of economic efficiency. However, output based, particularly if value of output is used, are preferred on the equity principle, since higher costs must be borne by those who have higher ability to pay. Water pricing can also take alternative forms. Flat-fees type water charges do not promote water conservation, whereas volumetric charges do. A charge based on quantity used has the considerable advantage of allocating the costs to the beneficiaries in direct proportion to the amount of their benefits, assuming that their benefits are in proportion to the amount of water used. However, if the water use per unit of benefits is different in different uses, such an approach may lead to somewhat inequitable charge for water services.

Benefits taxes are instruments that can be applied to tax the beneficiaries. The nature of these instruments might be in the form of area-based taxes or betterment levies for specific purposes, such as for flood protection, industrial development activity, among others. Indirect methods of financing include government revenues in general. These could be from general taxes, or from implicit taxes that are added to the final sale value of a commodity.

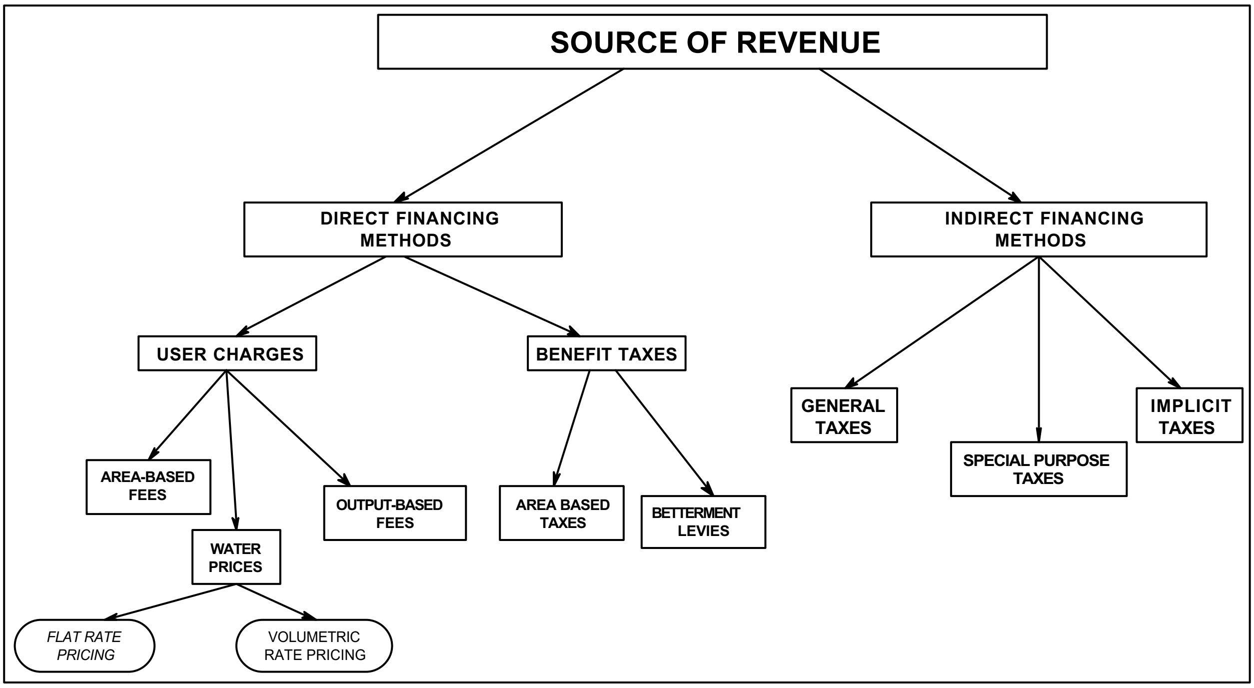

Figure 2. Financing Options Available to Governments for Water Supply Development Projects

Determination of User Charges Under Joint Public and Private Benefits

Presence of public and private benefits raises a crucial question about how should such water supply projects be financed? In economic theory, user charges are appropriate only for the private benefits. Here again, definition of benefits is limited to direct benefits. If certain water use results in significant amount of indirect benefits elsewhere, popularly called externalities of that water use, even the user charges should reflect these on the basis of equity considerations. For public benefits (benefits to members of the society with public goods characteristics), the appropriate method of financing is through government coiffures.

The above method of financing raises the question of how should one determine whether water users are being subsidized or not. The commonly used practice of comparing the cost of water supply development and direct revenues (through user fees) is not appropriate for situations where both public and private benefits exist. Such a situation is very commonly encountered in the case of water resource development projects. Furthermore, users of water creating positive externalities should be rewarded just as much as those creating negative externalities should be penalized.

Developing such user charges under the condition of private and public goods requires a careful attention to cost allocation and design of user fees / price for water. The most crucial question is that related to concept of cost, which in this context should be economic costs and not accounting (financial) costs. In the literature several criteria have been identified for determining user fees. For example, according to the World Bank (see Teerink, 1993), these include (1) cost of service; (2) ability to pay; (3) opportunity cost; (4) incremental cost; and (5) market driven. Cost of service based criteria (including incremental costs) provide a basis for determining the resources allocated to water resource development that needs to be recovered. However, under the presence of multiple users, determination of these costs to individual users becomes rather complex. Furthermore, cost-based rate design is not necessarily a conservation rate in the sense of implying conscious bias in rate design against large-volume users. The rate structure could send this message.

Ability to pay, like the previous criteria, could be applied but only for the direct water users. This raises the question of how should one handle the indirect benefits, if any, and benefits emanating from the operations of these projects that do not involve water use.

Opportunity cost is a method of pricing where prices are set equal to the value to society that could be achieved if the investment were made elsewhere or benefits realized from alternative opportunities that must be foregone. When a certain volume of water is being withdrawn, it is not available (at the same time and location) for other uses. Under these conditions, water is said to have an opportunity cost since the continued abstraction by one user reduces the amount available to another user. Over time, changing patterns of income, population, and other elements of regional growth may shift the demand for a publicly supplied good or service, such as water. This creates a rising opportunity cost. If project beneficiaries are not confronted with this opportunity cost, the publicly supplied good would tend to remain in its original use and larger economic benefits from its use in other economic (social) sectors (uses) will be foregone. Thus, opportunity cost is not merely a function of scarcity. Water may be scarce, but if there is no demand for it, it does not have an opportunity cost. In essence, opportunity cost depends not simply on the amount of water available but also on the nature of the demands on it.

Market driven pricing results in fluctuating price depending upon demand and supply. Water right for the use of water is transferable, thus shifting water use from low value to higher value uses. Again this type of system would only apply to direct water users.

Analysis of Cost of Water Supply Under Joint Private and Public Benefits

Taxonomy of Costs

Total costs of water supply project can be identified in several ways. A most commonly use framework is to first divide them into two sets: Common water supply project works and Specific costs. The first category of costs includes those costs that are related to common infrastructure needed for two or more benefits. Typically these costs relate to complex combination of structural and equipment components that are interdependent (i.e., that depend upon each other to provide full functionality of the project infrastructure for all the beneficiaries).

Specific costs are the costs of a facility that has the following characteristics:

(1) These costs are identifiable and part of the water supply project costs.
(2) Their functions are exclusively for a single set of beneficiaries.
(3) Other benefits would still occur as intended even if this facility was missing.
(4) It is not structurally integrated into the common project works.

The common water supply project works costs are further divided into joint or common costs and separable costs. Joint costs are those costs that provide two or more benefits. A separable cost is a part of the common works but is associated with a single beneficiary. An example of this may be a canal designed solely for the purpose of municipal water user, or a turbine generating hydroelectric power. Each of the common and separable costs can be further classified into two basic categories: One, fixed investment or one-time costs; and Two, operating and maintenance or variable costs.

Classification of Total Costs by Cost Category

For a given water supply system, thus, there could be five types of costs: (1) Common fixed costs; (2) Common variable costs; (3) Separable fixed costs; (4) Separable variable costs; and (5) Specific Purpose Costs. Distinction between common and separable costs, however, is somewhat unclear at times. Under these circumstances, benefit of doubt should be given to common costs. In other words, if the cost item was not specific to a single or a specific use, it needs to be treated as a joint or common cost.

Once specific purpose costs are determined, these are separated out from the total costs of the water supply project. The next step in the study methodology is to categorize various items of cost into the remaining four categories. Furthermore, if there are more than two water uses within a given system, common costs should be further categorized by the specific users. For example, if a canal is used to supply water for irrigation as well as for municipal water use, some of its costs are common to these two users. A reservoir, on the other hand, could serve the needs of recreationalists, in addition to irrigators, municipal and domestic users. Development of a fair and equitable cost recovery criterion / mechanism requires that these costs be allocated in a fair manner to the users, ideally at various levels of disaggregation.

Concept of Cost Relevant to Cost Recovery Criterion / Mechanism

The cost of providing water in a system can be measured in a number of ways. For the variable costs the concept is very simple, since these expenditures are limited to a year. However, such is not the case with the fixed costs, which could be perceived in at least four alternative manners, such as:

(1) Depreciated value at the time of developing the cost recovery criterion / mechanism;
(2) Replacement value of the facilities using the then (original) set of standards;
(3) Replacement value using present-day standards; and,
(4) Current market value or economic worth of the facility.

The first measure is the traditional way of estimating the total cost basis for cost recovery criterion / mechanism. The investment is assumed to have taken place, and the annualized cost of this investment is to be recovered through user fees. The second and third measures of cost are futuristic in nature, and present a problem for designing user fees. Unless a commitment has been made by the agency to spend this money, it is not a realized cost, and therefore, should not be a target for cost recovery. The last measure of cost is a combination of first and the third measure. It estimates the current worth of the facility by taking into account both the present state of the facility (similar to the first measure) plus the investment needed to make it conform to the replacement value with present-day standards. It may alternatively reflect the market value of assets with similar characteristics. The most appropriate basis for recovering past costs is the original cost method.

For separable cost, different items of costs that could be accounted for include: (1) Salary and payroll expenses; (2) Non-Pay Operating expenses; and (3) Minor Capital expenses. The first two items are legitimately a part of the separable cost. However, the third item could be controversial, since it may create a situation of double counting with capital costs, depending on the method of valuation used.

Methods of Apportionment of Common Costs

In the presence of common costs, in order to make clear and unambiguous decisions about cost recovery criteria / mechanisms, the basic question that needs answering is: What should each of these users be charged if they were to be based on a cost of service principle? To arrive at a fair share of total costs for a given user, apportionment of common costs is required. There are several ways to apportion common costs and results may be drastically different from each other. Furthermore, some methods may apply only under some conditions. Five methods of apportioning common costs are suggested in the literature. These are: (1) Revenue Based Principle; (2) Output Based Principle; (3) Benefit Based Principle; (4) Attributable Cost Principle; and (5) Separable Cost - Remaining Benefit Based Principle of allocation of fixed costs.

One of the most commonly used types of cost apportionment is based on the share of revenues generated by each user of the joint product. A major advantage of this type of apportionment is that it is easy to administer. However, it has two major limitations. One, if revenues are based on the rates that are in turn, based on apportioned common costs, there is some circularity in this estimation process. Two, application of this principle requires that all users be charged for the use of the product. If some users cannot be charged on account of the nature of goods produced by the system (such as public goods), this method would not lead to a fair share of apportioned common costs.

Another way to apportion common costs is to base it on the amount of water being used by each user. This method has one severe limitation in the context of allocation of costs under joint public and private benefits. It requires that all benefits from the system must be generated through use of water.

Another equally arbitrary basis for apportioning common costs is the share of benefits received by a beneficiary from the project. This method is similar to the revenue-based principle, except now one could include all beneficiaries whether charged or not. This method would however, lead to user fees more close to the ability to pay, provided all users were to be assessed some share of the total cost.

Attributable costs basis requires allocation of common cost in proportion the basis of the share of the total attributable costs. One major limitation of this approach is that quite often, common and attributable costs may not correspond perfectly, thus their use in apportionment may create distortions.

The Separable Cost - Remaining Benefits (SCRB) method apportions to each user its separable costs plus a share of the remaining common costs. After all separable costs are determined, these are subtracted from the total. The remaining costs are allocated using the following three principles:

(1) No project user should be assigned a cost that is in excess of the value of the benefits derived from the project goods;
(2) No project user should be supported by other beneficiaries; and,
(3) No purpose should be assigned a cost that is any greater than would be incurred if that use were to be supplied by the most economic alternative single-purpose project.

The SCRB follows a number of well-defined steps. More details on these can be found in Gittinger (1982), Grenney et al. (1998), and Young, Odaks and Hashimoto (1982). Some studies have criticized the use of such methods as being arbitrary. Some arbitrariness perhaps may be based on the practice in some jurisdictions (such as in United States, as reported by Le Moigne et al., 1994) to allocate more of the joint costs to "non-reimbursable costs", since these are paid by the federal government, resulting in lower water charges to users.

One of the advantages of applying the SCRB procedure for cost allocation is that it is applicable to various types of situations. Included here are situations where there are all direct water users within the water supply system, as well as to situations where there are some direct water users, while others benefit either from the spill-over effects, or through the presence and operation of the water supply project.

Illustrative Cost Recovery Level Under Joint Benefits

The purpose of this section is to develop a model of a multiple benefits generating water resource project and apply the method of SCRB for allocating cost to various users. In the next section, this model is used to demonstrate the effect of excluding externalities in the determination of cost recovery levels.

The illustrative project selected is a multiple use project. Hypothetically it is located in southwest Saskatchewan, in a region bordering with Montana State, USA. It has components of irrigation, flood control, domestic and municipal water supply, and other uses of water. Irrigation is the major use of water, through fully serviced irrigation projects (under federal jurisdiction), storage of water for delivery to the provincial irrigation projects, as well as use of water by private irrigators near the water bodies or canals. In addition, water is used for urban water use, recreation, domestic and livestock (stockwater) water needs, and for wildlife purposes (through creation of wildlife refuge near water bodies). The project also provides flood control benefits to the region. It is also postulated that the water supply system has increased the economic security of the region (through regional development and economic stability, including drought proofing).

Application of Separable Costs – Remaining Benefits Procedure

Application of the SCRB to a given water supply project requires a number of pieces of information to be collected, including the followings:

(1) Benefits to various water users;
(2) Total costs of the system, further broken down into specific purpose, common costs, and separable costs;
(3) Cost of the project if it were to be built for a single purpose.

The procedure of allocating costs to various beneficiaries (water users) is shown in Figure 3. In this figure, for the sake of space considerations, the number of beneficiaries is restricted to three – agricultural, recreational, and external (indirect). The procedure starts with the identification of specific purpose costs. Once these are removed for each of the three users, procedure then concentrates on the other two types of costs – common costs and separable costs.

In the procedure of the allocation of common costs, capital costs are converted into annualized costs. This requires further information on the length of time a project (and its various components) would be able to serve at the current level of investment, and at the same time producing the same level of benefits.

Special attention needs to be paid to the last set of information -- Cost of the project for single user. For some complex systems may require detailed assessment of the nature of the system that could be designed for a single type of water use. For example, if a system includes irrigators and urban water users, this cost assessment would involve assessment of two elements of costs:

(1) Detailed design for the capacity of the system, as it would be for one or the other use (for urban water use, the capacity of the system would be smaller); and,
(2) Cost of additional infrastructure that would be required for each of the uses.

The allocation procedure involves a number of steps. The first step is to obtain the total costs and divide them into separable costs and common costs. Each of these is converted into present value. Alternative cost for generating each benefit is then established, and converted into present value as well. Information on benefits is treated in a similar manner. The lesser of either the benefits or single purpose cost is called the "justifiable expenditures" for each water user. Separable costs are deducted from the total remaining justifiable expenditures. The total remaining common costs are then allocated to each water user according to the distribution of the total justifiable expenditures. This becomes the share of the common costs attributed to a given water use.

Water Use and Other Details on the Illustrative Project

Details on the types of uses and level of water intake are shown in Table 4. Major use of water in the entire system is for irrigation, where 76% of the total water (excluding international apportionment water use) is used for this purpose. Water left in the rivers and tributaries to flow to USA is governed by legal treaties between the two countries and administered by the International Joint Commission. This raises the interesting question about how should

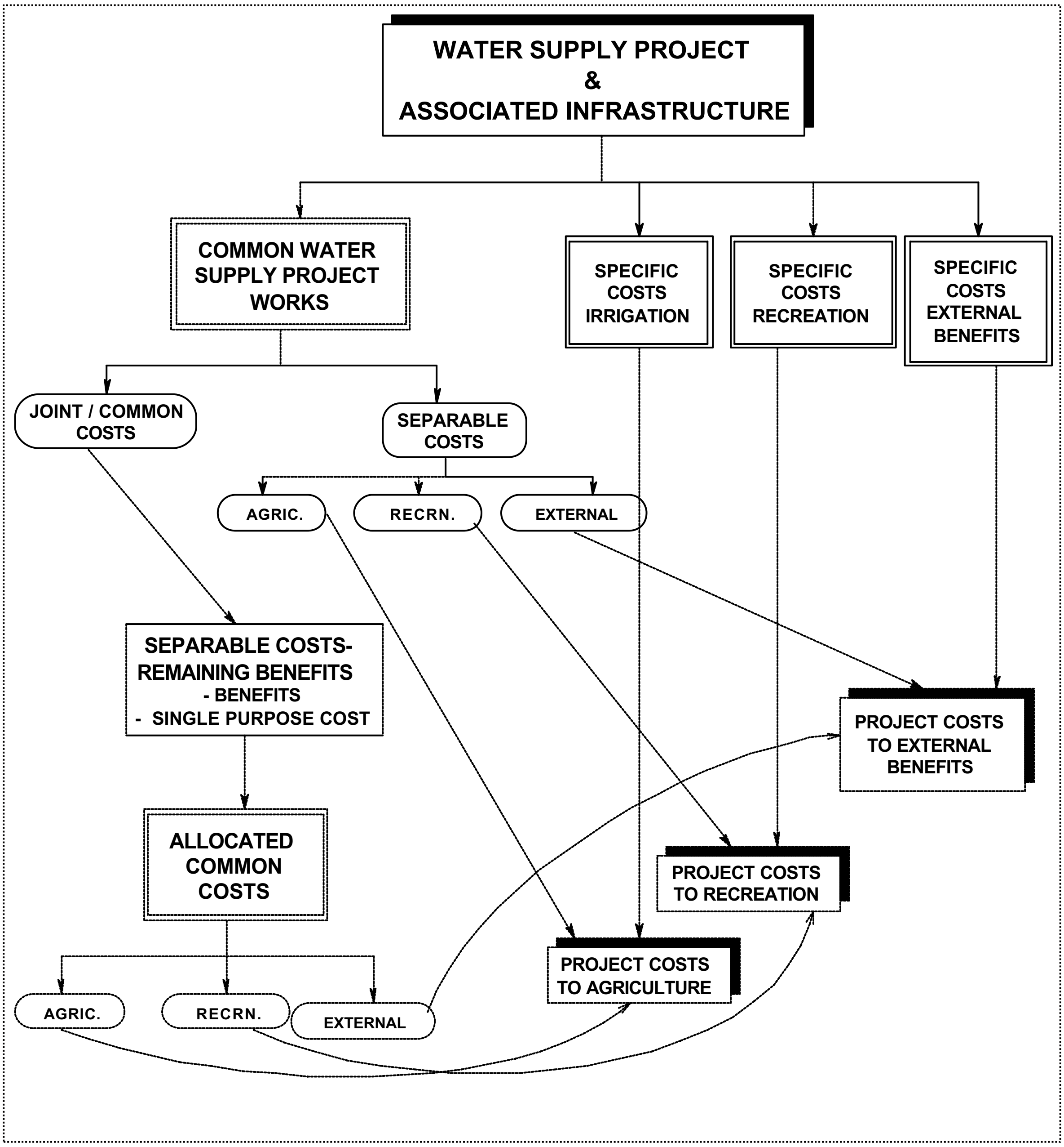

Figure 3: Methodology for Allocation of a Project's Costs under Multiple Beneficiaries

international apportionment water use be treated. If one assumes that structures and other investment incurred are required for such apportionment, then the quantity of water used should be included. If one assumes that the structures in the project region were developed for meeting other domestic water uses, (and not international apportionment water use), then such costs should not be included. This question should be given a special attention in any future application of this methodology.

Classification of water users and resulting benefits was done on lines suggested above. Various types of beneficiaries were divided into two basic groups: Those enjoying Public goods, which included international apportionment, flood control, and economic security; and those enjoying Private goods, which included irrigation, urban and domestic water use. However, a third category was developed – Regulated Public Goods. These goods include private benefits by are somewhat regulated by the public agencies. Included here are activities such as: recreation and wildlife related benefits (consumptive and non-consumptive). Some of these goods are un-priced, while water used for irrigation and domestic purposes creates further externalities (economic development impacts).

Estimation of Cost

Total cost of the water supply system for the illustrative case was estimated by estimating various capital and operating costs. Capital costs were converted into annualized costs using an interest rate of 5% and the respective life of the project. This total cost of the project was estimated at $732,100 per annum. At the very outset a specified item of cost (which are unrelated to the water use) was netted out. This cost was related to administration. This cost was estimated to be $5,000 and was over and above the cost noted above. The remaining cost for water supply system, as shown in Table 4, are now $727,100 per annum.

For the illustrative system, estimates of following types of costs were made for various water users and / or beneficiary groups: Separable Capital costs, and Separable Operations and Maintenance costs. Distribution of the total cost into separable and common costs is shown in Table 4. Total annualized common costs are estimated to be $659,400, in addition to the total separable costs of $67,700 per annum.

Once the common costs have been identified, the next step is to allocate them in a fair and equitable manner to various water users and / or beneficiaries. The procedure of Separable Cost - Remaining Benefits was used. This procedure, as noted above, requires two additional sets of information: One, cost of building the project for a single purpose only, which is provided in Column 4 of Table 4; and Two, benefits from each of the water uses. The former was based on expert opinion.

Table 4: Information on the Illustrative Project in Southwest Saskatchewan in Year 2000 Dollars

Particulars	Water Use in dam^3	Annualized Separable Cost	Cost of Single Purpose Project in $	Benefits to Society in $
Private Benefits				
Irrigation	11,750	$50,000	$400,000	$638,000
Urban	550	$2,000	$100,000	$33,000
Domestic and Stockwater	2,000	$5,000	$100,000	$33,000
Drought Proofing for Farmers	0	0	0	$58,750
Sub-Total Private Benefits	**14,300**	**$57,000**		**$849,750**
Public Good (Regulated)				
Wildlife	1,000	$500	$10,000	$110,500
Recreation	0	$200	$200,000	$60,000
Sub-Total Public Goods (Regulated)	**1,000**	**$700**		**$170,500**
Pure Public Goods				
International Apportionment	10,000	$5,000	0	$5,000*
Economic Development	0	0	$3,000,000	$1,789,470
Flood Control	0	$5,000	$200,000	$10,000
Sub-total Pure Public Goods	**10,000**	**$10,000**		**$1,804,470**
Total	**25,300**	**$67,700**		**$2,824,720**
Annualized Common Costs		$659,400		
Total Annualized (Common and Separable) Costs		**$727,100**		
Share of Private Benefits incl. Economic Development Benefits				30%
Share of Private Benefits excl. Economic Development Benefits				82%

* Since international apportion benefits to the project region are difficult to estimate, they were equated to the level of cost incurred by the water supply agency to perform these services.

Estimation of Benefits

Benefits were estimated using the method of consumer and producer surplus, as commonly followed for such estimations. All benefits except those for international apportionment were valued for the hypothetical project. Since benefits of international apportionment of water are somewhat controversial, these were equated to the level of costs incurred by the water-supply agency. These benefits are shown in the last column of Table 4. Private benefits were also estimated using the same procedure. The total value of private benefits estimated at $849.75 thousand, which is 82% of the total benefits, if economic development (externalities of water use) benefits are not included, and 30% if these are.

Estimation of Economic Development Benefits

Estimation of economic development impacts was undertaken using standard input-output analysis. A model of the Southwest Saskatchewan was developed using 1996 transactions for the provincial economy. The non-survey method using location quotients was applied to regionalize the economy into project region and rest of Saskatchewan. Economic development benefits were estimated as the value of additional regional economic activities generated by the existence (pursuing) a given water use / related activity. This value was measured as new household income generated in the region. For each sector both indirect and induced linkages were included. In addition, for both of these types of linkages, backward and forward effects on economic activities were included. Forward effects include those activities that use products produced under a direct water use activity. These could be first-round or second-round forward linkages. Feeding of forages produced under irrigation to raise cattle is the first–round forward link of irrigation. Processing of these cattle to produce meat and meat products is the second-round forward linkages of irrigation. In this study all these linkages were included.

All private beneficiary groups were included for estimation of indirect (through purchase of inputs for their respective operations) and induced (through the purchase of consumer goods by workers and entrepreneurs) impacts of their economic activities. The value of water for economic / regional development was estimated to be $146.22 per dam^3 of water intake, or $70.73 per dam^3 of water stored in the system.

Estimation of Cost Recovery Level

Determination of user fees requires an understanding of a fair and equitable level of total cost for a specific beneficiary group. In this study, this level of cost recovery was equated to the level estimated using the SCRB procedure. Two simulations were made, one using the value of economic development on the basis of units of water intake from the water supply system, and the other using the value per unit of water stored in the system. These simulations are called, respectively, ‘Simulation Low’ and ‘Simulation High’.

Estimated shares of common costs for various public (pure and regulated) and private goods are shown in Table 5. The total cost of the system under the two scenarios remains unchanged, as one would expect. However, its distribution between private and public goods is different. Under the ‘Scenario Low’, share of the total cost to private users is estimated to be $212 thousand per annum, some 29% of the total. However, as one uses the higher level of contributions of water supply project to region’s economic development, this share reduces to $144 thousand, or almost 20% of the total.

Table 5. SCRB Based Cost Shares for Various Beneficiary Groups, Alternative Scenarios

Water User / Beneficiary Group	*Simulation Low*		*Simulation High*	
	Allocated Cost (10^3 \$)	**Cost per dam^3**	**Allocated Cost (10^3 \$)**	**Cost per dam^3**
Irrigation	155.6	\$13.45	109.1	\$9.29
Drought Proofing	15.9	\$1.35	8.9	\$0.76
Domestic & Stockwater	33.4	\$17.05	20.9	\$10.46
Urban	7.4	\$13.71	5.0	\$9.15
Total Private Goods Beneficiaries	**212.1**		**144.0**	
Wildlife	3.3		2.1	
Recreation	16.4		9.3	
International Apportionment	5.0		5.0	
Economic Development	483.9		561.0	
Flood Control	6.4		5.8	
Total Public Goods Beneficiaries	**515.0**		**583.1**	
Total	**727.1**	**\$28.74**	**727.1**	**\$28.74**

Effect of Excluding Economic Development Benefits on Cost Shares

Let us assume that policymakers do not consider economic development benefits as legitimate part of the benefit bundle. What would be the impact on the private cost recovery level, and thus, on the user fees for private water users? This is summarized in Table 6. Under this scenario, private cost recovery level would have to increase significantly. The increase is estimated to be from \$212 thousands per annum under the situation of economic development benefits included to \$640 thousand per annum, when these are not – an increase of 202%. In contrast, public goods costs would decline by 83%, from \$515 thousand to \$87 thousand per annum. Under this scenario, private users would have to bear 88% of the total cost, as against only 29% under the 'Scenario Low'.

The increased burden resulting from ignoring external benefits for a water user can be calculated as the Rent Recovery Index (RRI). A RRI is calculated as follows:

RRI = Total Cost Recovery Level / Total Benefits from the use of Water

As shown in Table 4, total benefits from using water for irrigation is \$638 thousand per annum. The RRI under 'Scenario Low' is 0.24. This index rises to 0.70 under the Alternative Scenario. Raising the RRI level would have significant impact on the use of that water for that purpose. Overtaxing benefits of water users may result in loss of those uses, and may defeat the purpose the projects were built for in the first place.

Table 6: Comparison of 'Simulation Low' with Alternative Scenario (with Economic Development Benefits excluded)

Water User / Beneficiary Group	Cost Share in 10^3 $ under		% Change over Scenario Low	Per Unit Cost ($/dam^3)	
	Scenario Low	Alternative Scenario		Scenario Low	Alternative Scenario
Irrigation	155.6	446.2	186	$13.45	$37.98
Drought Proofing	15.9	59.7	275	$1.35	$5.08
Domestic & Stockwater	33.4	111.7	234	$17.05	$55.84
Urban	7.4	22.3	201	$13.71	$40.58
Total Private Goods Beneficiaries	**212.1**	639.9	202		
Wildlife	3.3	11.2			
Recreation	16.4	60.9			
International Apportionment	5.0	5.0			
Economic Development	483.9	0			
Flood Control	6.4	10.1			
Total Public Goods Beneficiaries	**515.0**	87.2	-83		
Total	**727.1**	727.1	--	**$28.74**	**$28.74**

Conclusions and Implications for Rate Making

Key conclusions arising from the analysis for the setting of user fees from this study are as follows:

(1) Public benefits should be considered in the establishment of private user fees, otherwise there is a risk that fees will exceed private benefits received, and my create situations of excess capacity on water supply projects.

(2) Private water uses should not be expected to cover the full costs of water development and operations in the multi-objective nature of the projects.

(3) Estimation of burden on water uses through estimation of Rent Recovery Levels is an appropriate measure of equity and fairness. This consideration should be a one of the criteria for planning water supply projects, not after they have been built.

(4) Irrigation user fees should be designed to encourage increased productivity and greater economic efficiency in water use for this purpose. Furthermore, these charges should include benefits from both irrigation and drought proofing, since both are inseparable at times.

(5) The SCRB methodology provides useful information for user fee planning. It provides a fair and justifiable basis for costs that should be recovered, establishes the domain for such user fees and is sensitive to the inclusion of certain types of water users and their respective benefits in the calculation of cost recovery.

(6) Calculation of subsidy to water users must also take into account other direct revenues generated by the water users, as well as allowance for positive externalities.

Using economic efficiency maximization and equity criteria, under joint public and private benefits, water charges should not ignore public benefits. Ignoring these externalities would impact the cost recovery level perhaps to the level that it might impact the water use level. This may result in not meeting the original mandate of these projects – the purpose for which these were built initially. Under these conditions, if full cost recovery is the goal of the water supplying agency, and if optimum efficiency of water use is achieved by equating the marginal value product of water to the marginal cost of "producing" water, a water price high enough to cover fixed costs may restrain water use below the optimum level. A better policy might be to assess the variable costs through water quantity charges and fixed costs through other charges. Therefore, if there is an excess capacity year round, and if fixed costs could be considered sunk costs, user charges may be based on the marginal cost of the project, which now becomes the operating and maintenance cost of the system.

As noted above, there are three functions of prices: economic, financial, and social. The social function is a mixed bag of policies and actions whereby water pricing may be used to promote income redistribution, economic stability, or to develop backward areas and encourage investment by beneficiaries (Carruthers and Clark, 1981). However, for policy making social goals are equally, if not more, important.

Cost recovery should be a criterion in planning water supply project. The change in the policy of full cost recovery after projects have been built would lead to more misallocation of society's resources.

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UK and Global Insurance Responses to Flood Hazard

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Abstract: In this paper, the risk of flood is examined from several perspectives; first, there is an exploration of the essential requirements for a sustainable insurance market, and the importance of adverse selection and the vicious circle.

Then there is an overview of the different private insurance solutions to flood risks around the world. These fall into two categories, the 'option' system and the 'bundle' system. From this it is very clear that only the 'bundle' system is sustainable, and it is the only system which has had success in penetrating the market.

In many countries the State has taken a role in providing compensation to its citizens after a disaster, and again the approaches of different governments have been compared, and some of the problems identified. The role of the State is very important, but if it wants private insurance to flourish, it needs to make a conscious decision <u>not</u> to provide compensation to its citizens but to concentrate on renewing infrastructure and making sure that insurance is available and affordable for all.

Insurance is a very cost-effective way of spreading risk, and insurers have developed techniques to help them to measure and manage risks. One of these, the 'risk triangle' (developed by the author) is explained, and examples given of how it can be used in practice.
The impacts of climate change will be strongly felt by the global insurance industry; not only is the growth in catastrophe claims costs likely to continue at an ever increasing rate, but also the demand for catastrophe insurance cover from citizens, commerce and the State. Some insurers around the world are actively involved in research work to mitigate climate change, find cost effective adaptation mechanisms, and develop new products to meet the growing demand for cover.

The insurance industry cannot solve these issues on its own, and it needs dialogue and where possible, partnership with the State and the research community. Examples of experience in the UK are given. Insurers can bring data, expertise on risk management, risk transfer, and claims handling expertise to the table. The State can establish the conditions for a sustainable market in the face of a growing risk.

The Canadian Institute for Catastrophic Loss Reduction sets an excellent example for the rest of the world to follow. As society enters a period of greater uncertainty about natural hazards, the protection of lives and property needs such solutions.

Insurers around the world need to move from a passive approach, waiting for the claims to come in, to an active approach, where they are pro-actively trying to understand and control their futures. In the UK an interesting situation has emerged this year. Flood insurance is so

widespread that it is now taken for granted by the community at large. The insurance industry now threatens to withdraw cover from high hazard areas unless the government takes firmer action to control the risk.

Introduction

The severe weather events seen around the world in the last few years are consistent with the scientists' predictions about climate change. For insurers, faced with other factors which increase claims costs, such as higher sums insured and more people choosing to live in hazardous areas this presents a growing challenge.

Many around the world are talking about the need for a more proactive approach from the insurance industry to use its expertise to manage the growing risks, and to enlist the help of the research community and government to understand, quantify, and manage these risks. Canada, with its Institute for Catastrophic Loss Reduction is in many ways leading the way.

In this paper, it is not possible to adequately cover all types of covers or perils, so the author has chosen to concentrate on general principles from the point of view of flood insurance. Flood is already a major cause of losses to life and property, and is likely to be an even greater cause of losses in the future due to climate change.

Language Problems

In recent years, insurers have increasingly found themselves talking to academics and government and have learned that each talks in a different language. Even within the insurance industry most practitioners are too busy with day to day problems to actually sit back and think about the general principles of what they are doing.

The following notes were designed to help to explain insurance to non insurance audiences, but they may be of interest to experienced insurance people simply because they attempt to portray the essentials of the business in a non traditional way.

How Insurance Works

For a risk to be insurable, there are a number of requirements. The author has created the Mnemonic "BASIC MUD" which sums these up:

B Big enough "book" of business, i.e. collection of risks for a statistical spread
A Adverse selection minimised through good knowledge of each risk.
S Sustainable over a number of years for various future scenarios so the risks can be spread over time and reserves built up.
I Information readily available from reliable sources about hazard, vulnerability, exposure and claims
C Consistent with existing insurance practices, systems, customs and law.

M Moral hazard low and manageable.
U Uncertainty about the potential loss.
- At least one of the following must be uncertain:
Will it occur?
When will it occur? - Or

How much will it cost?

D Demand for insurance must exist (or have potential to be created) and must be effective, i.e. there must be enough customers prepared to pay the price that insurers need to charge for providing sustainable insurance.

Adverse Selection

Where the customer knows more about his risk than the insurer, or where the insurer, through ignorance, incompetence, regulation, or market forces has failed to recognise the extent of the risk with adequate premium levels, the customer can select against the insurer. With flood insurance only the customer in the flood risk areas will want to insure for flood, for example.

The Vicious Circle

Commodity business such as household and motor insurance is largely price driven and based on statistical analyses. Commercial business such as fire or liability cover for factories and offices is written on a more individual basis. For either type of business, accurate underwriting is necessary to avoid the vicious circle. The circle works like this:

Premiums are too low for the risks insured
Losses are incurred
Across the board increases in premium are applied.
“Good” risks, for example householders who are careful and have a low propensity to claim, or businesses which are well managed, will find cheaper premiums elsewhere, (or will chose not to insure at all) and will cancel their policies.
Because the increases have been inadequate for bad risks, more of these will be attracted, or retained, so a higher proportion of the book will be “bad” risks.
Losses are incurred
Further across the board increases in premium are applied.
The cycle continues until all the good business has gone.

The Virtuous Circle

Premiums are too low for the risks insured
Losses are incurred
Across the board increases in premium are rejected; instead, highly selective rating increases are applied, and risk management advice is given to policyholders to help them reduce their risks.
“Good” risks, for example householders who are careful and have a low propensity to claim, or businesses that are well managed, will be encouraged to stay.
“Bad” risks will find cheaper premiums elsewhere and will cancel their policies. Alternatively the underwriter will introduce risk management measures and policy conditions to improve the bad risks.
A higher proportion of the book will be “good” risks.
Profits are made
Further very selective increases in premium are applied, together with discounts for good risks, for example a no claims bonus.
The cycle continues until all the “bad” business has gone, or has been improved.

Case study

Due to a statistical error, one major insurer charged much lower rates than the rest of the market for a particular type of risk. The underwriters were aware that their rates were out of line with the market and did not fully trust the picture being given by the statistics. Therefore, while they continued with the low rates, rather than accept all business coming their way (as some senior managers wanted), they became very selective about which risks they accepted. For years the insurer attracted good risks from other insurers until when the error was finally spotted, it was no longer a problem because the claims experience had improved so much that the low rates were now justified and the book was making a healthy profit.

Options and pitfalls of private insurance solutions

From studying two comparisons of a sample of countries around the world (Swiss Re, 1998 and van Schoubroeck, 1999) it seems clear to this writer, that there are really only two types of private insurance for residential properties, the 'option' system and the 'bundle' system. These are illustrated from the point of view of flood cover.

The Option System

Under this system, insurers agree to extend their policy to include flood on payment of an additional premium. This system can be found in Australia (Queensland and Northern Territories only), Belgium, Canada, Germany, and Italy.

There are a number of problems with this system. The biggest is adverse selection. Insurers tend to select against customers by only making the cover available in areas they consider to be safe, while customers select against insurers by only buying it in areas they deem to be risky. The result is that cover when it is available at all, is expensive, and has very low market penetration. From the point of view of the BASIC MUD rules, it is unlikely to be sustainable.

The Bundle System

In this system, cover for flood is only available if it is 'bundled' with other perils, such as storm, theft, earthquake, etc. This system is used in: Israel, Japan, Portugal, and the UK.

Insurers have the freedom to charge differential rates, but excessive rate increases can be mitigated because the risk is not only spread over time, but across perils, and across postcodes. People living in areas safe from flood still have to buy flood cover, if they want to get earthquake cover, for example, and vice versa.

This system seems to produce universally much higher market penetration, ranging from 40% in Japan to 95% in the UK.

While the opportunities for adverse selection by customers are minimised, there could still be some 'cherrypicking' by insurers.

In the UK there is a practice amongst finance houses that lend money to those wishing to buy a house, to insist that the house be insured in order to protect their collateral. These finance houses will usually arrange block policies with a preferred insurer who then has to accept any property his principal decides to lend money on. Recent changes in the rules means that the individual does not have to insure under the block policy and some insurers are actively encouraging such borrowers to move their insurance to them. They only offer this encouragement of course, where the borrowers live in a safe area, and ultimately there could be a vicious circle situation for the finance house.

The role of the State in the compensation of flood victims

Analysing the same sources as in the previous section the writer has concluded that, apart from the USA, which has a rather different system, there are three categories of state involvement in compensation for flood victims, and these are outlined below. First, however a general point needs to be made; there seem to be no examples of a State deciding to arrange for reinsurance cover from foreign reinsurers, all the costs are kept within the boundaries of the country. This could be dangerous if there is a major catastrophe or series of catastrophes because the State may find itself in financial difficulties, or at the very least find it difficult to attract capital investment in the future without some element of compulsion, such as a levy or insurance tax.

Reinsurance offers a very cost-effective way to spread the risks across the economies of other countries so that if one country is hit by disaster, other countries automatically step in with support.

<u>No state compensation for citizens</u> (although there may be grants for infrastructure)
Argentina, Germany, Israel, Japan, Portugal, UK

This causes severe problems for those where insurance is not available or is not affordable. Such people are often the hardest hit when a flood strikes, and the resulting stress and other health consequences could seriously affect the economy.

Procedures to provide compensation in hardship cases
Australia, Canada, and China

This is a pragmatic solution, but not necessarily the best. The State may not be well geared up to assess how much compensation to pay or to administer it efficiently, whereas insurers have the systems in place to pay out fair levels of compensation. Also some citizens might regard such compensation as ‘charity’ and be too proud to accept it.

Compensation only by decree after the event
Belgium, France, Italy, and Spain

This can be dependent on the whim of a politician who could be influenced by many other issues, not all entirely objective. The main effect is that while such a scheme can be very expensive for the State, the citizen is never sure in advance if he will be protected, and may be reluctant to invest in his property if he thinks it may be flooded.

The role of insurance in risk management

The World faces five major global risk issues;
Population growth, with consequent strains on natural resources
Degradation of soil and land due to erosion, logging, and over cultivation
Loss of Biodiversity. Flora and fauna that might have great value to future generations is being lost.
Water shortages and pollution, leading to famine and, potentially, war

Climate change, leading to sea level rise, and more frequent and severe natural disasters, as well as the possible spread of diseases into new areas, and loss of life from heat stress factors.

As these risks become more severe, people will need to find ways to adapt to a changing world and ways to mitigate the adverse effects on life, property, and the environment.
Of all the risks shown above, insurers are most concerned about climate change, because they will be in the front line. If it is accepted that global risk is increasing, then it becomes increasingly important to understand the components of risk. In the past, with a stationary climate, insurance underwriters could use historic loss data as a guide to future losses. With climate change and the desire of insurers to expand into writing risks in new territories, or writing new types of insurance products, historic loss data in itself is no longer a reliable guide to the future. A new analytical approach is needed. One approach which has been used for some years by insurance catastrophe modellers in Europe is the concept of the 'Risk Triangle' (Crichton, 1999).

The Risk Triangle

The hypothesis is that one should think about "risk" as the area of an acute angled triangle. The sides are represented by "hazard", "vulnerability", and "exposure". If any one of these sides increases, the area of the triangle, hence the amount of the risk, also increases. Conversely, if any one of the sides reduces, so the risk reduces. Risk is therefore a combination of the interaction of hazard, exposure, and vulnerability.

Perhaps an example will make this clearer. Imagine a building site with Fred standing on scaffolding with a hammer.
What are the chances of Fred dropping the hammer? (Hazard)
What are the chances that Dave will be passing underneath at that
precise time and be struck by the hammer? (Exposure)
What are the chances that Dave will be wearing a protective helmet?
(Vulnerability)

It is even possible for a perceived risk in itself to result in losses, for example property on the edge of a cliff could suffer a loss of value due to the risk of it falling into the sea, without the event actually happening.

The Risk Triangle concept is based on the following definitions:

1. Risk is a potential loss, the occurrence, or the size of which, is uncertain.
2. Risk depends on hazard, vulnerability and exposure. If any <u>one</u> of those elements is missing, there is no risk.
3. Hazard refers to the frequency and severity of an event or the severity of a source of danger that may cause a loss.
4. Vulnerability measures the extent to which the subject matter could be affected by the hazard.
5. Exposure is the accumulated value and proximity of the subject matter.
6. Subject matter is the life or health of people or animals, or the property, data, or environmental assets that are under consideration.

Global catastrophe losses for insurers have shown a huge increase in recent years (see graph). This is not all due to climate change; certainly the hazard seems to have been high in the last decade with many more storms and floods, and while this is consistent with climate change, it was only recently that the scientific community have been prepared to say that climate change was the cause of so many events. The problem is that it is not just hazard that is increasing, exposure is increasing as wealth increases and as more people want to or are forced to live in more hazardous areas such as coastlines. Vulnerability is also increasing, as our society becomes more complex and inter-dependent.

So, the argument goes, if risk is to be managed, the most effective way is to manage each of the three components of risk so far as is possible, because any reduction in any of the components will reduce risk. The first component, hazard, is perhaps the hardest to manage.

Hazard

The Working Group I (WGI) contribution to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) "Climate Change 2001:The Scientific Basis" was published earlier this year. The full report, which runs to over 1000 pages, has been over three years in production and is the work of 123 Lead Authors from around the world. They in turn drew on 516 Contributing Authors. The report went through extensive review by experts and governments. In line with the IPCC Principles and Procedures, after line-by-line consideration, the governments unanimously approved the Summary for Policymakers of the report and accepted the full report.

The report shows an increase in severity for nearly all the projected impacts of climate change, including global warming and more extreme precipitation events, almost all caused by increases in greenhouse gas (GHG) emissions. It makes disturbing reading.
Now it could be argued that insurers cannot do anything about climate change, but that would be wrong. More than 80 insurers around the world have signed up to a Statement of Environmental Commitment and a core group have been actively lobbying governments for some years for tougher controls on GHG emissions. These insurers recognise that they are in the front line when it comes to climate change impacts.

At another level, insurers have been lobbying in the UK for greater spending on flood defences to mitigate the flood hazard, and have been funding various research projects to quantify the hazard from flood and other natural perils, largely prompted by their concerns over climate change.

One of the problems they have encountered is that scientists can sometimes find it hard to recognise that some of the answers may lie outside their own discipline, and multidisciplinary research is still relatively rare, at least in the Earth sciences in the UK. Insurers in the UK have been trying to address this through a research initiative funded jointly by a consortium of insurers and the State, which is aimed at linking science and insurance. The insurance input has guided scientists along paths which lead to practical benefits, and has encouraged a more multidisciplinary approach to solutions.

The partnership solution

It is clear that international experience shows that the ‘bundled’ policy concept reduces adverse selection and achieves much higher penetration rates. However in the face of increasing uncertainty about future climate, for such covers to be sustainable there needs to be a partnership between private insurers and the State. To illustrate this, the risk triangle has been used to show some examples of how insurers are working with the Governments of England and Scotland and their agencies to find ways to reduce flood risk.

Hazard

Hazard can be reduced by better flood defences, not necessarily spending more, but improving the spending priorities. The Association of British Insurers (ABI) has funded major research on the condition of the sea defences in England and also on inland flood issues and made the findings available to government (Crichton and Mounsey, 1997). In some cases, there have been jointly funded research projects. These have helped to identify the areas where new defences are needed, or where maintenance work is required. All of this costs money, a lot of money, but the State has to balance spending on flood defences with other demands such as schools and hospitals.

The fairest way to assess priorities is a cost benefit appraisal; the damage which would be saved by having a flood defence can be calculated if cost figures for flood damage are known. Insurers are in an excellent position to collect data on flood claims costs to assist the State with such appraisals.

For the Sydney floods in 1986, the Canberra Centre for Resource & Environmental Studies produced a data collection form for loss adjusters to collect information on types of properties affected by the floods and the costs. A similar form was introduced in the UK some years later (Crichton, 2001). In the UK, it is called the FASTER form (Flood and STorm Event Report) and it has been used to collect data from 25 insurers on thousands of UK floods since 1993. These data are held in the UK National Flood Insurance Claims Database maintained at the University of Dundee, and tables have been published showing the average losses to be expected for different property types for different levels of flood (Black and Evans, 1999). These data could potentially be used to supplement the comprehensive academic database held at the Middlesex University Flood Hazard Research Centre to help review priorities on flood defence spending, as well as help underwriters assess their risks.

This partnership approach could result in a more active role for insurers; if flood insurance reached a reasonably high penetration, the State could consider a levy on insurance premiums to pay for additional flood defences. Insurers would recognise that in the long run this would reduce claims costs, and might well be supportive in a partnership context, - provided the insurers had a say in where the defences should go.

Vulnerability

The data referred to above are also potentially useful in identifying which types of buildings are most vulnerable to flood damage. If insurers were in partnership with the State, they could go further and actually have input into future building regulations to ensure that new buildings in flood hazard areas used more resilient materials and designs.

A more controversial next stage, which again would require consultation and partnership with insurers and a reasonably long lead in time, say five years, would be to make the new regulations retrospective. This would mean that when an insurer is repairing flood damage, it would be required to use more resilient materials and make changes in the design of the property where possible. For example if a floor needs replaced, and the ceilings are high enough, why not build the new floor 300mm higher? The long lead in time would be needed to allow insurers to adjust their premium levels to cater for the short term increase in claims costs, but in the long term, claims costs should fall and result in reduced premiums.

An effective flood warning system can reduce vulnerability significantly. A warning given around two hours before the flood can mean that up to 50% of the contents of a typical house can be saved from flood damage. A good flood warning system should therefore be encouraged. Again, insurers could club together to help to fund it, and they could use their 24 hour telephone helplines proactively to assist with disseminating warnings and giving advice, not just to their own customers but to everyone.

Exposure

In the UK, planning authorities decide whether or not a new development is acceptable. In Scotland, the National Planning Guideline for flood specifically calls for local authorities to establish 'flood appraisal groups' to consult with a representative of the insurance industry as to the flood insurance implications of their planning strategies. This has resulted in such planning strategies generally being tightened up when it comes to development in flood hazard areas, and planners now follow an 'insurance template' showing what levels of hazard are acceptable to insurers for different types of development (Crichton, 1998).

The UK Insurance Template

A big problem that has been encountered is that the State has hitherto had a fairly arbitrary and basic approach to setting standards of protection. In the UK the State has three levels of protection, for flood defences. For central London, (including Parliament!), the standard is 1,000 years, for the rest of the coast around England, the standard is 200 years, while for everywhere else, the standard of protection ranges from 20 to 100 years. The insurance industry has supplied local planners with an 'insurance template' (Crichton, 1998) which shows what level of protection is needed to enable it to provide flood cover at normal terms. The essentials of this template are reproduced below.

Category One - Strategic Sites

Facilities which must continue to function in times of flooding, for example, emergency services, hospitals, electricity supplies, telephone exchanges, mobile telephone and broadcasting transmitters, and emergency control centres.

Such developments should not be permitted in flood hazard areas unless very high standards of local defences can be guaranteed.

Category Two – Residential

Facilities where the public sector is prepared to provide a high standard of flood defences where necessary. The minimum level of protection which would enable insurers to offer cover at normal terms for residential properties is at least a 200 year return period up to the year 2050, after taking climate change into account.

The standards proposed by insurers are as follows:

Type of housing	Standard of protection return period
Sheltered housing, and homes for the disabled and elderly	1,000 year

Children's homes, boarding schools, hotels, hostels	750 year
Basement flats	750 year
Bungalows without escape skylights	500 year
Ground floor flats	500 year
"Flashy" catchments (little or no flood warning available)	500 year
Bungalows with escape skylights	300 year
Caravans for seasonal occupancy only, provided adequate warning notices and evacuation systems are in place	50 year
All other residential property	**200 year**

In each case up to the year 2050, taking climate change into account.

Most Scottish local authorities which have active flood appraisal groups have now accepted that the 200 year return period should now be the standard to be applied to new housing developments, and that, say, a 100 year return period is no longer adequate.
The template is not prescriptive, it merely shows what level of risk is acceptable for private insurance at normal terms. It is not the place of the insurance industry to dictate where new houses should be built, but it does perhaps have a duty to warn planners and developers if insurance is not going to be available or will be costly.

As the Scottish Planning Guideline points out, for the 100 year flood, there will be a 51% chance of at least one such event during the 70 year lifetime of a building.

Category Three - Commercial and Industrial

Developments where the owners would be responsible for providing their own defences, or where the flood hazard is considered to be less important than other considerations, such as the need to be close to a river.
Some developments in this category may need special treatment, however, for example:

- Where the site will attract the public, especially young children and old people (such as health centres and leisure centres),

- Where large numbers of the public are likely to gather, and where evacuation routes are limited,

- Refuse tips or areas where hazardous materials are to be stored or processed,

- Waste water and sewage treatment plant. (Sewage could escape onto adjoining land.)

Health and safety must always be the prime consideration. It should be remembered that flooding could often occur very quickly without warning, leaving little time for evacuation.

7. Availability and Affordability Issues

A unique feature of the UK insurance industry is that back in 1961, it gave a guarantee to Government that for residential properties, it would not refuse to offer insurance on the grounds of the flood risk.

This has had the effect that in many ways flood insurance has been taken for granted by government, planners, and developers, and many housing developments have taken place since 1961 in high flood hazard areas.

Is this sustainable in the longer term if the property is going to be repeatedly flooded?

In the UK, the ABI have had to give warnings to government that the industry will not be able to guarantee to be able to provide flood cover after the end of 2002 unless government take firmer action of planning issues and flood defences.

If the guarantee is removed, there could be dire consequences in terms of blight on properties. Even in cases where an insurer has agreed to continue to provide cover, one could imagine a situation where after a flood, it would want to cancel that cover. One solution might be to change the policy cover so that rather than rebuild the house so it can be flooded again, the insurer could declare the property a total loss and pay the policyholder a cash sum in exchange for the title deeds. It could then demolish the property and sell or give the land to the State to be turned into open space for recreation or a similar purpose.

8. The benefits to the State in encouraging private insurance solutions

There are benefits for the State in encouraging private insurance for flood, not only can it avoid any obligation on the State to make payments to victims, it can help the community get back on its feet quickly. The insurance industry is experienced in handling claims efficiently, objectively and sympathetically. It also has the mechanisms for spreading the cost around the world through global reinsurance.

Unfortunately, many people cannot afford to buy insurance. It is particularly sad but true that those in lower socio economic groups not only tend not to insure, but also tend to live on cheaper land, and cheaper land tends to be more susceptible to flooding. These people are also more vulnerable because they are unlikely to have savings or the ability to borrow from conventional sources in order to get back onto their feet. This could have serious consequences for the local economy, and apart from the humanitarian aspects, it makes economic sense to enable as many people as possible to be able to get back to leading normal lives as soon as possible. In the UK, insurers have worked in partnership with local government housing associations to develop "pay with rent" schemes where for a couple of pounds a week extra on the rent, the tenant can have some basic insurance cover. In some areas there is a cross subsidy for the elderly so that they can have cover even cheaper.

The State could do much to promote such schemes; for example if someone is on welfare, with food and rent paid direct by the State, it would make sense for the State to pay for his or her insurance as well, perhaps funded from a levy on insurers. The cost is unlikely to be very high, as a proportion of all welfare payments, but it would demonstrate that the State is looking after its more vulnerable citizens.

9. Uncertainty

Whatever climate change brings, it will bring increasing uncertainty. Canada seems to have every type of natural hazard imaginable, so Canadians should be familiar with uncertainty. Climate Change Models are still crude, because no one really knows how all the mechanisms of climate work. Even in the UK with its relatively kind climate, insurers have had to face bewildering extremes of storm and flood with a gradually increasing trend.

The research community has responded well to these challenges, and is learning the need to work at the boundaries of their disciplines and with other disciplines. After all, that is where the really interesting research lies. Insurers should be increasingly ready to help. They really have no option.

Conclusions

So what conclusions can be drawn from all of this, particularly in the context of residential flood insurance in Canada?

First, it is essential for the State, the academic community and the insurance community to talk to each other, generate trust and forge partnerships to help to manage the risk.

Secondly, the private insurance solution offers the most efficient, effective way to provide compensation to flood victims, but only if the cover is provided in a bundled system.

Thirdly, for the sake of equity, there should be arrangements made to enable the less well off and those in higher hazard areas to be able to afford cover.

Many of the solutions offered in this paper and practical and well proven. Some have not yet been tried, but are being actively considered in the UK. The author would welcome comments.

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“Demand Management” and “Water as an economic good”; paradigms with pitfalls

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Abstract: In certain circles demand management is seen as one and the same thing as economic pricing. This thinking is stimulated by the Dublin principle that water should be considered an economic good. But is this reasoning correct? Is economic pricing an adequate means to reach more desirable levels of demand? There is considerable misunderstanding about what the concept of water as an economic good implies. In this paper it is argued that water pricing should primarily serve the purpose of financial sustainability through cost recovery. Moreover, in water pricing adequate attention should be given to equity considerations through e.g. increasing block tariffs. Instead of economic pricing there is a need for defining a reasonable price, which provides full cost recovery but which safeguards ecological requirements and access to safe water for the poor. Giving a reasonable price to water has the additional benefit that it sends out a clear signal to the users that water should be used wisely, but the prime target of water pricing remains cost recovery.

A major argument of neo-classical economists is that economic pricing of water will facilitate the re-allocation of water from sectors with lower added value (e.g. agriculture) to sectors with a higher added value (e.g. urban water use). However, the value of alternative uses of irrigation water is often grossly over-estimated. Adequate and effective regulations may suffice in order to achieve the optimal allocation of water resources.

1. Water as an economic good

Since the Dublin conference on Water and the Environment (ICWE, 1992) it has become generally accepted among water resources managers that water should be considered an economic good (the four Dublin principles, see Table 1). However, what this entails is not all that clear. The problem is not with the terminology. It is the interpretation that causes confusion. One can distinguish two schools of thought (Van der Zaag & Savenije, 2000, p51). The first school maintains that water should be priced at its economic value. The market will then ensure that the water is allocated to its best uses. The second school interprets 'water as an economic good' to mean the process of integrated decision making on the allocation of scarce resources, which does not necessarily involve financial transactions.

The latter school corresponds with the view of Colin Green (2000) who posits that economics is about “the application of reason to choice”. In other words: making the right choices about the allocation and use of water resources, on the basis of an integrated analysis of all the advantages and disadvantages (costs and benefits in a broad sense) of alternative options.

Table 1: The Four Dublin Principles (ICWE, 1992)

1. Water is a finite, vulnerable and essential resource which should be managed in an integrated manner.
2. Water resources development and management should be based on a participatory approach, involving all relevant stakeholders.
3. Women play a central role in the provision, management and safeguarding of water.
4. Water has an economic value and should be recognised as an economic good, taking into account affordability and equity criteria.

The concept of Integrated Water Resources Management (IWRM), in line with the first Dublin principle, implies the following four aspects (Savenije & Van der Zaag, 2000, pp.15-18):

a) considering all physical aspects of the water resources at different temporal and spatial scales (the integrity of the hydrological cycle and the related quality aspects);
b) applying an inter-sectoral approach, recognising all the interests of different water users (including environmental, social and cultural requirements);
c) giving due attention to the sustainability of water use and the rights of future generations;
d) involving all stakeholders, at all levels in the management process, giving due regard to women.

These four aspects, each in a different way, are at variance with the first school's interpretation that "water is just another economic good that needs to have an economic price".

The first aspect of IWRM states that water is not divisible into different types or kinds of water. It may be groundwater at some stage, at a later stage it will become surface water. Earlier in the water cycle it was rainfall and soil moisture. But it all remains the same water. Use of soil moisture diminishes the availability of groundwater; use of groundwater diminishes the availability of surface water etc. Thus any use of water affects the entire water cycle. Since water is a resource vital to life for which there is no substitute, for water no choice exists between resources. The only choice to be made is how to allocate water, and finding the most efficient way of using it. Water, then, is fundamentally different from other economic goods. If one needs energy, for instance, one can choose between solar power, wind, hydropower, fossil power, nuclear power, etc. If one needs vitamins, one can choose between different kinds of fruit. The market mechanism works almost naturally for such kind of goods. With water that is not the case. One cannot easily choose another type of water without tapping the same resource.

Related to this first aspect is the temporal variability. The availability of the resource depends on climatic variability, but also on land use and human interference, sometimes hundreds of kilometres away. Also demand varies over time, both in the short and long term, as the structure of the economy and population changes. In section 5 of this paper an example of the significance of this temporal variation is presented.

The second aspect of IWRM, to consider and balance all sectoral interests, limits the applicability of neo-classical economic principles also. There are important water uses that have a high societal relevance, but a very limited ability to pay, particularly the environmental, social and cultural requirements. Yet most if not all societies respect these interests. Decisions on water allocation appear to be taken seldom on purely "economic" (using the word in the interpretation of the first school) grounds. On the contrary: governments generally take decisions on the basis of political considerations with strong considerations for social, cultural and sometimes environmental interests. Of course, economic and financial considerations are an integral part of these decisions, but they seldom are the overriding decision variable. This pragmatic approach is in agreement with the second school of thought.

The third aspect, calling for long-term sustainability, makes the application of economic principles (in the classical sense) even more difficult. Economic analysts can easily demonstrate that the future has no value (in monetary terms). The discount rate makes any future benefits (or costs) further than, say, 20 years ahead valueless and irrelevant. This, like the previous aspect, illustrates clearly that economic thinking in this limited sense differs from attributing societal or personal values to things. Most individuals would agree that personal health, happiness, beauty, safety, the future of your children, education and well being are more important than money. Societies (and to a much smaller extent the market) spend large amounts of money on these qualities of life. Yet it is extremely hard to value these qualities in monetary terms, let alone their future value.

Finally, the aspect of participation, which by itself corresponds with the second and third principles of Dublin, requires decision making processes in which the interests of all stakeholders are considered. This aspect precludes economic pricing, or at least makes it extremely difficult. Proponents of water markets disagree with this point of view, since they believe that if a market is properly structured and supervised all different interests will be well accounted for. Experience has learned that this may be possible for certain sub-systems (aquifers) or sub-sectors (irrigation) of the water sector, but that it is very complicated for more complex systems in a multi-sectoral and multi-interest environment (Jaspers, 2001).

In sum, the first (neo-classical) interpretation of "water as an economic good" has led to considerable misunderstanding in the debate, both at the Dublin conference and at the Earth Summit in Rio de Janeiro later that year. This misunderstanding still continues. Many observers feared that the adoption of this Dublin principle would lead to economic pricing of water, which would damage the interests of the poor and make irrigated agriculture virtually unfeasible. As a result, a number of disclaimers were added to the 4th Dublin principle, stating that water is also a "social" good (whatever that may imply) and that water should be affordable to the poor.

In the second school of thought there is no confusion. Water economics is understood to "deal with how best to meet all human wants" (Gaffney, 1997), making the right choices about the most advantageous and sustainable uses of water in a broad societal context. This is fully in agreement with the other Dublin principles and the concept of IWRM. Considering water as an economic good is about making integrated choices, not about determining the right price of water. One can say that water pricing is the pitfall of the concept "water as an economic good".

2. Water demand management

Demand management is defined as the development and implementation of strategies aimed at influencing demand, so as to achieve efficient and sustainable use of a scarce resource. Besides efficiency, it should promote equity and environmental integrity. Water demand management should not be seen as merely aiming at reducing demands or achieving higher water use efficiencies ("more crops per drop"). Demand management is another approach to water resources management that contrasts with the traditional supply management, aimed at increasing the supply whatever the demand. It differs from supply management in that it targets the water user rather than the supply of water to achieve more desirable allocations and sustainable use of water. Apart from structural measures, (such as low-flush cisterns for toilets, leak detection and control systems in distribution networks, and drip irrigation in agriculture) demand management strategies mainly consist of non-structural measures: economic and legal incentives to change the behaviour of water users; and the creation of the institutional and policy environment that enables this approach.

In short, demand management aims at achieving desirable demands and desirable uses (in principle, this implies that demand management may also include measures aimed at stimulating water demand in sectors where current use is considered by society to be undesirably low). This is the same thing as making the right choices about water utilisation. Hence "water as an economic good" is fully compatible with demand management, if well interpreted.

Demand management has many instruments among which:
- Quota. Setting an upper limit to the amount of water that may be used for a certain purpose.
- Licence to use. Issuing licences for withdrawals or discharges, subject to control and for a limited period of time.
- Tradable water right. The creation of a water market where stakeholders can buy and sell water rights within a well defined legal framework.
- User charges. Pricing of water services related to the type of service and the type of water use. Besides the cost recovery element, these charges may include demand management charges or subsidies to stimulate certain behaviour.
- Subsidies, grants, soft loans, product charges, tax differentiation, tax allowances, and other economic incentives to stimulate the allocation of water to certain preferred water uses, or to make undesirable behaviour less attractive.
- Penalties. A system of financial and legal enforcement incentives (fines and premiums) that provide the other instruments with "teeth".

Besides these implementation incentives, an important component of demand management is awareness raising, education and training. There are many examples where advocacy and the provision of alternative approaches to enhance the efficiency of water use have yielded considerable reductions in water use and pollution.

Although the first school of thought promotes economic water pricing as the most important demand management tool, there is limited scientific evidence to support that claim. Mohamed (2001) shows that in Egypt water pricing is not an effective demand management instrument. Quota are more effective and have the same result.

It appears that also with regard to the concept of "demand management", the pitfall lies in water pricing. Let us have a closer look at water pricing: what the purpose of water pricing is, how it influences demand, and how it may be used to enhance the sustainability of water supply in an equitable manner.

3. Water pricing

In contrast to the point of view expressed by the first school, water pricing is not an instrument for water allocation, but rather an instrument to achieve financial sustainability. Only if the financial costs are recovered can an activity remain sustainable. A good illustration of this premise is the "free water dilemma".

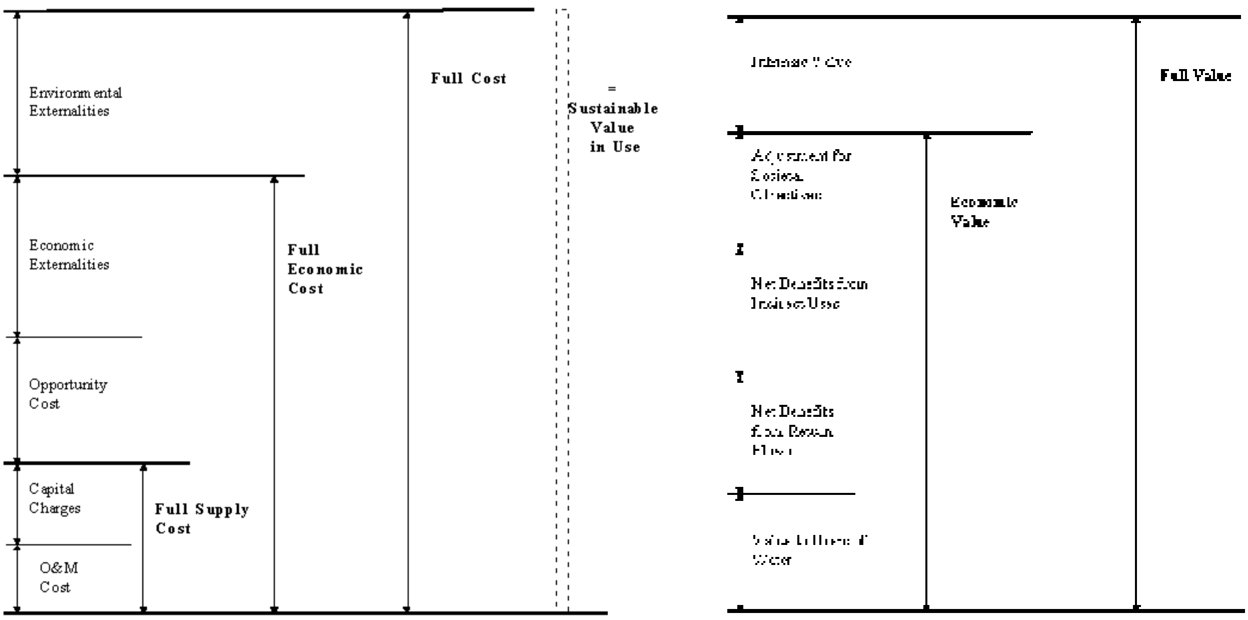
> **Free water dilemma:** If water is for free, then the water provider does not receive sufficient payment for its services. Consequently, the provider is not able to

> maintain the system adequately and, hence, the quality of services will deteriorate. Eventually the system collapses, people have to drink unsafe water or pay excessive amounts of money to water vendors, while wealthy and influential people receive piped water directly into their houses, at subsidised rates. Thus the water-for-free policy often results in powerful and rich people getting water cheaply while poor people buy water at excessive rates or drink unsafe water.

Hence water pricing is an important instrument to break the vicious circle of the "free water dilemma". But how high should the price be, and what is the impact of water pricing? To answer this question, it is necessary look at both the costs and value of water. Figure 1 shows the build-up of costs and values according to Rogers et al. (1997).

In the build-up of the costs, Rogers et al. (1997) distinguish the full supply cost (the financial costs related to the production of the water), the full economic cost and the full cost. The distinction between the latter two is open to discussion. Some economists would say that the economic cost include the full supply costs plus the opportunity cost (the cost of depriving the next best user of consuming the water). These economists consider all other impacts to be externalities. Of these, particularly the environmental externalities and the impacts on long-term sustainability are difficult to quantify in monetary terms. Therefore Rogers et al. make a distinction between economic externalities and environmental externalities. In the broader definition of the "second school of thought", however, both types of externalities should be part of the economic decision problem.

A similar problem arises in the definition of the value of the water. The value to the user may be quantified by his/her willingness to pay, but there are additional benefits, such as benefits from return flows, multiplier effects from indirect uses and in a broader sense the benefits to meeting societal objectives. The latter aspect is often neglected by the "first school" economists since also here it cannot always be quantified in monetary terms, but it is essential to the integrated decision process. The last part, the intrinsic value consists of cultural, aesthetic and merit values of water, also very difficult to quantify in monetary terms. If we use the definition that economics is "about applying reason to choice" then the Full Cost and the Full Value of Rogers et al. should be used for making allocation decisions.



General Principles for **Cost** of Water   General Principles for **Value-in-Use**

Figure 1 General Principles for Cost and Value of Water (Rogers et al., 1997)

It is obvious that a certain allocation of water is attractive when the Full Value is higher than the Full Cost. Determining these values and costs is precisely what is required in economic analysis. Once the decision has been taken to allocate the water on economic grounds, then the next issue is to decide on the financing of the allocation. For the first school, this is no problem. The price should be the Full Economic Cost, or the Full Cost. But that is not necessary. In principle, if society finds the allocation a good idea, then society may decide to finance the allocation completely. This is common practice with security (police and defence), judiciary and administration, and most countries subsidise education and health from government funds. Interestingly, unlike sectors such as security, health and education, the water sector in many countries is able to attain cost recovery. (In certain cities of Zimbabwe the water account produces a surplus which these cities use to subsidise other sectors, such as basic health care.)

The decision how to allocate water resources on economic grounds comes first, and should be conceptually separated from the decision how this allocation should be financed.

For water pricing the following considerations are important:
- the institution responsible for the supply of the water should have sufficient autonomy to operate and maintain the system adequately and sustainably;
- only when it has functional autonomy, including financial autonomy, can it perform its task in a sustainable fashion;
- there should be full cost recovery and preferably reservations for future investments;
- it is important to give due attention to equity considerations to prevent that the weakest people carry too high a burden;
- the price should be "reasonable", allowing for full cost recovery, but in line with the ability to pay of consumers;

- those who can pay an economic price (in industries and highly developed urban areas) should pay a high price and by doing so, cross-subsidise the poorer strata of society;
- it is possible, in principle, to provide poor people with a minimum amount of water for free; it is however often considered more sustainable to ask for a nominal connection fee (within their ability to pay) or charge a subsidised 'lifeline' rate, which gives them a claim on a proper service.

In applying this approach of a reasonable price, one comes automatically to increasing block tariffs, or a stepped tariff system as Ronnie Kasrils (2001), the Minister of Water Affairs and Forestry of South Africa, calls it. By applying these increasing block tariffs, one can reach full cost recovery, institutional sustainability, equity and, purely as a fringe benefit, send out a message to the large water consumers that water is precious and needs to be conserved. Only in this sense, as an afterthought, is water pricing a demand management tool.

4. Demand management implications of water pricing

With ordinary economic goods there is a relation between price and demand following a demand curve. The dimensionless slope of this demand curve is called the price elasticity of demand. It is defined as the percentage of increase in demand resulting from a percentage of increase in price. This elasticity is a negative number since demand is expected to decrease as price increases. The general equation for the demand-price relation (the demand curve) is:

$$Q = cP^{E}$$

where Q is the quantity of demand for the good, P is the price of the good, c is a constant and E is the elasticity of demand. The elasticity E for water normally ranges between -1 and 0.

This equation is difficult to apply for the water sector as a whole, but for certain sub-sectors (urban water use, industrial water use, irrigation) it may serve the purpose of analysing the effects of tariff changes. The problem with the equation is that E is not a constant. It depends on the price, it depends on the water use and it varies over time. So it is an equation with limited applicability.

Primary uses of water have a special characteristic in that the elasticity becomes rigid (inelastic; E close to zero) when we approach the more essential needs of the user (Figure 2). People need water, whatever the price. And for the most essential use of water (drinking) few alternative sources of water are available. For sectors such as industry and agriculture demand for water is generally more elastic (E closer to -1) which is more in agreement with the general economic theory. This is because alternatives for water use exist in these sectors (e.g. introducing water saving production technologies, shifting to less water demanding products/crops). For basic needs, however, demand is relatively inelastic or rigid. In urban water supply, elasticities are therefore generally close to 0, unless additional (non-financial) measures are taken. Poor consumers often only can afford to use small amounts of water (the basics), and any increase in tariffs will have little effect because they cannot do with less water. For large consumers (the ones that irrigate their gardens, own cars that need to be washed etc.) the ability to pay is such that the need to save money on water is limited. In the latter case, awareness campaigns, regulation, policing, leak detection, renewal of appliances, etc. are often more effective than the price mechanism per se. (The increasing block tariff system, by many societies accepted as achieving the best compromise between efficiency and equity for domestic water supply, poses an interesting paradox with neo-classical economics. It prices the highest value use (the most essential requirements such as drinking and cooking) lowest (first block at "lifeline" tariff), and the lowest value use (less essential uses such as washing a car) highest. The increasing block tariff system is a clear example of societies having decided that neo-classical economics do not apply to the provision of domestic water services.)

When the demand for water is inelastic, as is the case for urban water, the water provider may be tempted to raise tariffs, since this will always result in higher revenues, while water consumption drops only slightly. The provider may not be interested in curbing water demand through other means (e.g. through awareness campaigns or through subsidising the retrofitting of houses with water saving devices). It is therefore that water utilities should preferably remain publicly owned. If privatised they should operate within a stringent and effective regulatory environment.

5. Water allocation between sectors

One of the main reasons why neo-classical economists promote economic pricing of water is that it supposedly facilitates the re-allocation of water from sectors with lower added value to sectors with a higher added value. Such re-allocation will obviously be advantageous to society as a whole. The classic case is the different values attained in the agricultural and urban sectors. According to Briscoe (1996), the value attained in urban sectors is typically an order of magnitude higher than in agriculture. (However, in economies with many industries depending on the agricultural sector, the multiplier effect of agricultural production is high, and therefore the value added by water may be under-estimated when only using farm-gate prices of agricultural produce; Rogers, 1998.)

So, if water is currently used in the agricultural sector, the opportunity cost, i.e. the value of the best alternative use, may be 10 times higher, subject of course of "location and the hydraulic connections possible between users" (Briscoe, 1996). Thus a shift towards the higher value use is often promoted.

Whereas the opportunity cost of water for domestic water use may be highest, the moment availability is higher than demand, the opportunity cost of the water will fall to the next best type of use. It is just not possible to consume all the water at the highest value use.

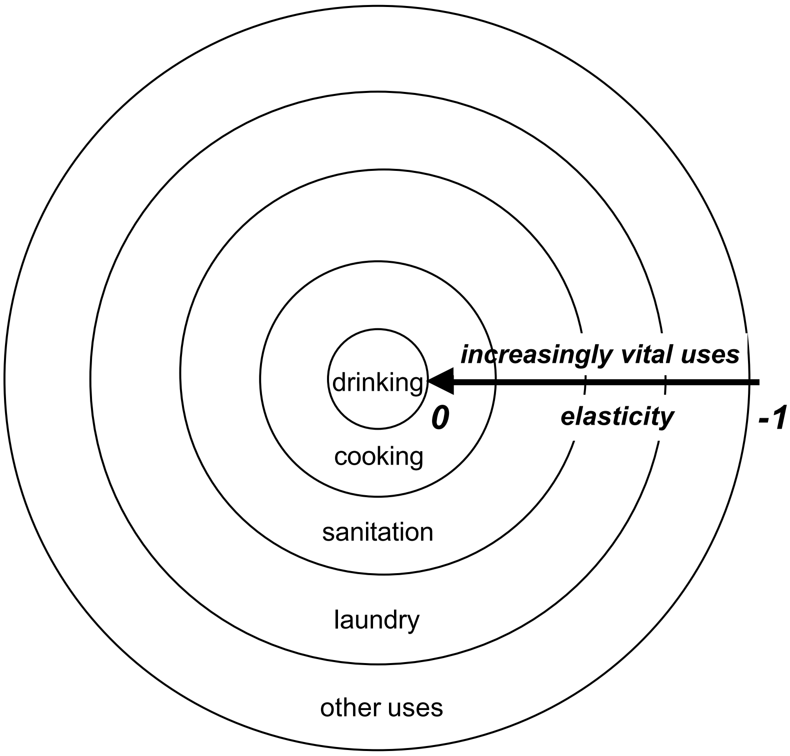


Figure 2. Schematic figure of different uses of domestic water and their elasticities of demand

The proper opportunity cost for irrigation water may therefore be only half, or less, than the best alternative use (Rogers et al., 1997). Even then some economists seem to forget that the reliability of supply acceptable to irrigated agriculture is much lower than that for urban water supply: a storage dam yielding x m^3 of water supplied to irrigation at 80% reliability, may yield only $0.5x$ m^3 (or less, depending on hydrology) for urban water supplied at 95% reliability. The effective opportunity cost of water used for irrigation should therefore again at least be halved. The resulting opportunity cost is thus only a fraction of what some neo-classical economists claim it to be. (This is corroborated by the following observation: in poor neighbourhoods in Zimbabwean cities, many households use domestic water (which is charged at between 0.15 and 0.50 US$/$m^3$) for market gardening; indicating that even at these tariffs irrigation appears to be profitable.)

The emerging picture, then, is fairly straightforward and common sense: the sectors with highest value water uses should have access to water. In many countries these sectors require only 20-50% of average water availability, and these demands can easily be satisfied in all but the driest years. In most years much more water will be available, and this water should be used beneficially, for instance for irrigation. There is therefore no need for *permanent* transfers from agriculture to other sectors, except in the most heavily committed catchment areas of the world. What is needed is a legal and institutional context that allows *temporary* transfers of water between agriculture and urban areas in extremely dry years. It is our view that no market is required to cater for such exceptional situations. A simple legal provision would suffice, through which irrigators would be forced to surrender stored water for the benefit of urban centres against fair compensation of (all) benefits forgone. This compensation should, however, not be calculated in terms of market prices, since in dry years this price may be many orders of magnitude higher than in normal years. Why should an irrigator be allowed to hold a city's population hostage and be compensated as a speculator?

In those heavily committed catchments where permanent transfers of water out of the agricultural sector are required, normally amicable negotiated solutions can be agreed, provided the laws allow this to happen. Rosegrant and Gazmuri (1996: 276-77) report a case of a factory financing the construction of a water saving drip irrigation system for an irrigation scheme, thereby obtaining the right to use the water thus saved.

In sum, many economists have not recognised the importance of the temporal variability of water availability, as well as the different reliabilities of supply required by different water using sectors. Figure 3 shows the variation of supply and demand in an imaginary case. It shows that, in general, primary (domestic) and industrial demands, with the highest ability and willingness to pay, require a high reliability of supply, which is normally achieved through relatively large storage provision. Also environmental demands are not the most demanding on the resource. Agricultural water requirements tend to be much higher, fluctuate strongly but also accept a lower reliability of supply.

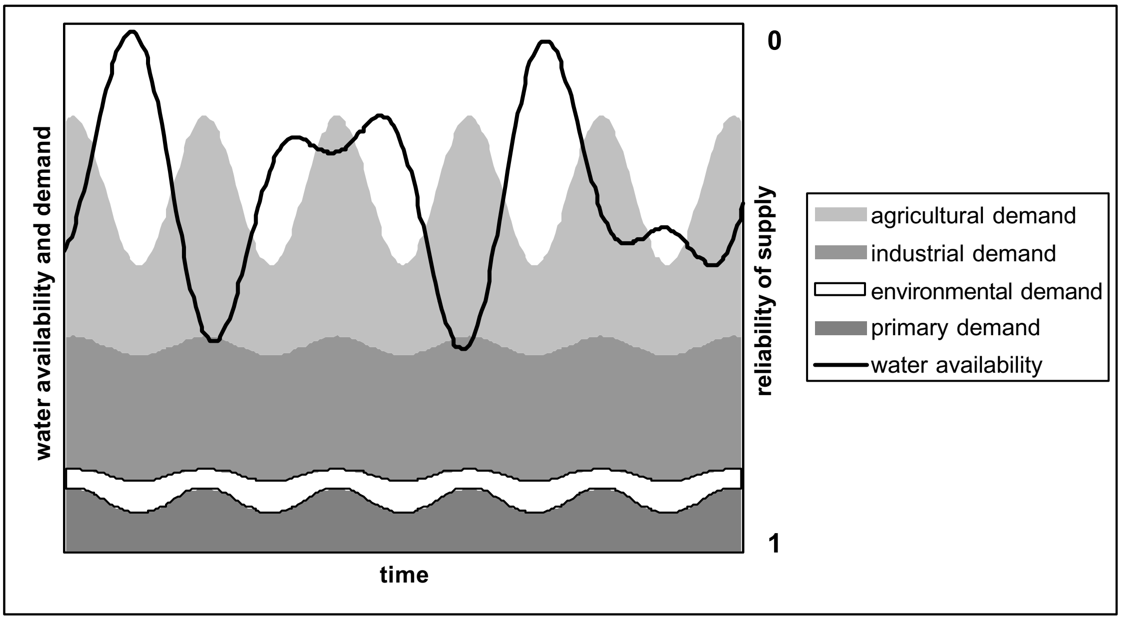


Figure 3. Variation of water availability and demand, and reliability of supply

6. Conclusion

This paper has attempted to show that "water as an economic good" and "demand management" are compatible concepts when considered in the context of Integrated Water Resources Management. Both are instruments towards balanced and integrated decisions on the allocation of a scarce resource, for the benefit of society as a whole. Water economics is about making the right choices about water resources development, conservation and allocation. Financial considerations are only a part of this "benefit-cost" analysis and seldom the main consideration. If water pricing is considered the main (or sole) instrument of demand management and economic planning, it will be a major pitfall. Both demand management and economic planning should have much broader scopes, and the core function of water pricing should primarily be cost recovery. If costs are recovered through increasing block tariffs, implicit cross-subsidies are built into the system, which on the one hand satisfy social and equity criteria and guarantee financial sustainability on the other.

In the trade-off between inter-sectoral water uses, the aspect of temporal variability of water availability and of reliability of supply is crucial, and often overlooked by economists. The various water using sectors require different reliabilities of supply, which somehow has to reflect in the price of water. The paper has argued that for this reason the opportunity cost of irrigation water is often over-estimated. Applying water for biomass production will remain a significant, and vital, activity in future.

Within sectors, water markets and marginal cost pricing may in some cases be compatible with the concept of Integrated Water Resources Management, provided all externalities are indeed 'internalised' and transactions are regulated by a public body (Perry et al., 1997). The paper has argued that for the allocation of water between sectors no markets are required nor are these desirable. Adequate and effective regulations may suffice in order to achieve the optimal use of water resources, acceptable to society at large.

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The Role of Insurance in Promoting Non-Structural Mitigation of Natural Disasters

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Abstract: The insurance industry is active in promoting disaster loss mitigation. This includes the full range of mitigation options from structural to non-structural and public education measures. This paper sets out the justification for the insurance industry's increasing involvement over the past few decades and explains why the role of the insurance industry will likely continue to increase in the years ahead. It also describes a range of different actions that can be used to prevent disaster losses. Primary conclusions of the paper include the following: First, disaster losses are rising around the world and this trend is expected to increase in the future. Secondly, appropriate mitigative actions hold great potential for reducing vulnerability and thereby confronting this alarming trend of rising disaster losses.

Keywords: Natural disasters, disaster mitigation, insurance, non-structural mitigation

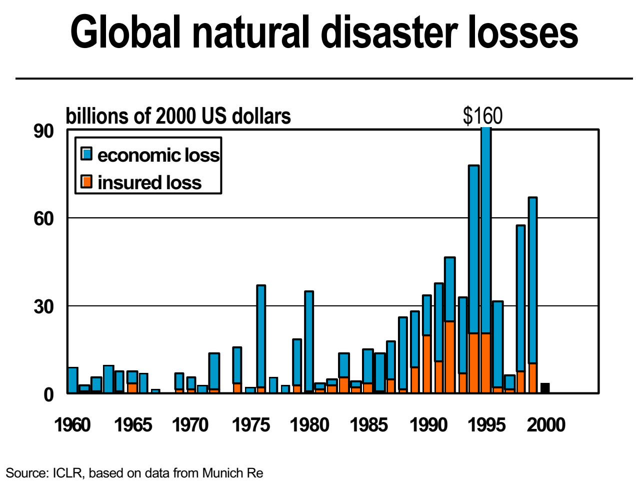
Introduction

Natural disaster damage losses have been doubling every five to ten years since at least the 1960s (Kovacs & Kunreuther, 2001). While losses have been rising at an alarming rate there has been progress toward greater understanding about why these losses are on the rise, also there is a growing body of research to identify actions that can be used to prevent future disaster losses. The greatest potential to successfully confront this trend comes through building more disaster resilient communities (Mileti, 1999). This involves greater focus on a reduction in society's vulnerability to nature's hazards through greater investments in both non-structural and structural mitigation.

This paper will address three issues. Why are disaster losses rising around the world? Secondly, what can be done to confront this trend of rising disaster losses? And third what specific actions can be taken by insurers and the research community to reduce future disaster losses?

Why are disaster losses high and rising around the world?

Disasters are a serious threat. During the 1990s, the International Federation of Red Cross and Red Crescent documented 2,800 events that occurred around the globe (Day & Walter, 2000). These events were responsible for the loss of 500,000 lives and displaced more than 2 billion people. In addition to the enormous human consequences these events caused $700 billion U.S. dollars worth of property damage (Day & Walter, 2000).

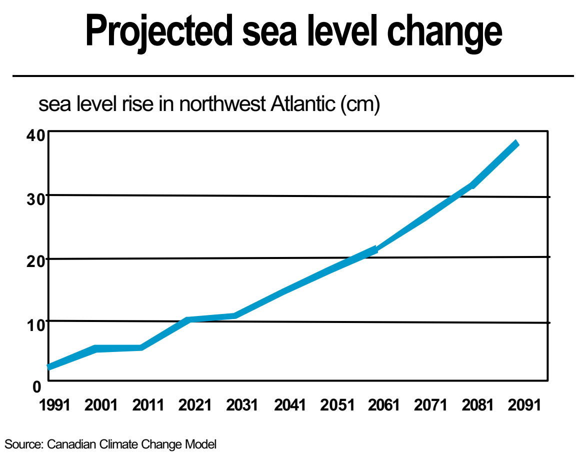


These losses are part of a long-term trend of rising disaster losses stemming back to at least the 1960s. Evidence of this trend can be seen with disaster damage expenses doubling every five to seven years (Munich Re, 2001). Disaster payments include a range of sources including claims made on private insurance companies, disaster relief payments made by governments, charitable donations and international aid. Demands have increased on all funding sources due to rising disaster loss payments. This trend must be confronted.

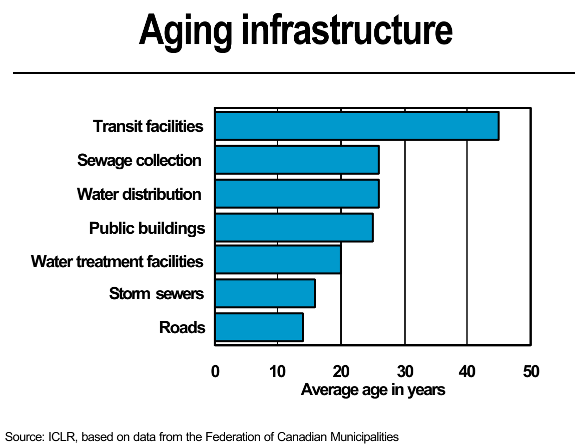
There are three primary factors that are driving disaster losses higher. These include:

- changes in the climate
- aging infrastructure
- more people and property at risk

Research has demonstrated that the world's climate is changing. In some instances these changes may reduce the risk of disaster losses, including the reduced likelihood of winter storms in northern regions (IPCC, 2001). Also, changing temperatures are altering the nature of events, such as overland flooding incidents that generally occur somewhat earlier in the year. However, there is growing evidence that several extreme climate events are happening more frequently and with greater severity. For example, global warming is contributing to rising sea levels and increased risk of sea surge (IPCC, 2001). The rate of global warming differs considerably across different parts of the country, with the largest increases found in continental and northern climates, like central Canada, and the smallest adjustments typically happening in mid-ocean climates (IPCC, 2001).



The risk of storm surge activity and coastal flooding is increasing (IPCC, 2001). In addition, climate change is significantly increasing the likelihood of extreme precipitation events. Events that typically happened once every 40 years are now often happening once every 20 years or sometimes once a decade as a direct consequence of recorded climate changes. These adjustments are expected to continue in the years ahead.



The second factor contributing to high and rising losses is the poor state of our aging infrastructure. Many facilities were erected decades ago and have not been appropriately maintained. They were designed at a time when current pressures and expectations were unknown. Increasing demands from a more complex and demanding society coupled with population growth and other factors has put enormous strain on the existing infrastructure, particularly in older urban centers (Allouche, 2001).

Beyond the age of the existing systems there has been a sharp reduction in spending made around the world toward new systems and toward the maintenance of existing systems (Allouche, 2001). For example, over the last 30 years many countries spent only half what they used to spend as a share of economic activity on infrastructure. This decision to not properly maintain and upgrade systems has increased the risk and added to the rise in disaster losses.

In addition to aging infrastructure the enormous growth in the number of people and properties in areas of risk are significantly attributing to the soaring costs of natural disasters. The world's urban population continues to grow at a remarkable pace and projections show that this trend will continue for many decades to come (United Nations, 1999). According to the United Nations in the next 30 years it is predicted that the number of people living in large urban centres will increase to five billion people, up from one billion people as recently as 1950 (United Nations, 1999). The escalating urban population has been evident in both developed and developing countries. This population growth has a great impact on the number of people affected by hazards such as flooding. Indeed, during the 1990s almost 1.5 billion people in Asia alone were displaced due to flood risk (Day & Walter, 2000).

The number of people affected by flooding is largely dominated by the adverse impact in developing countries whereas the property values affected by flood damage include very large adverse impacts in developed countries including Europe and North America (Day & Walter, 2000). In Canada, the United States and most other affluent countries the insurance industry has assumed financial responsibility for most of the catastrophic damages to home and businesses. Overland flood risk is often the only significant peril that is typically excluded from private insurance coverage (Kunreuther & Roth, 1998). In Canada, the Flood Damage Reduction Plan was the primary program since the 1970s for managing flood risk but during the 1990s Environment Canada withdrew its support for the program and no other level of government has effectively filed this void (Shrubsole, 2000). In the United States, flood management includes the National Flood Insurance Program established as a governmental program with private delivery (Hightower & Coutu, 1996).

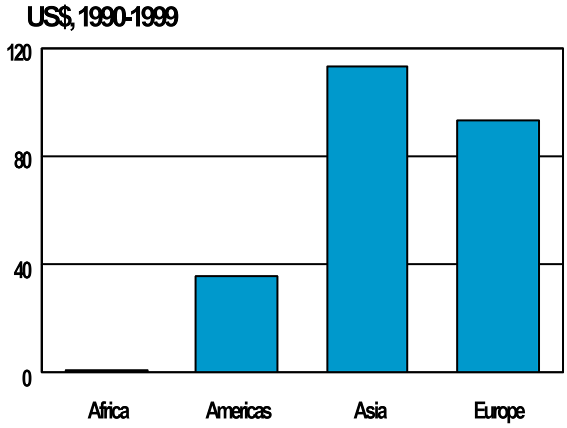
What can be done to confront this alarming trend of rising disaster losses?

Frequently there are extreme events that happen in very remote area, perhaps in the middle of the ocean, and these events may include enormous hazards inflicting a great deal of energy. Yet they are not called a natural disaster because they do not confront a vulnerable community. Therefore a natural disaster occurs when one or more of nature's hazards and a vulnerable community come together. Accordingly, a framework for action to prevent disasters must include both an effort to manage the impact of hazards and perhaps more importantly actions to reduce vulnerability.

Over the past century there have been a number of different initiatives to try to prevent the increase in the frequency and severity of extreme events. Perhaps the most ambitious and actively supported initiative has been the project looking at climate change and efforts to reduce greenhouse gas emissions (IPCC, 2001). The broad objective has been to try to reduce the impact of human interventions on the rate of change in climate patterns. This stems from the strong evidence that some extreme events have increased in frequency and severity due to the impact of human interventions (IPCC, 2001).

There have also been a variety of initiatives that have been tried around the world seeking to modify weather patterns. This has included cloud seeding to bring on precipitation particularly during periods of drought (Krauss, 1999). Cloud seeding has also been a strategy used to try to manage hail damage by modifying storm clouds so that hail formation is reduced (Krauss, 1999). There remains an absence of scientific consensus about the effectiveness of weather modification programs although the majority of circumstances show some possibility for improvement. Indeed, the Canadian hail reduction program appears to have significantly reduced hail damage during a period of increased storm activity (Krauss, 1999).

Value of flood damage



Source: ICLR, based on data from the Red Cross

In addition there has been a number of very large-scale efforts to try to modify hurricanes and other severe events. These interventions were soon halted and have since been viewed as potentially dangerous attempts to influence natural behaviors (Etkin et al, 1998).

The preferred method of preventing disaster losses is through aggressive actions to reduce vulnerability. To accomplish this objective there are three main methods to build resilience to nature's hazards including structural measures, non-structural measures and public awareness. Structural measures include the broad range of opportunities such as dams, levy's, sea walls and other engineered structures that can be effective mechanisms for protecting communities (Lecomte & Gahagan, 1998). The floodway constructed in Manitoba is an example where a relatively modest investment has contributed enormous life and property saving (IJC, 2000). Structural measures have been a popular means of managing risk, particularly flood risk, around the world for a considerable period of time.

There is a broad range of non-structural measures that can also be very effective in reducing flood damage. Indeed, the theme of the 2001 UNESCO conference hosted by the Institute for Catastrophic Loss Reduction is to identify and clarify the role of non-structural measures for flood risk reduction. This can include plantings that reduce beach erosion, healthy marshes to help manage flood risk, land use planning to keep structures and people away from vulnerable areas, building codes and code enforcement, and effective warning systems. A range of non-structural measures holds enormous potential for reducing disaster losses (Mileti, 1999). Furthermore, non-structural measures are typically far less costly to put in place to maintain than large structural measures (Mileti, 1999).

The third component of effective disaster prevention is increased public awareness. Informed families and business managers are best able to manage nature's hazards (ICLR, 1999). This encompasses the Institute's objective of establishing a culture of disaster prevention. Effective public awareness programs include a range of activities to better educate the public at large, those involved in the construction and maintenance of buildings and critical decision makers about the kinds of actions that can improve community resilience to natures hazards (Kovacs & Kunreuther, 2001). This could be an extremely effective way to share the large body of research findings coming from the many thousands of events that have happened around the world that have been studied. We need to use these lessons to protect communities in the future so they do not experience the kinds of losses that have happened in the past.

What actions can be taken to reduce vulnerability?

In this closing section the author will examine the actions that can be taken to reduce vulnerability to natures hazards. The focus will be on the role of the insurance community, the role of the Institute for Catastrophic Loss Reduction and the role of individuals involved in flood research to reduce the risk of further losses.

Actions that insurers are taking to appropriately manage disaster losses are broad ranging and include at least three areas. First, insurers are in the business of paying disaster claims. It is very important that losses are paid promptly and put funds in the hands of the homeowners and businesses to reestablish and rebuild as quickly as possible. Around the world insurers are paying many billions of dollars of disaster claims every year. For many hazards, particularly in developed countries, insurers are the primary funding mechanism to fund disaster loss issues (ISO, 1996). Perhaps the major exception around the world is that insurers play a relatively small role in the management of flood risk, which are often seen as uninsurable events (ISO, 1996). However the insurance industry addresses other perils like the risk of damage due to earthquakes, hurricanes, windstorms, tornadoes and many other events where insurers are the primary source of support for most homeowners and businesses (ISO, 1996).

Insurers are also very active around the world lobbying public institutions and helping to make the case for improved disaster preparedness, prevention and management strategies (Kovacs & Kunreuther, 2001). The experience of the insurance community can be very helpful to public authorities trying to better plan their role in managing disaster risk all around the world. A critical element of the international efforts of the insurance community to help share their understanding about disaster management has been the continuing focus on the important role of mitigation (Kovacs & Kunreuther, 2001). It is good business to make wise investments today to reduce disaster losses tomorrow. Relatively small investments before a hazard strikes can significantly reduce and often eliminate disaster loss payments that would have occurred after the event (ICLR, 1999).

The third role that insurers are currently involved in is the active investment in disaster research (ICLR, 1999). In Canada this includes the establishment of the Institute for Catastrophic Loss Reduction. In other countries important organizations have been established with support from the insurance community to better understand these risks. For example, the Institute for Business and Home Safety in the United States has for many years played a leadership role in the U.S. and international discussions about reducing disaster risk management.

The primary role of our Institute has been the production of quality and relevant research. Since 1998, the Institute has published more than a dozen research reports and plays an active role in working with the research communities to develop improved information about the importance of disaster mitigation investments. A theme included in all our reports is the identification of opportunities to invest in disaster prevention, detailing specific actions that can be taken now to reduce disaster losses in the future. The Institute has funded research on the impact of severe weather events on auto collisions, mapping of hail risk, development of improved tools to predict the risk of coastal flooding and the study of seismic risk in eastern Canada. Additionally, we have funded an assessment of the risk of fire damage following an earthquake in seismically vulnerable areas like Vancouver.

The Institute is also actively working to provide networking opportunities for researchers from a number of different disciplines to share their work. This has included academics from around the world being put into a position to better understand and learn about research conducted by others. Concepts like multi-disciplinary research can lead to more comprehensive analysis of the full range of risks.

Finally, the Institute is active in working on awareness programs to help the business community, including insurers, better understand the current state of research and the knowledge that is in place.

Conclusions

A key role of the flood research community is to provide quality relevant research that will better identify actions that can be used to reduce flood damage in the future. These efforts will be strengthened through increased interaction with people from other disciplines and other backgrounds to improve the comprehensive nature of the research. It is also very important to use organizations like UNESCO to compile and promote best practices around the world in terms of flood risk management.

The insurance community is likely to become even more active in the promotion of disaster mitigation in the years ahead. These efforts are based on the view that action today can be effective in improving our resilience tomorrow through the building of safer homes and structures. Remember that Noah built the arc before the flooding began.

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Floodplain Residents' Preferences for Non-Structural Flood Alleviation Measures in the Red River Basin, Manitoba, Canada

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Abstract: Based on the assumption that there is a general gap in information about social aspects of flood /floodplain management, the authors undertook several surveys on rural and urban residents' preferences for selected non-structural flood alleviation measures in the Red River basin, following the 1997 flood of the century. In addition to regular multiple choice and preference scaling questions, each survey contained a discrete choice experiment (a stated preference approach), which allows explicit modeling of tradeoffs. For this purpose, respondents were shown a set of choice cards displaying varied profiles of hypothetical flood /floodplain management policies and each of the respondents was asked to select the most preferred profile from a set. The survey on emergency flood evacuation indicated that in their preferences for evacuation procedures, residents were sensitive to the level of risk present. The majority of the residents preferred voluntary evacuation at the 50% risk of hazardous flooding, but had no objection to mandatory evacuation at a 99% level of risk. The choice experiment was less successful in modeling preferences for floodproofing policies. In that case, the majority of respondents consistently preferred the option of floodproofing their homesteads, irrespective of the incentives that other policy options had provided. Some of the additional survey questions suggested that the absence of a typical tradeoff behavior might have been due to the fact that a government policy on floodproofing had already been announced. The latter might have unduly influenced the responses to the hypothetical scenarios. We conclude the paper by suggesting that social science research can make significant contributions to the management and policy design of non-structural flood alleviation measures, especially when investigating management options and outcomes in a tradeoff context.

Key Words: floodplain residents' preferences, emergency evacuation, floodproofing, relocation, discrete choice experiment

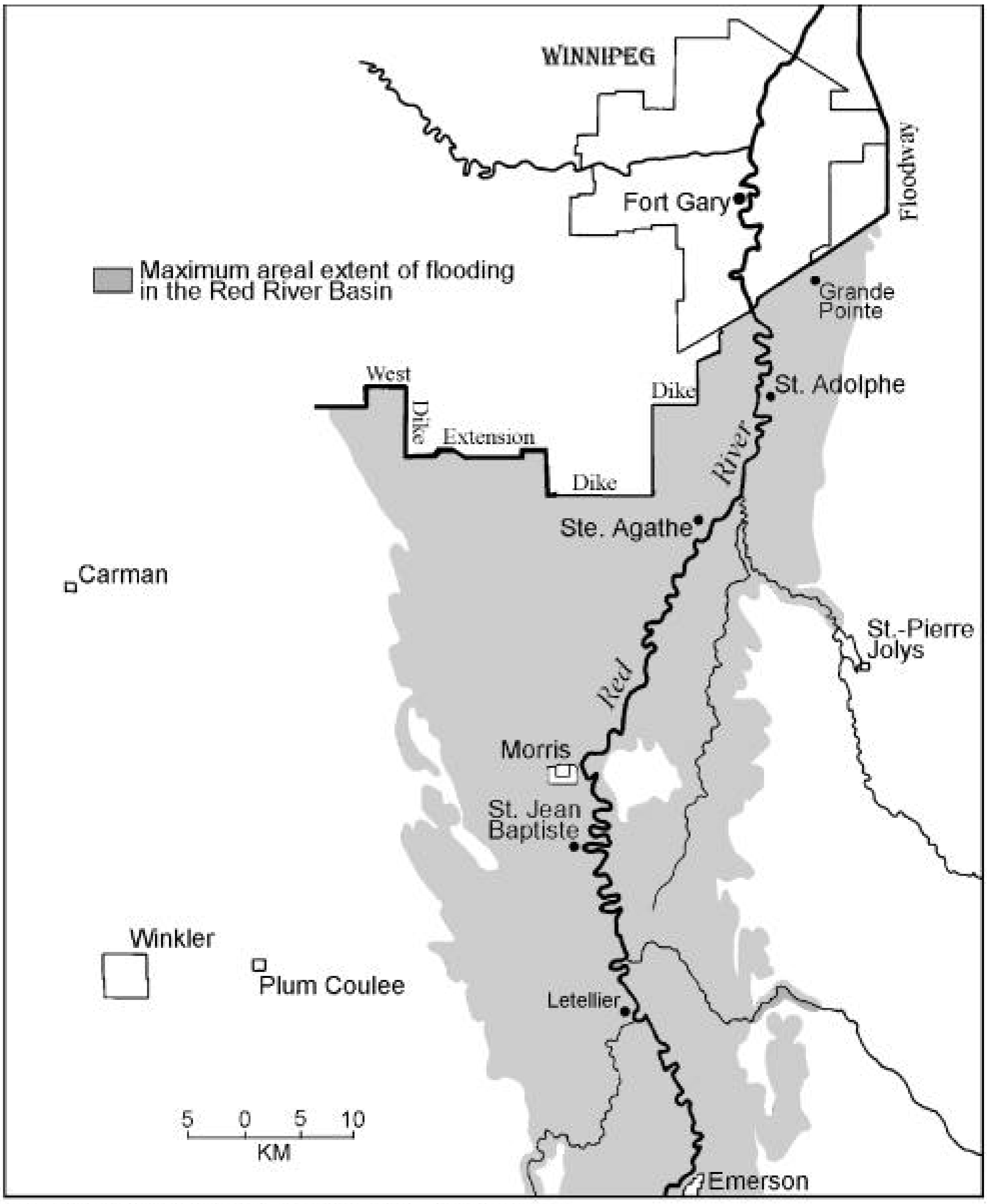
Introduction

For more than a century, industrial societies have relied heavily on physical structures for controlling flood problems. During this period the extent of reliance on structural measures has evolved from the initial 'levees only' policy in the Mississippi basin to a combination of levees and other supplemental structural measures, such as reservoirs, fuse-plug levees, floodways, and channel improvement projects (Wilkins 1996, 220). Despite enormous expenditure on such measures, Gilbert White (1945) pointed out that the magnitude of flood damage in the United States had increased steadily during the past century. As an alternative to relying solely on structural measures, he proposed a new paradigm of 'human adjustment to the floodplain environment' by advocating a combination of structural and non-structural approaches as "practicable measures to minimize the detrimental impacts of floods" (Wright 1996, 249). Non-structural approaches involve adjustment of human activity to accommodate the flood hazard (James 1975), while structural methods are based on flood abatement or the protection of human settlement and activities against the ravages of inundation (Alexander 1993, 132). Only during the last twenty-five years have non-structural measures received increasing attention in the United States and in Canada (Goddard 1976; Muckleston 1976; Watt 1995). Still, structural measures and their failure to provide complete flood protection have continued to dominate the debate over the efficacy of structural vs. non-structural measures. Extensive levee breaches in the Mississippi basin during the great flood of 1993 were, perhaps, the most recent reminder of failure of structural flood control measures (Myers and White 1993; Tobin and Montz 1994; Bhowmik et al. 1994; Bhowmik 1996). In Canada, mass evacuation in the Red River basin during the 1997 flood, which was provoked largely due to the threat of over-dike flooding or breaching of ring dikes around several urban communities, provides further evidence of continued vulnerability of structural flood alleviation measures (Rasid et al. 2000). At the same time one needs to credit structural measures, such as the Red River Flood Control System, for saving the City of Winnipeg from a major flood disaster (Winnipeg Free Press 1997).

Since the introduction of the Flood Damage Reduction Program (FDRP) in 1975 (Bruce 1975; Watt 1995), the provinces and territories of Canada have adopted the dual approach of combining structural and non-structural measures in their floodplain management policies (de Loë 2000). The Province of Manitoba has developed a set of institutional arrangements to implement some of its most crucial non-structural measures, such as flood forecasting and warning system, emergency response governance, and the delivery of disaster assistance (Haque 2000). Following the 1997 'flood of the century' in the Red River basin, the province has announced a comprehensive program of floodproofing, buyout and relocation (Canada-Manitoba n.d.). These extensive structural and non-structural flood alleviation measures have been designed and implemented with minimal contribution from social science research. The need for such research assumed urgency following the 1997 flood of the century, when the floodplain residents were confronted with the traumatic experiences of such a catastrophic event, and all of its associated effects, such as property damage, mandatory or enforced evacuation, and the uncertainty over flood compensation. The objective of this paper is to present results from several studies that focused on social aspects of the flood and flood management and were carried out in the Red River basin between 1997 and 2000. These studies focused on the residents' perceptions of the flood event and on their preferences for non-structural flood alleviation measures, such as emergency evacuation procedures and floodproofing. All case studies were undertaken in small urban communities and rural areas south of Winnipeg, combining traditional approaches of hazard perception research with a multivariate behavioural model, called discrete choice experiment (DCE), which is a novel method for assessing lay preferences and their tradeoff behaviour.

The 1997 Flood in Historical Contex The Red River originates in South Dakota and crosses the US-Canada border near Emerson, MB, following a highly meandering course northward to Lake Winnipeg (Figure 1). Throughout most of its length the river occupies the lower part of the Lake Agassiz Plain, a vast expanse of proglacial lacustrine deposition laid down during the late stages of the Wisconsin glacier (Rannie 1980, 208). In southern Manitoba, the Agassiz Plain forms a 20-40 km wide shallow basin, which is bounded in the west by the Southwest Uplands and in the east by the Canadian Shield (Corkery

1996). The gradient of the river channel, between Emerson and Winnipeg, is extremely low, ranging between 1 and 2 cm/km. In such a topographic setting, potential for flooding is naturally high, especially in the spring, if high soil moisture conditions coincide with heavy spring snow melt and /or precipitation. The 1997 spring flood was initiated by such a combination of unfavourable hydro-meteorologicalconditions. The entire basin received significantly higher than normal amounts of winter snowfall and by the end of winter accumulation of ground snow cover was nearly twice the normal thickness (*Winnipeg Free Press* 1997, 1). In late March, the uppermost part of the basin in Minnesota and North Dakota experienced the first phase of flooding following a rainstorm. Throughout the month of April several other storms coincided with heavy snowmelt runoff, leading to successively larger flood crests along the downstream communities. The City of Grand Forks, ND, in particular, experienced the most catastrophic flood of the century, which caused massive devastation of its downtown core (*Winnipeg Free Press* 1997, 10-11). The flood crest crossed the US-Canada border at Emerson on 17 April.



Source: Manitoba Conservation Radarsat Imagery

Figure 1. Flood of the Century: Maximum areal extent of flooding in the Red River Basin, 27 April - 4 May

Figure 2 illustrates peak flood levels at selected stations in southern Manitoba during a critical period of about three weeks from 17 April to 4 May. The highest unregulated discharge of the basin was estimated at 4536 m^3/s at the James Avenue gauging station in Winnipeg, downstream from the confluence with the Assiniboine (Topping 1997). This figure, which was based on an assumption of no flood control structures in the basin, represents the largest flood of the 20th century in the Red River basin, with a return period of 101 years; hence the term "flood of the century" (Figure 3). Data on the magnitudes of selected historical floods in the Red River basin indicate that the peak discharge in 1997 surpassed the previous records of the 1950 and 1996 floods by a wide margin. As the configuration of the shoreline of this swelling body of floodwater changed rapidly, the *Winnipeg Free Press* (1997) dubbed it as *A Red Sea Rising*. At its peak stage, the basin had been filled with at least 3 m deep floodwater (Figure 2). The maximum width of flooding across the valley ranged from about 15-20 km in the south (near Emerson) to 20-30 km in the north (south of Winnipeg) (Figure 1). The only features that remained above this vast expanse of water were a number of ring-diked urban communities along Highway 75 (see Figure 4) and isolated farmsteads that had private dikes around them.

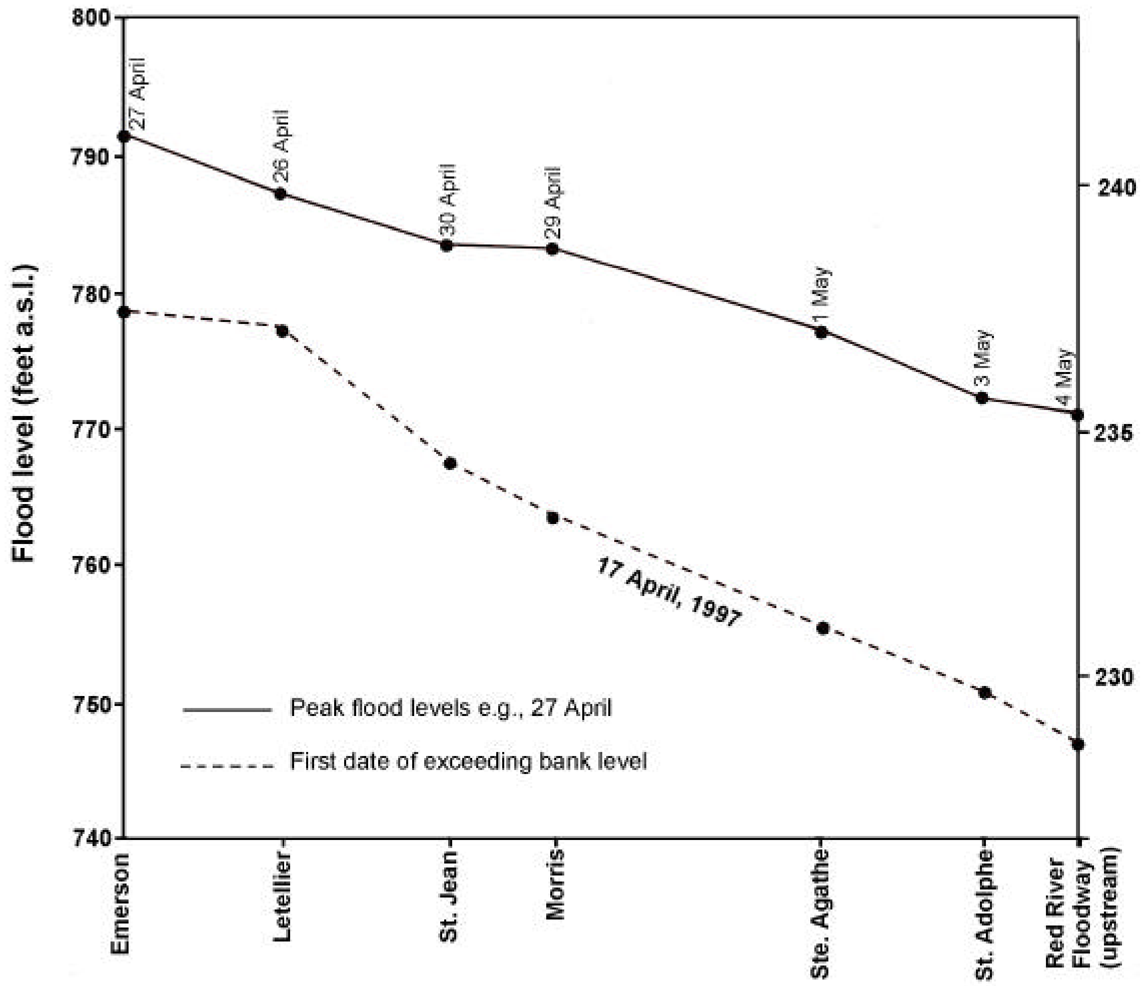


Figure 2. 1997 Flood of the Century: Flood levels of the Red River on selected dates

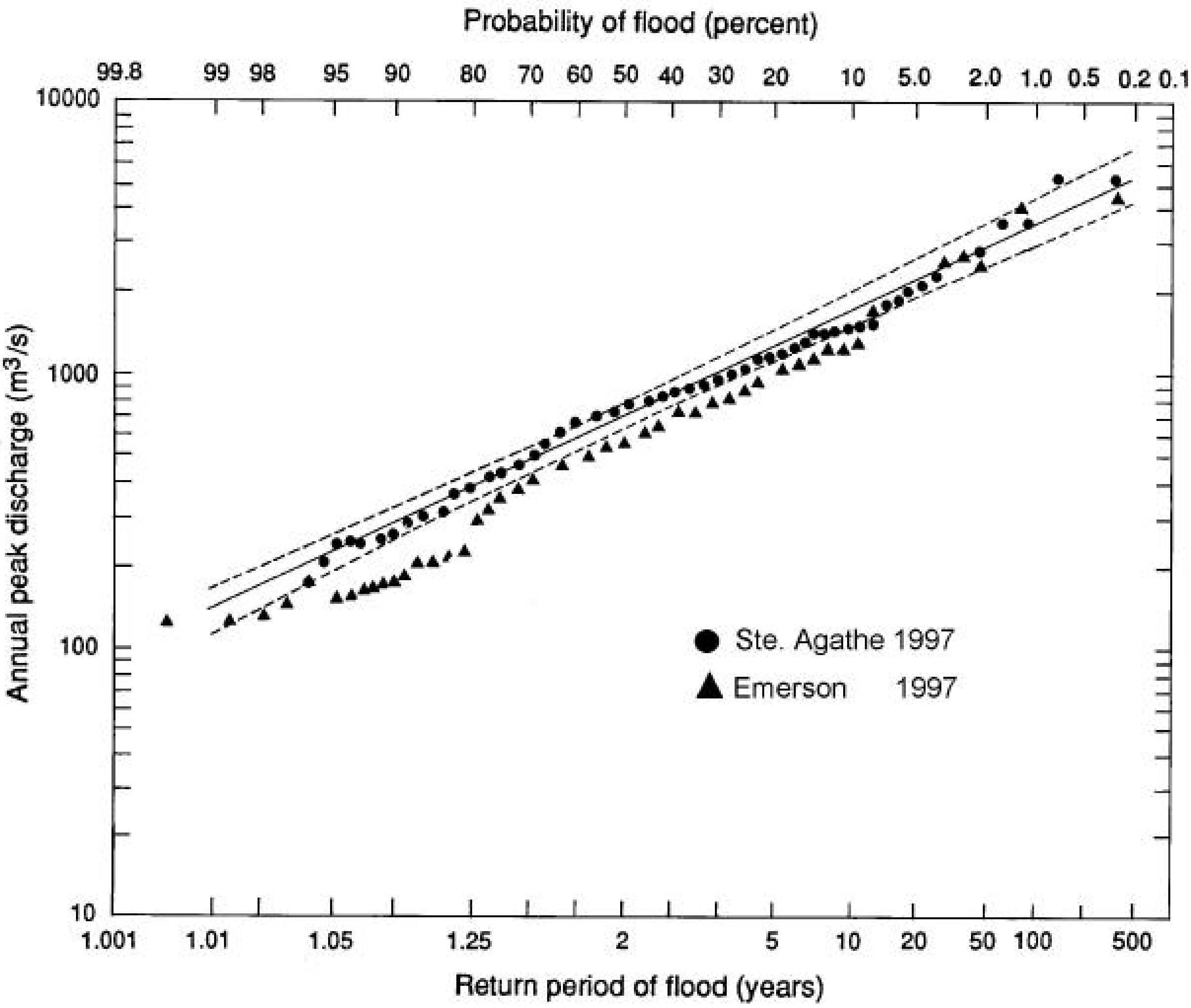


Figure 3. Flood of the Century: Flood-frequency curve for the Red River at Emerson and Ste. Agathe, 1875-1997 (Source: Water Resources Branch.)

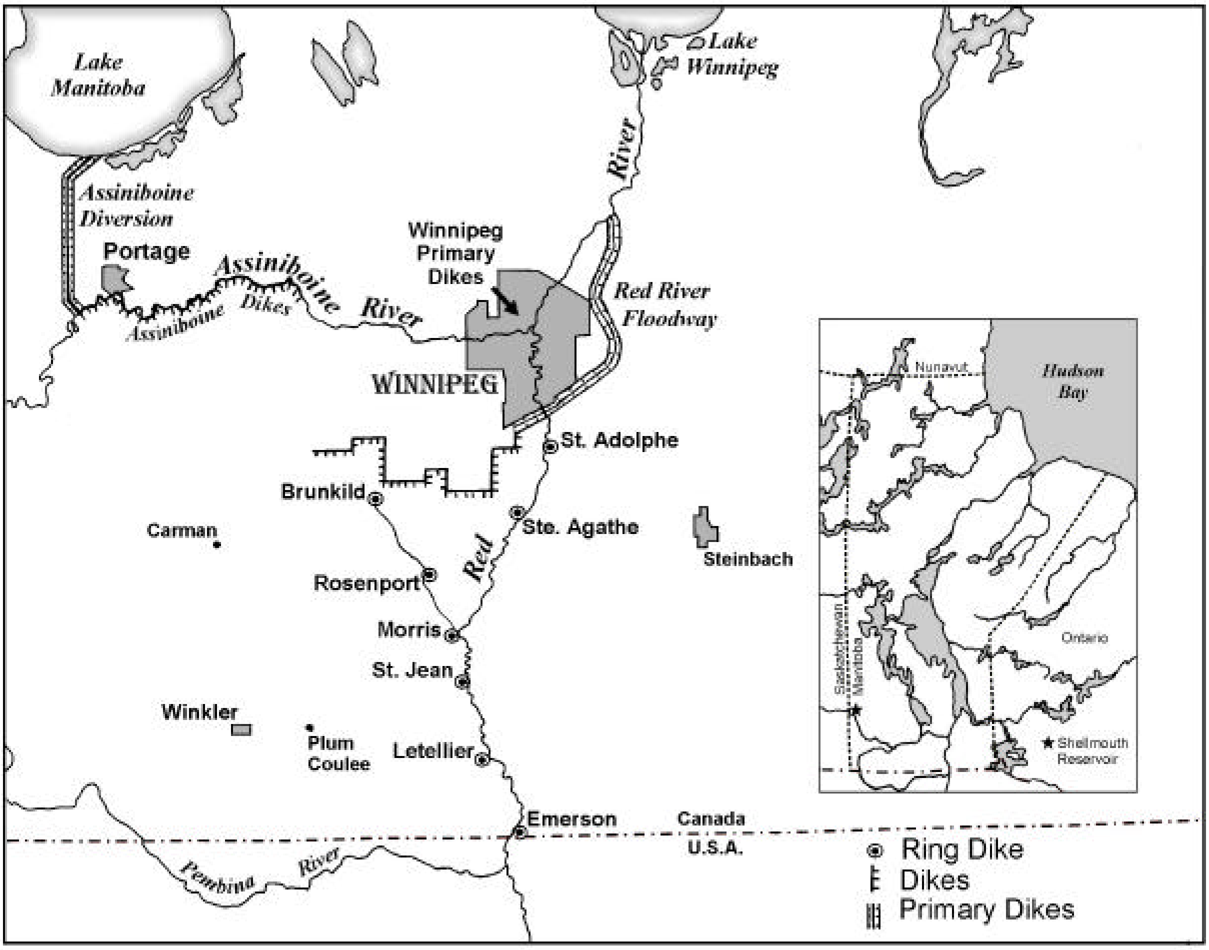


Figure 4. Flood control Structures in Southern Manitoba

Flood Control Structures in the Red River Basin

Types of Flood Control Structures

The Red River basin is an important section of the productive agricultural belt of southern Manitoba. The flat terrain of the basin has attracted agricultural settlement for more than a century. Major expansion of the city of Winnipeg took place during the relatively flood-free period between 1900 and 1950 (Rannie 1980, 209). Several smaller urban communities along the Red River between the Canada-US border and Winnipeg also experienced population growth during this period. Following the catastrophic flood of 1950, a comprehensive flood-control system was built, largely to protect the urban communities (Figure 4). By far the most important component of this system is the Red River Floodway, a 48 km long bypass channel that diverts floodwater away from the City of Winnipeg. The floodway was constructed in 1968 upon the recommendation of a Royal Commission that was established shortly after the catastrophic flood of 1950. The operation of the floodway is controlled through an inlet structure, which has two submersible gates, each 34 m wide and 11 m high. These are kept below the low water level under non-flood conditions but are raised in times of flood to control the separation of flow through the bypass channel and the City of Winnipeg. The floodway has a normal design capacity of 1700 m^3/s, with an emergency bankfull capacity of 2832 m^3/s (Gonzalez and Doering 1999, viii-7).

The Assiniboine Diversion (also called Portage Diversion), a 29 km long floodway, located approximately 100 km upstream of the confluence of the Assiniboine with the Red River at the heart of Winnipeg, is a complementary flood control system (Rasid 1987). It has been designed to divert up to 708 m^3/s of flow from the Assiniboine into Lake Manitoba at times of peak flow in the Red River. Additional reduction in flood discharges is provided by storage in the Shellmouth Reservoir, which is located further upstream on the Assiniboine near the border of Manitoba and Saskatchewan. It has a storage capacity of 863,400m^3.

Besides storage and diversion of floodwater, ring dikes around several smaller urban communities and rural farmsteads constitute another complementary flood prevention measure. These dikes have been built and upgraded following successive major floods. For example, the initial dike projects following the flood of 1966 included eight communities: Emerson, Lettellier, Dominion City, St Jean Baptiste, Morris, Rosenort, Burnkild, and St Adolphe (Figure 4). Following the flood of 1979, the diking systems were upgraded to provide protection to the 100-year level. A new ring dike has been constructed around Ste Agathe following the 1997 flood, which inundated this community for the first time. The post-1997 project standard for all ring dikes and elevated farmsteads in the basin has been set at the 1997 flood level + 2 ft of freeboard allowance.

In addition to the ring dikes around smaller urban communities, at least three other major dike systems complement the flood control structures of the province. First, the Winnipeg Primary Dikes have been built between the Red River Floodway and the perimeters of the city, to protect the city from emergency overflow from the floodway. Second, to prevent overflow of the Red River into the La Salle River, upstream of the floodway, the West Dike extends diagonally for about 64 km in a southwestern direction from the floodway. Third, the Assiniboine Dikes protect the farmlands from over-bank inundation along a low-lying stretch of the river between Portage La Prairie and Winnipeg (Figure 4).

Performance of the Red River Floodway During the 1997 Flood

The exceptionally high water levels of the 1997 flood presented a critical test for the operation of the Red River floodway. The main challenge was to maintain water levels in the Red River through the City of Winnipeg below the berms of its protective embankments (primary embankments) without inducing higher than natural flood levels in the upstream floodplain, which would have occurred without the presence of any flood control structures. According to the 1984 Water Resources Branch (WRB) rules of operation, the maximum stage in the Red River in downtown Winnipeg that would not cause overboard spilling was set at 7.77 m at the James Avenue Bridge (local datum). During the 1997 flood, the floodway was in operation between 21 April and 3 June. The water level at James Avenue had risen to 5.48 m by April 21. By that time the floodwater had been discharging through the inlet structure of the floodway. To regulate the amount of flow through the bypass channel, the gates of the inlet structure were raised successively on 21 April, 24 April and 1 May. By 4 May, the peak discharge of the floodway at 1840 m^3/s exceeded its normal design capacity (but was still below its emergency bankfull capacity) and the water level in the Red River reached 7.47 m at James Avenue at 2265 m^3/s. From 5 May to 2 June, the gates of the inlet structure were lowered at several stages until 3 June when water ceased to flow through the floodway channel.

The decision to operate the floodway at the level of 7.47 m at James Avenue, instead of at 7.77 m as suggested by the 1984 rules of operation, was based on considerations of at least three factors. First, many sections of the primary dikes had inadequate freeboard allowances for wind set-up. Second, many sewer outlets were situated below 7.77 m and were not gated against backflow. Third, several secondary dikes around riverbank properties would have overtopped at 7.77 m (Haque 2000). However, this decision had some adverse impacts on upstream water levels in the floodplain, particularly between Grande Pointe and Ste Agathe. The residents of these communities argued during post-flood reviews that their communities were flooded because water was diverted to save the City of Winnipeg. A hydraulic analysis by a consultant confirmed this assumption. Based on the Danish hydraulic model MIKE 11, Klohn-Crippen (1998) estimated that the operation of the floodway had indeed raised the water levels above the "natural levels" by an estimated 0.61 – 0.64 m between the floodway channel and Grande Pointe. This finding later helped approximately 200 residents of Grande Pointe to qualify for full government compensation for their flood damage (Haque 2000; Redekop 1998). Additional analysis by the same consultant indicated that Ste Agathe would have flooded under natural conditions, irrespective of the operations of the floodway (Burn 1999).

Performance of the Flood Control Dikes

All flood control embankments in the Red River basin (locally called dikes and ring dikes around communities and individual farmsteads) played a significant role in protecting the urban communities from direct inundation. Out of the six communities that are located either directly on Highway 75 or adjacent to it, five had permanent ring dikes around them (Table 1). Ste Agathe did not have a permanent ring dike because it is situated on relatively high grounds. As data in Table 1 indicate, the maximum depth of flooding (i.e. the maximum flood level above the bankfull stage) at Ste Agathe reached up to 1.43 m above the bankfull stage during its historic peak discharge of 3683 m^3/s. In contrast, the equivalent depth of flooding in the remaining five communities ranged between 2 m and 4.5 m. As the historic flood peak kept on rising rapidly, the Rural Municipality of Ritchot built a temporary earth embankment along the riverside of Ste Agathe. However, this embankment proved to be ineffective in preventing inundation, because floodwater entered the town from the west by overtopping Highway 75 and the railway embankment (Burn 1999).

Unlike the 1993 Mississippi flood, none of the ring dikes experienced direct breaching or failure. However, there were persistent threats of overboard spilling due to wind-induced waves during peak flood levels. Data on design elevation of dikes in relation to the maximum flood levels provide evidence of potential hazards of overboard spilling (Table 1). Most of the ring dikes around the five communities ranged in elevation between 2.5 and 5 m above the bankfull stage. The depth of flooding fell short of this range in most cases by less than 1 m. The peak flood levels rose very close to the top of the dikes: within 0.5 m at Lettellier and 0.66 m at Emerson and St John Baptiste. To prevent overboard spilling, it was necessary to reinforce and raise these dikes temporarily by sandbagging, up to an additional elevation of 0.5–0.7 m. In the case of St Adolphe, the maximum flood level rose above the crests of its existing dikes. The town was protected from direct inundation entirely by reinforcing and elevating its dikes by an additional

Table 1 Depth of Flooding in the Red River Basin during the Flood of the Century, 1997
(data in meters, feet in parenthesis)

Station	Maximum flood level (a.s.l.)	Depth of floodwater above minimum flood level	Design elevation of dike (a.s.l.)	Elevation of reinforced dike (a.s.l.)
Emerson	**241.54** (792.50)	**2.83** (9.30)	**242.18** (794.60)	**242.91** (797.00)
Letellier	**239.77** (786.71)	**2.01** (6.61)	**240.32** (788.50)	**240.96** (790.60)
St.Jean Baptiste	**239.01** (784.20)	**3.84** (12.60)	**239.68** (786.40)	**240.17** (788.00)
Morris	**238.75** (783.34)	**4.24** (13.94)	**239.56** (786.00)	**239.98** (787.40)
Ste. Agathe	236.66 (776.48)	1.43 (4.70)	No dike	No dike
St. Adolphe	**235.44** (772.50)	**4.57** (15.00)	**235.29** (772.00)	**236.36** (775.50)
Above Red River Floodway	235.08 (771.30)	3.44 (11.30)	No dike	No dike

Source: Manitoba Conservation, Water Resources Branch

1.07 m (Table 1). Even the dikes around Morris, which has the highest and most extensive system of embankment, were elevated by an additional 0.4 m.

In addition to upgrading the ring dikes, sections of the Winnipeg Primary Dike were raised by about 0.3 m. Perhaps the most dramatic structural flood alleviation measure during the 1997 flood was the construction of the Z-Dike (also called Brunkild Dike), which was a 32 km extension of the existing West Dike system. This extension was necessary to prevent overflow of floodwater from the Red River into Winnipeg through the La Salle River (Clayton 1999). Further, to minimize the risk of overboard spilling, sections of the West Dike were raised by an additional 1.5–2.5 m.

Non-Structural Flood Alleviation Measures in the Red River Basin

Flood Forecasting and Warning

The 1997 flood in the Red River basin resulted from a series of hydro-meteorological events, such as heavy precipitation in the fall of 1996, exceptional snowpack, a less than ideal temperature pattern, high soil moisture content, untimely runoff, and an April blizzard (Shrubsole 2000; Morris-Oswald et al. 1998; IJC 1997). By monitoring these events and forecasting the impending flood peaks, the Hydrological Forecasting Centre (HFC) of the WRB, Manitoba Department of Conservation, was one of the first government agencies that prepared the people of the Red River basin and all emergency management organizations for this catastrophic flood. The HFC employed an index type model to predict the volume of runoff from the basin and water levels in the Red River. Some of the leading variables of the model included: (a) an antecedent precipitation index (API) based on weighted monthly precipitation from May to October, (b) cumulative winter precipitation, including spring rain, (c) a degree-day type melt-index, and (d) a winter temperature index to estimate sublimation losses and soil temperature. The flood routing from Emerson to Winnipeg had been routinely executed for several decades by employing the Muskingum method (Warkentin 1999). This method consisted of a first flood outlook and a second flood estimation. The former postulated one of the three types of scenarios for the spring flood: a *median outlook* based on average future weather, a *lower decile outlook* based on favourable weather and an *upper decile outlook* relying on unfavourable weather conditions. The second flood estimation is an operational forecast; it is released on a daily basis during the spring runoff and the streamflow regime.

In 1997, the HFC issued an upper decile outlook in February and March, which suggested that the magnitude of the projected spring flood would exceed any previous flood of the century. Following the blizzard in early April, the flood outlooks were last updated on 10 April 1997. The first operational forecast was issued on 19 April, which raised the previous flood outlook by 0.3 m of river level. The forecasts were raised again the next day following a crest in Grand Forks that was higher than expected. On 27 April, when the peak flow in the Red River at Emerson coincided with that of several other tributaries in Manitoba, the forecast was revised again for higher levels in the Red River. Finally, the forecast for the water levels in the floodway was revised repeatedly prior to the peak flow, as operational flow measurements were available.

Overall, repeated revisions of water levels introduced an element of uncertainty for flood warning. Overland flooding contributed another uncertainty because it hampered accurate forecasting of water levels on the floodplain. It was a major contributor of surface runoff on the floodplain and flood damage to numerous farms (IJC 1997). It also resulted in underestimates of the flood crests at the Red River floodway by as much as 1.5–1.7 m (Morris-Oswald et al. 1998). Perhaps, more significantly, the community of Ste Agathe was unexpectedly inundated by overland flow for the first time (Shrubsole 2000). An adverse outcome of such uncertainty with flood forecasting was that some of the floodplain residents ignored flood warnings. For instance, not all farmers accepted offers made in April to have their livestock removed from flood-prone areas (Shrubsole 2000; IJC 1997).

Emergency Preparedness and Response

All three levels of the government — municipal, provincial, and federal — had to make a concerted effort to cope with this catastrophic flood. Such involvement of multiple levels of the government was mandated by the emergency response system in the Province of Manitoba, as in other provinces of Canada. This system is based on the principle that "the responsibility for emergency remains with those closest to the emergency" (Clayton 1999). Thus, a flood-affected individual bears the initial responsibility for coping with the flood disaster. As the magnitude of the emergency increases and an individual's capacity to cope with it diminishes, this responsibility shifts successively from individual to municipal, to provincial and, finally, to federal levels. The 1997 flood in the Red River basin provided a classic case study of coordination of emergency management strategies among the various levels of government. Initially, the reeves and mayors of rural municipalities and urban communities of the basin had the legislative authority to declare an emergency for their local administrative units. As the flood magnitude exceeded the municipal capacity to cope with the disaster, the provincial and federal emergency management authorities assumed major responsibilities for administering emergency measures. In all, fifteen federal and fourteen provincial government agencies provided assistance to minimize the impact of flooding (Clayton 1999). All federal activities were coordinated by the Emergency Preparedness Canada (EPC), whereas the provincial activities were coordinated by the Manitoba Emergency Management Organization (MEMO). Further, according to the Manitoba Emergency Measures Act, which was passed in 1987 and amended in 1997, MEMO had the legislative mandate to assume the responsibility for overall coordination of all emergency flood management strategies.

Among the federal agencies, the Department of National Defence, i.e. the Military, played perhaps the most significant role in providing both structural and non-structural flood alleviation measures. In all, nearly 8500 military personnel, 2850 military vehicles, 131 watercraft and 34 aircraft participated in sandbagging operations, dike construction and maintenance, temporary repair of roads and bridges, search and rescue operation, transportation of persons and materials, etc. (Clayton 1999). The Department of Indian and Northern Affairs Canada provided assistance to the Rosseau River First Nation for raising of dikes, transportation of people, and evacuation plans. Agriculture Canada helped in transporting grains and evacuating livestock. Coast Guard Canada assisted in search and rescue operations, transportation of sandbags and installation of floating booms at the base of the Z-dike. Public Works Canada performed structural inspection of homes and buildings. Among the provincial agencies, the Water Resources Branch (WRB) of Manitoba Department of Conservation played a leading role in forecasting the flood, operation of all flood control structures and construction of the Z-Dike. The Department of Highways and Transportation provided direction for the inspection and maintenance of roads and bridges and coordinated the development of alternative traffic route plans in anticipation of flooding.

Due to the hierarchical nature of the emergency response system, municipal authorities were an important link in the implementation of local emergency plans and in the execution of the broader Manitoba Emergency Plan. Consequently, the MEMO community advisors were deployed to meet with local authorities and ensure that community plans were current, and to arrange for public meetings to disseminate flood information. All flood-affected municipalities (at least eighteen) requested the assistance of the province. Over a period of several weeks, preparedness and response activities melded together (Clayton 1999).

On 23 April, the province recommended that all communities at risk in the flood-projected area should commence the mandatory evacuation process. Subsequent evacuation notices were issued on 25-27 April based on the progression of the floodwater. The issuance of the provincial evacuation order was based on two principles: (a) the protection of life over property, and (b) the requirement to exercise duty of care (Clayton 1999). However, the evacuation orders were a source of confusion for local authorities and the public they intended to serve. The notion of mandatory evacuation was problematic for local authorities and the property owners in terms of authority and responsibility for implementation. Many residents complained that they were unsure if the military, the MEMO, or the local authority was responsible for the implementation of the evacuation order. These complaints were publicized widely in the news media. One of the most common complaints was that the residents would have preferred to stay back in their homes, to protect their property from flood damage.

Floodproofing and Relocation

The 1997 flood in the Red River basin demonstrated that the design standards of most of the existing flood control structures in the province were inadequate or barely adequate for handling a flood of this magnitude. Therefore, the governments of Canada and Manitoba announced a $130 million flood infrastructure enhancement program in August 1998, to cope more effectively with a future flood of similar or greater magnitude (Caligiuri and Topping 1999). The revised design standard for all reconstructed and new structures has been set at the flood level of 1997 + 2 ft. The program offers the rural floodplain residents an option of either (a) floodproofing their homes or (b) relocating to a ring-diked community or to a flood-free zone. Floodproofing may include one or more of the following features: (a) raising a home or a building on an earth pad or on an elevated structures, (b) constructing a ring dike around buildings, and (c) building a properly-engineered structural or assembly dike (Canada-Manitoba n.d., 3).

The financial incentives for floodproofing include a reimbursement of up to $60,000 from the program (i.e. cost to government), while the owner pays the lesser of 25% or $10,000 of the eligible costs. The maximum reimbursement of $60,000 per application means that any costs in excess of $70,000 are not eligible for assistance (Caliguiri and Topping 1999). The incentive for relocation to a flood-free zone is even more attractive. In this case, the program will buy out the existing home at the assessed market price and will offer an additional relocation allowance of $30,000. The homeowner will still hold the title to his /her vacated property.

Social Science Research on Non-Structural Flood Alleviation Measures

The above summaries of the events surrounding and following the 1997 flood in the Red River basin serve as reminders that both structural and non-structural flood control measures inevitably are designed for the residents, and affect these very residents. The discussion also reveals that residents may not necessarily perceive any one of these measures as being in their best interest, that incomplete information or inaccuracies in media reports may lead to biased perceptions, and that top-down decision approaches may misinterpret residents' needs and knowledge. The technical complexities of structural measures appear to have prevented the emergence of more participatory forms of decision making and the inclusion of social science research into decision-making. In the remainder of this paper, we will present results from three different surveys we completed between 1997 and 2000 in both rural and urban communities along the Red River south of Winnipeg. We would like to acknowledge at the outset that surveys are only one method among many for researching social aspects of flood hazards. However, we consider surveys as an important method for capturing the opinions, perceptions and preferences of the silent majority of floodplain residents, whose perspectives are frequently ignored by decision-making processes. The sections below will focus on respondents' perceptions of flood damage, evaluation of emergency evacuation policies, and their preferences for long-term floodplain management policies, specifically floodproofing and relocation.

The Surveys

Among the three surveys, the first one was conducted in the wake of the 1997 flood among the residents of four small urban communities on the Red River — Emerson, Morris, Ste Agathe and St Adolphe — to assess respondents' opinions on emergency evacuation procedure. The subsequent surveys dealt with rural residents' perspectives on floodproofing and relocation. One of these surveys was conducted during the summer of 1998, coinciding with the announcement of the Canada-Manitoba floodproofing program. The other was undertaken in the summer of 2000.

Each of the survey instruments consisted of two distinct components. In the first part, a standard multiple-choice questionnaire elicited information about the socio-economic and demographic background of the respondents, the various types of damages the respective respondents endured during the 1997 flood, and the existing floodproofing features in a respondent's home and homestead. Furthermore, respondents were asked several attitudinal and preference questions, such as reasons for living on the floodplain, and attitudes towards (or preferences for) flood management and policy issues. In most cases respondents were asked to evaluate respective items on a Likert scale.

The second part of the survey employed a discrete choice experiment (DCE), for the purpose of modeling respondents' trade-off behavior when confronted with hypothetical policy alternatives or management outcomes. In the 1997 study, the DCE focused on evacuation procedures. Respondents chose between hypothetical descriptions of three potential flood evacuation alternatives: mandatory evacuation, voluntary evacuation, and no evacuation. The hypothetical scenarios varied by the amount of notification time provided for evacuation, the amount of flood relief, and the risk of hazardous flooding, i.e. the chance of over-dike flooding or breaching through dikes (Table 2a). The two rural surveys dealt with long-term floodplain management policies. In the 2000 rural survey, the choice cards presented four alternative floodplain management policies: floodproofing, buyout and relocation, buyout and life lease, and do nothing. The attributes and attribute levels used to compose each of these alternatives included monetary contribution by the government for floodproofing and relocation, content compensation for life lease, and disaster relief (Table 2b). (For further details on the DCE method please refer to the next section).

For the urban survey, respondents were selected by using a systematic sampling proportionate to the total number of houses in each community. Thus, in Morris, the largest of the four communities, 50 respondents were sampled by selecting every tenth household out of a total number of 524 houses. In Ste. Agathe, the smallest of the four communities, on the other hand, an attempt was made to interview every fourth household, to obtain a sample of at least 30 out of 132 houses. In St. Adolphe, every sixth or seventh household was interviewed to obtain a sample of 40, whereas in Emerson a sample of 50 was obtained from approximately 250 houses, by interviewing every fifth household. Thus, in all, 170 interviews were completed in four communities. For the rural surveys, a random sampling was adopted. Approximately 640 farmsteads were identified on a series of 1:50,000 property ownership maps for seven rural municipalities that were flooded in 1997. Boundaries of flooded areas were delineated on these maps by using RADARSAT satellite imagery. The farmsteads within each rural municipality were numbered sequentially. A sample of 102 respondents was drawn at random (by using a random number table), proportionate to the total number of farmsteads in each municipality. In all surveys, one or two field assistants conducted door-to-door interviews with the respondents (usually the household heads). Each interview, including both the DCE and the descriptive part of the questionnaire, lasted between 30 and 45 minutes.

Table 2. Experimental Variables and their Levels for the Discrete Choice Experiments

(a) 1997 Urban Survey: Emergency Evacuation

Variables (Attributes)	Attribute levels
Evacuation mode *(alternative specific constant)*	No evacuation Mandatory evacuation Voluntary evacuation
Notice of evacuation	1 day 2 day 4 day
Flood relief	75% 80% (current) 90%
Risk of hazardous flooding (chance of over-dike flooding or breaching)	50% 75% 99% (current)

(b) 2000 Rural Survey: Floodproofing vs. Relocation

Variables (Attributes)	Attribute levels
Floodplain management policy *(alternative specific constant)*	Status quo (do nothing) Floodproof Buyout and relocation Buyout and life lease
Floodproofing (maximum government contribution)	\$50,000 \$60,000 \$70,000 (current) \$80,000
Relocation allowance (besides buyout)	\$30,000 (current) \$50,000 \$70,000 \$90,000
Content compensation (besides life lease)	40% 60% 80% 100%
Disaster relief	70% 80% (current) 90% 100%

Background to the Discrete Choice Experiment (DCE)

The DCE belongs to the family of multi-attribute stated preference models (Timmermans 1984), because respondents choose among hypothetical alternatives. The method is decompositional, as opposed to compositional (for an example of the latter see the theory of reasoned action in Ajzen and Fishbein 1980), because respondents evaluate whole alternatives that are defined as combinations of attributes. The alternative profiles are constructed by following statistical design principles, such as fractional factorial designs (e.g., Raktoe et al. 1981). If respondents rate or rank each full profile separately, the technique is usually referred to as conjoint analysis (Green and Srinavasan 1978). In a discrete choice experiment (DCE), two or more such hypothetical profiles are combined to choice sets, and respondents choose the most preferred alternative (profile) from each set they are asked to evaluate (Louviere and Woodworth 1983; Louviere 1988). The statistical analysis of such choice based responses is typically conducted by using the random utility model (RUM) (McFadden 1974).

In the RUM, individual behaviour is considered to be deterministic, but due to the inability of the research process to account for all influencing attributes and the requirement to aggregate choices across individuals, the modeling of behaviour is undertaken stochastically (Train 1986; Ben-Akiva and Lerman 1985). Therefore, it is assumed that the overall utility (U_i) contained in any one alternative is represented by a utility function that contains a deterministic component (V_i) and a stochastic component (e_i). Selection of one alternative over another implies that the utility (U_i) of that alternative is greater than the utility of any other alternative (U_j). The overall utility of alternative i is represented as (McFadden 1974; Train 1986):

$$U_i = V_i + \varepsilon_i \qquad (1)$$

An individual will choose alternative i if $U_i > U_j$ for all $j \neq i$. However, since the utilities include a stochastic component, one can only describe the probability of choosing alternative i as:

$$\text{Prob}\ \{\text{i chosen}\} = \text{prob}\ \{V_i + \varepsilon_i > V_j + \varepsilon_j\ ;\ \forall j \in C\} \qquad (2)$$

where C is the set of all possible alternatives. If one assumes that, for the entire sample, the stochastic elements of the utilities follow a Gumbel distribution, the standard multinomial logit (MNL) model can be specified (McFadden 1974; Ben-Akiva and Lerman 1985):

$$\text{Prob}\ \{\text{i chosen}\} = e^{Vi} / \sum e^{Vj} \qquad (3)$$

where the aggregate probability of choosing alternative i equals the exponent of all the measurable elements of alternative i over the sum of the exponent of all measurable elements of all j alternatives. This standard MNL model supports the estimation of parameters that allow one to express the choice probability of a given alternative as a function of the attributes comprising that alternative and those attributes of all other alternatives in the choice set.

Following an orthogonal Resolution III fractional factorial design (Raktoe et al 1981), a total of 18 choice sets were required to estimate each of the two models (i.e. one for the urban and the other for the rural survey). These 18 sets were blocked orthogonally into two sets of nine sets each, and each respondent evaluated one set. Data were collected during personal interviews and, therefore, each choice set was presented as a separate flash card. The response task involved choosing one of the alternatives from each card (see Figure 5 a and b, for example). In addition to the nine cards in one set, a tenth card containing a scenario that was not part of the design was first presented to familiarize the respondents with the task.

(a) Emergency evacuation policies

OPTION 1	OPTION 2	OPTION 3
Evacuation: **mandatory**	Evacuation: **voluntary**	Evacuation: **no evacuation**
Notice of evacuation: **4 days**	Notice of evacuation: **1 day**	
Flood relief: **80%**	Flood relief: **90%**	Flood relief: **80%**

If the risk of hazardous flooding were **50% (1 in 2 chances)**, which one of the three options would you choose?

(b) Floodplain management policies

Which of the 4 policies on this card would you choose? **Cs 2**

POLICY 1 Flood Proof	POLICY 2 Buyout & Relocate	POLICY 3 Buyout & Life Lease	POLICY 4 Status Quo
GOVERNMENT PAYS *$80,000 MAX*	*RELOCATION ALLOWANCE* *$90,000*	*CONTENT COMPENSATION* *60%*	
DISASTER RELIEF (if flood exceeds level of 1997 + 2 ft) *70%*			*DISASTER RELIEF (if flood exceeds level of 1997 + 2 ft)* *70%*
❐	❐	❐	❐

Figure 5. Sample choice cards for (a) emergency flood evacuation and (b) flood-proofing vs relocation

Results and Interpretations

Respondents' Estimates of Flood Damage

The total flood damage in the Red River basin during the 1997 flood has been estimated at $500 million (Burn 1999). Almost every flood-affected resident of the basin experienced some losses. However, rural residents incurred significantly greater losses compared to urban residents, and the types of damages experienced by the two respective groups also differed. Although all surveyed urban communities were evacuated, respondents' experience of flooding differed significantly among them, depending on the efficacy of flood protection by their ring dikes. Data in Table 3 indicate that Emerson and Morris were both protected most effectively by their embankments, as not a single respondent experienced any direct flooding inside their homes. In contrast, Ste Agathe, which did not have a permanent ring dike, was most vulnerable to all categories of direct and indirect flood-related problems. Its residents experienced the most serious problem of sewer backup in the basement (N = 26 out of 30 or 87%), followed by groundwater seepage (17%) and direct flooding inside home (13%). The magnitude of its flood problems was reflected primarily in the depth of sewer backup, which averaged at 1.6 m. Even the depth of direct floodwater on the main floor was substantial, averaging at 6.2 cm. St Adolphe experienced minor flood-related problems, compared to Ste Agathe, but at least two respondents (5%) reported floodwater inside their homes. Only one respondent (2.5%) reported sewer backup, but its depth was significantly higher than that in either Emerson or in Morris. Although the latter communities did not experience direct inundation, groundwater seepage in the basement (of insignificant depth) was experienced by several of their respondents. As expected from the diverse nature of its flood-related problems, significantly higher proportions of the Ste Agathe respondents experienced flood damage to a larger number of items, ranging from foundation of homes to carpet, furniture and appliances.

Table 4 presents data on flood damages in rural areas. Data have been segmented here into three groups according to respondents' preferences from choice cards. Thus, the mean sizes of land holding were, respectively, 809 acres for those who preferred floodproofing (N = 75), 390 acres for those who preferred relocation (N = 10), and 595 acres for those who opted for doing nothing (N = 15). The extent of flooding becomes very obvious in these data. Between 73% and 91% of the properties were flooded. The average depth of flooding on the yard ranged from 1 m to 2 m. The depth of flooding in the basement ranged from over one-third of a meter to 2 m. Most of the respondents experienced direct inundation on the main floor of their homes, ranging from 2 cm to 40 cm. The average depth of floodwater in the crop fields varied from 0.95 m to 1.81 m. As expected from this catastrophic flood, farmers sustained major crop losses, amounting to averages of at least $5000 to nearly $15,000. Major monetary losses resulted from damages to barns and machinery, with estimated losses averaging between $12,000 and over $22,000. Damages to homes (including carpet and furniture), were similar or higher (averaging $14,000 to $38,000). Other damages, as reported in Table 4, were also substantial.

Table 3. 1997 Urban Survey: Effects of Flooding on Personal Property During the 1997 Flood

	Emerson N = 50	Morris N = 50	Ste. Agathe N = 30	St. Adolphe N =40
Nature of Flooding				
Floodwater inside home on the main floor (% of respondents)	0	0	13	5
Sewer backup in basement (% of respondents)	2	2	87*	2.5
Groundwater seepage in basement (% of respondents)	34*	12	17	5
Mean depth of floodwater on the main floor (cm)	0.00	0.00	6.20	0.78
Mean depth of sewer backup in the basement (cm)	4.74	0.45	160.00**	9.60
Items damaged (as reported by respondents)				
Carpet	14%	2%	87%*	7.5%
Furniture	8%	2%	59%*	7.5%
Dry wall	8%	0	80%*	10%
Foundation	4%	0	52%*	2.5%
Furnace	6%	0	90%*	2.5%
Water heater	6%	0	93%*	2.5%
Washing machine	0	0	50%	0
Dryer	0	0	47%	0
Freezer	0	0	54%	2.5%

* Respective community differs significantly from other three communities combined (Chi-Square Test $p < 0.05$)

** Respective community differs significantly from other three communities combined (Kruskal-Wallis H-Test $p < 0.05$)

Note: Cells may have had expected cell frequency violation.

Source: Authors' Questionnaire Survey, August 1997

.**Table 4.** 1998 Rural Survey: Nature of Flooding in Personal Property and Flood Damage

Group 1	Group 2 (Floodproof)	Group 3 (Relocate)	(Do nothing)
Size of land holding (acres)	**Mean**	**809**	**390595**
(std dev)	(886)	(405)	(705)
Percent of land flooded in 1997	**Mean**	**91**	**98 73**
(std dev)	(17)	(7)	(38)
Depth of flooding on the yard (m)**	**Mean**	**1.03**	**2.020.61**
(std dev)	(0.83)	(0.63)	(0.66)
Depth of flooding in basement (m)**	**Mean**	**0.79**	**2.00.36**
(std dev)	(1.05)	(0.84)	(0.72)
Depth of flooding on main floor (m)	**Mean**	**0.12**	**0.40.02**
(std dev)	(0.35)	(0.39)	(0.07)
Depth of flooding in crop fields (m)**	**Mean**	**1.53**	**1.810.95**
(std dev)	(0.84)	(0.81)	(0.56)
Loss of crops ($)	Mean	$14,637	$5,000$5,714
(std dev)	(51,011)	(10,000)	(14,393)
Barn and machinery damaged ($)*	**Mean**	**$22,264**	**$12,300$19,811**
(std dev)	(70,817)	(14,014)	(58,204)
Damage to home (includingCarpet and furniture) ($)**			
	Mean	**$15,456**	**$38,000$13,818**
(std dev)	(27,327)	(40,133)	(45,170)
Other damages ($)**	Mean	$12,477	$18,967$409
(std dev)	(66,368)	(27,709)	(1044)

Kruskal-Wallis 1-way ANOVA Test: **Differences among the groups are significant at *p <0.01*; *Differences among the groups are significant at *p <0.05*
Source: Authors' Questionnaire Survey, August- September 1998

Floodplain Residents' Perceptions of Flood Alleviation Measures

To gain some insights into floodplain residents' preferences for structural and non-structural flood alleviation, both urban and rural respondents were asked to rate the effectiveness of a selected number of measures (Tables 5 and 6) on a 5-point Likert scale. Data in Table 5 indicate that there were significant inter-community differences in the urban respondents' perceptions of the effectiveness of all of the suggested flood alleviation measures, with the exception of upgrading ring dikes around town. With mean rates ranging between 4.37 and 4.83, the respondents from all of the four urban communities emphasized the importance of this measure. This high approval rating of the temporary structural measure appear to reflect the respondents' successful experience with the sandbagging operation for reinforcing the ring dikes around their communities. The remaining items were rated more favourably by respondents from Ste Agathe and St Adolphe, confirming the expectation that respondents' flood hazard experience influenced their perceptions about the need for implementing several of these measures.

In the rural survey (Table 6), the mean scores for the Likert scale rating have been grouped by respondents' preferences for floodplain management policies (i.e. floodproofing and relocation), which was another question in the same survey. Flood prevention through upgrading ring dikes and sandbagging around personal property were highly preferred measures of those who opted for floodproofing (mean scores = 4.22 and 4.42, respectively). These measures were still approved, but with a lower aggregate score (scores of 3.38 to 3.88) by those who opted for relocation. Predictably, the measure to relocate inside a ring-diked community was rated significantly more favourably by the group who preferred relocation (score of 3.5), compared to those who preferred floodproofing (1.16). The last two measures, namely flood insurance and check dams on tributaries, were rated slightly more favourably by the group who preferred doing nothing compared to the remaining two groups. However, these differences on the last two measures were not statistically significant (Table 6). Contrary to the expectation, respondents who preferred relocation rated elevating homes above flood levels more favourably than those who chose floodproofing. Otherwise there seemed to be a predictable relationship between respondents' preferences for floodplain management policies (i.e. floodproofing vs relocation or do nothing) and their perceptions of effectiveness of the suggested structural and non-structural flood alleviation measures.

Urban Residents' Preferences for Emergency Evacuation Policies

As mentioned earlier, one of the most contentious issues during the 1997 flood revolved around the mandatory evacuation orders, which caused much confusion and resentment (Clayton 1999). Many residents felt that if they could demonstrate that they were properly prepared for the flood event, they should have been allowed to stay at their homes to maintain pumps and monitor the integrity of their private flood protection systems (Burn 1999). The mandatory evacuation orders by the MEMO were based on the concerns over potential dike failure or spilling over ring dikes, resulting in hazardous flooding and threats to life. However, much of these technical concerns were not communicated properly to the residents. Besides such issues of risk assessment and risk communication, many residents had reservations about the limited amount of notification time for evacuation. They were also uncertain about the level of post-evacuation compensation (flood relief) for their property losses (Rasid et al. 2000). These concerns stood at the core of the study undertaken during the summer of 1997, in which these issues were explored with some

Table 5. 1997 Urban Survey: Respondents' Perceptions of Effectiveness of Flood Alleviation Measures (average values of 5-point Likert scale rating, where 1 = least effective and 5 = extremely effective)

	Emerson N = 50	Morris N = 50	Ste. Agathe N = 30	St. Adolphe N =40
Upgrade ring dikes around town				
Mean	4.44	4.67	4.37	4.83
(std dev)	**(0.93)**	**(0.69)**	**(1.13)**	**(0.45)**
Sandbag during major floods*				
Mean	3.94	2.42	3.83	3.30
(std dev)	**(1.11)**	**(1.55)**	**(1.02)**	**(1.36)**
Improve disaster relief*				
Mean	3.29	3.53	4.07	3.92
(std dev)	**(1.11)**	**(1.49)**	**(1.31)**	**(1.08)**
Provide flood insurance policy*				
Mean	2.83	3.56	4.11	3.59
(std dev)	**(1.36)**	**(1.44)**	**(1.42)**	**(1.19)**
Build check dams on tributaries*				
Mean	2.20	2.98	3.22	2.66
(std dev)	**(1.25)**	**(1.51)**	**(1.40)**	**(1.28)**

* Significant inter-community differences (Kruskal-Wallis H-Test: $p < 0.05$)

Table 6. 1998 Rural Survey: Respondents' Perceptions of Effectiveness of Flood Alleviation Measures (average values of 5-point Likert scale rating, where 1 = least effective and 5 = extremely effective)

Group 1	**Group 2**	**Group 3**	
	(Floodproof)	(Relocate)	(Do nothing)
Upgrade ring dikes around property**			
Mean4.22	**3.88**	**1.80**	
(std dev)	(1.59)	(1.81)	(1.66)
Sandbag during major floods**			
Mean4.42	**3.38**	**2.07**	
(std dev)	(1.35)	(2.0)	(1.83)
Elevate homes*			
Mean	2.73	3.38	1.53
(std dev)	(1.80)	(2.00)	(1.41)
Relocate inside a ring-diked community**			
Mean1.16	**3.50**	**1.27**	
(std dev)	(0.73)	(2.07)	(1.03)
Provide flood Insurance policy			
Mean1.34	**1.25**	**1.80**	
(std dev)	(1.11)	(0.71)	(1.66)
Build check dams on tributaries			
Mean2.16	**1.75**	**2.60**	
(std dev)	(0.73)	(2.07)	(1.03)

Kruskal-Wallis 1-way ANOVA Test: **Differences among the groups are significant at $p < 0.01$; *Differences among the groups are significant at $p < 0.05$

Table 7. 1997 Urban Survey: Results of the Discrete Choice Experiment on Emergency Evacuation

Alternative /attribute level	Parameter estimate	Standard error	t-value
Intercepts:			
NO EVACUATION	0.000		
MANDATORY EVACUATION	2.019	0.141	14.304*
VOLUNTARY EVACUATION	2.044	0.139	14.656*
Mandatory Evacuation			
Probability of hazardous flooding			
50%	–1.555		
75%	0.146	0.173	0.846
99%	1.408	0.203	6.923*
Notice of evacuation			
1 day	– 0.172	0.086	– 2.001*
2 day	0.079	0.084	0.941
4 day	0.093		
Flood relief			
75%	– 0.379	0.086	– 4.403*
80%	– 0.086	0.096	– 0.899
90%	0.465		
Voluntary Evacuation			
Probability of hazardous flooding			
50%	–0.750		
75%	0.197	0.171	1.155
99%	0.553	0.205	2.696*
Notice of evacuation			
1 day	– 0.086	0.079	– 1.092
2 day	– 0.013	0.081	– 0.155
4 day	0.099		
Flood relief			
75%	– 0.357	0.082	– 4.338*
80%	– 0.085	0.078	– 1.088
90%	0.441		
No Evacuation			
Flood relief			
75%	– 0.106	0.110	– 0.965
80%	0.106		

*p <0.05 McFadden's Rho Square: 0.30

Likert-scaling questions, and a discrete choice experiment. The DCE was analyzed as a conditional multinomial logit regression in Limdep software (Greene 1998). Table 7 lists the parameter estimates, standard errors and t-values for each attribute level used in the experiment. The attribute levels for the risk of hazardous flooding were selected on the basis of the theory of risk perception and the probability thresholds for natural hazards (Palm 1981). The intervals for notification time were extrapolated from the literature on evacuation notices for other disasters (Alexander 1993; Stephenson 1981). The rationales for the selection of attribute levels have been explained at some length in Rasid et al. (2000).

Because of the alternative-specific nature of the model, the highly significant intercepts for both mandatory and voluntary evacuation indicate that either of the modes of evacuation is about equally preferred over no evacuation notices, as long as all other parameters remain constant. Among the three attributes, the probability of hazardous flooding emerged as the most important determinant of evacuation choice. Respondents indicated significantly higher support for either of the two evacuation modes when the probability of hazardous flooding was extreme (99%), as opposed to moderate (75%), or low (50%). The part-worth utilities for the three levels of probability of flooding (chances of overtopping /breaching through dikes) suggest an approximately linear functional form, but the implied slope for this variable being much steeper for mandatory evacuation when compared to voluntary evacuation (Figure 6). In other words, mandatory evacuation is considered as a very acceptable emergency policy feature when there is a 99% likelihood of flooding to occur (asymptotic t-test: $t = 5.31$; Ben-Akiva and Lerman 1985, 161). It is regarded as about equal with voluntary evacuation in a situation of 75% likelihood of flooding. Given the linear trend in the estimate, the reverse is true at a low probability of flooding.

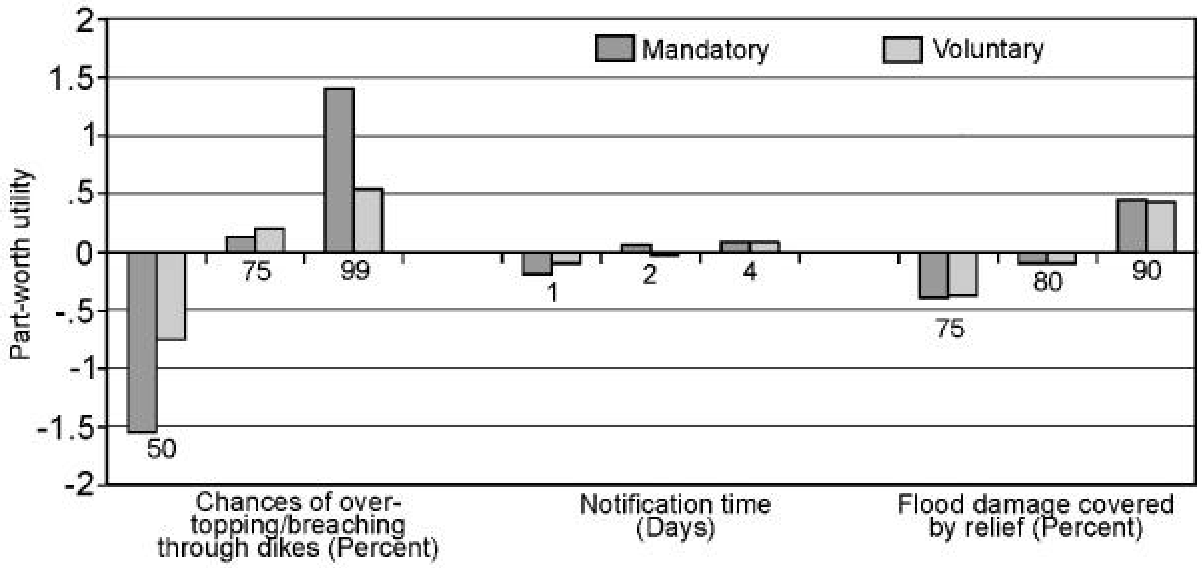


Figure 6. Part-worth utility of urban respondents' preferences for emergency evacuation policies

The number of days of notification for mandatory evacuation was significantly related to evacuation choice. Respondents viewed a one-day notice as a significant deterrent for both mandatory and voluntary evacuation, with the one-day notice considered even less acceptable in the mandatory situation. The results seem to follow intuition, as respondents would like to have some preparation time when a mandatory evacuation is issued, while for voluntary evacuation immediate compliance cannot be enforced anyway.

Respondents had strong views about the amount of flood compensation to be provided, with clearly opposing even a 5% reduction in disaster relief, and strongly favouring a 10% increase. This trend is very consistent for both modes of evacuation. The level of flood relief was the only variable included with the 'no evacuation' option, where it was allowed to vary between 75% and 80% only; it was deemed inappropriate to offer an improved benefit package at 90% as a reward for not evacuating. For this alternative, no significant difference was distinguishable between a 75% and 80% level of funding.

In summary, this study showed the importance of confronting the general public with a properly formulated tradeoff question, in which respondents choose among sub-optimal options, just like in real life. These findings stand in stark contrast to results we obtained about the acceptance of voluntary and mandatory evacuation in a uni-dimensional Likert-scale questions in the same survey: predictably, voluntary evacuation was preferred over mandatory evacuation when no further explanations were provided about the surrounding conditions (Rasid et al. 2000). The results of the DCE document the importance of asking policy and management related questions in a tradeoff type format, and our results prove that randomly recruited respondents are well poised to discriminate between relevant policy options.

Rural Residents' Preferences for Floodplain Management Policies

For the same reasons that we employed a DCE study to emergency evacuation policy, we also designed a study with hypothetical tradeoff scenarios to uncover residents' responses to long-term floodplain management policies (see above). These policies were targeted primarily at rural residents. Unfortunately, the fielding of the 1998 study coincided with the policy announcement. Compared to the generous incentives of the actual program, the attribute levels selected for the 1998 discrete choice experiment were overly conservative in retrospect. For example, we proposed a maximum relocation allowance of 90% of the total cost. This would have resulted in a 10% loss to the owner. The Canada-Manitoba program pays 100% for the buyout of the existing structure, plus a relocation allowance of $30,000. Consequently, most respondents did not trade off among the various proposed attributes, which obviously were not specified over a range that would make a difference to them, but simply selected their preferred alternative (i.e. floodproofing, relocation, and do nothing). Out of 96 valid cases, three-quarters (75-77%) preferred floodproofing, 14-16% preferred doing nothing, and 8-10% opted for relocation. It should be of specific interest to policy-makers that significant differences emerged among these three groups with regards to their experience of the 1997 flood. Predictably, those who suffered heavy flood losses preferred floodproofing (Table 8a). Statistical tests of association of selected structural and non-structural flood alleviation measures (Table 8b) further suggest that the first two groups rated these measures more favourably. The third group who preferred doing nothing under-rated the effectiveness of the suggested measures.

By 2000, many residents actually had filed their applications for the floodproofing program. It turned out that, contrary to the government expectations, the majority of residents had opted for the floodproofing option, despite an attractive relocation option that the officials would have preferred. Therefore we designed another choice experiment, consisting of the following four alternatives: (a) floodproof, (b) buyout and relocate, (c) buyout and life lease, and (d) status quo (do nothing) (Figure 5b). For alternative (b) we proposed significantly more attractive relocation allowances than the government offer, whereas we proposed lower support for two levels of the

Table 8. **1998 Rural Survey: Respondents' Preferences for Flood Alleviation Measures**

Floodproof	**Relocate**	**Do nothing**	
(a) Those who experienced	Percent of respondents	**the following:**	
Depth of flooding on the yard** *(N = 94)*	75	9	16
Depth of flooding in the basement** *(N = 94)*	77	8	15
Depth of flooding in the crop field** *(N = 94)*	76	8	16
Damage to barn and machinery* *(N = 66)*	77	9	14
Damage to home including carpet and furniture** *(N = 73)*	75	10	15
Other damages** *(N =74)*	77	8	15
(b) Those who ranked the	Percent of respondents	**following measures by** *using a Likert-scale*	
Permanent upgrading of ring dikes** *(N = 95)*	76	8	16
Sandbagging** *(N = 96)*	76	8	16
Elevate homes* *(N = 96)*	76	8	16
Relocate inside a ring-diked community** *(N = 96)*	76	8	16

Kruskal-Wallis 1-way ANOVA Test: **Differences among the groups are significant at $p < 0.01$; *Differences among the groups are significant at $p < 0.05$

Table 9. 2000 Rural Survey: Results of the Discrete Choice Experiment on Floodproofing and Relocation

Alternative /attribute level	Parameter estimate	Standard error	t-value
Intercepts:			
STATUS QUO (DO NOTHING)	0.000		
FLOODPROOFING	1.044	0.219	4.765*
RELOCATION	–1.484	0.227	–6.529*
Floodproofing			
Government pays			
$50,000	0		
$60,000	–0.026	0.201	–0.129
$70,000	0.179	0.204	0.878
$80,000	0.100	0.202	0.498
Relocation			
Relocation allowance			
$30,000	0		
$50,000	1.113	0.249	4.455*
$70,000	1.540	0.228	6.742*
$90,000	1.876	0.216	8.665*
Flood relief			
Government pays			
70%	0		
80%	0.085	0.246	0.347
90%	0.167	0.244	0.686
100%	0.051	0.248	0.205

*p <0.05 McFadden's Rho Square: 0.245

maximum government contribution for floodproofing. The disaster relief options remained at the status quo. Table 9 presents the results of this follow-up discrete choice experiment that was conducted in 2000. Because the alternative (c), ie. 'buyout and life lease' was chosen only rarely, it was combined with alternative (b) in the analysis. Despite very generous offers of relocation allowances in some choice sets, and a reminder for respondents to select an option from each of the choice sets based on its face value, the majority of respondents could not be enticed to choose an alternative other than the one already chosen.

Given the fact that the majority of respondents had opted for floodproofing, the intercept for that alternative is significantly more positive (as compared to the option 'do nothing'). In contrast, the 'buyout' alternatives were less attractive than the base alternative of doing nothing. The only other variable of significance is the relocation allowance, indicating that only at very high levels of compensation are these respondents willing to consider that option. In other words, the responses to the DCE are dominated by the alternatives that each respondent has selected already. The floodplain residents did not necessarily have a consensus that one option was better than all others, but the majority of respondents felt strongly for one alternative, regardless of the conditions associated with any of the other alternatives in any of the eight choice sets. A total of 72% of respondents (73 out of 102) opted for one alternative consistently (46 for the floodproofing option, 6 for buyout and relocation, 2 for buyout and life lease, and 19 for doing nothing).

When we segmented the responses between those who had applied for any one of the schemes offered (N = 81), versus those who did not (N = 21), the pattern of results in the estimates remained remarkably similar except in the intercepts. Applicants were more in favor of floodproofing (coefficient = 2.02, t = 6.34) and indifferent to the buyout options (coefficient = –0.49, t = –1.55), while non-applicants predictably disliked either of the options when compared to doing nothing (coefficient = –1.06, t = –2.24 for floodproofing, and coefficient = – 4.11, t = –5.37 for buyout).

It appears from the preceding analysis that the vast majority of the respondents, who had already applied for floodproofing, were not willing to consider financial incentives for relocation as a tradeoff for their choice of floodproofing. Living in a hazardous environment can be justified only if that environment is considered as a resource outweighing the risk (White 1974), and there ought to be other attractions or amenities for these rural residents to remain in the Red River basin. Therefore, the respondents were asked to rate the importance of several factors for living on the floodplain (Table 10). Out of the six factors, the two most abstract attributes, namely preference for rural living and attachment to land, yielded the highest ratings (mean scores: 4.07 and 4.67 respectively for the sample, i.e. very important to extremely important). These findings seemed to be instructive, because if these variables were the primary reasons for staying in the floodplain, perhaps no amount of financial incentives could change respondents' preferences. Fertile land was also somewhat important (mean score: 3.22 to 3.52). The moderate rating of "flood was not an issue" seemed to indicate that although the flood hazard did not deter the residents to reside on the floodplain, there was scope for improvement. Floodproofing seemed to provide such improvement. The scores for those who did not apply for floodproofing were not significantly different from those who applied.

Conclusion

This paper summarized the current situation for structural and non-structural flood alleviation measures in the Red River basin, and then presented results of several surveys of floodplain residents which provided insights into their perspectives on selected flood /floodplain management issues. The brief review of the performance of some of these measures revealed mixed results. On the positive side, the Red River floodway is credited for saving the City of Winnipeg from a major flood disaster (Caligiuri and Topping 1999; Winnipeg Free Press 1997). At the same time, the decision to maintain the water level in the Red River at about 0.3 m (1 ft) below its design level in Winnipeg, had contributed to abnormally high water levels at Grande Pointe and Ste Agathe, immediately upstream of the floodway. According to some of the key

Table 10. **2000 Rural Survey: Respondents' Attractions of Living on the Floodplain**
(average values of 5-point Likert scale rating, where 1 = least attractive and 5 = most attractive)

Attractions	Those who applied for floodproofing (N = 81)	Those who did not apply for floodproofing (N = 21)
Inherited property		
Mean 2.14	2.90	
(std dev)	(1.72)	(1.76)
Attachment to land		
Mean 4.07	4.10	
(std dev)	(1.23)	(1.22)
Fertile land		
Mean 3.22	3.52	
(std dev)	(1.64)	(1.54)
Cheap land		
Mean 1.60	1.90	
(std dev)	(0.98)	(1.04)
Flood was not an issue		
Mean 3.0	3.38	
(std dev)	(1.40)	(1.50)
Prefer rural living		
Mean 4.67	4.33	
(std dev)	(0.71)	(1.15)

informants and media reports, there was a widespread perception among the residents of Ste Agathe that their town was flooded because of the operation of the floodway and the construction

of the Z-dike. Contrary to this perception, hydraulic modeling by Klohn-Crippen (1998) had shown that even under natural conditions the town would have flooded (Burn 1999). The performance of the flood control dikes demonstrated similarly mixed results. Undoubtedly, the ring dikes around smaller urban communities and rural farmsteads protected these communities from direct inundation. However, as data in Table 1 indicated, the floodwater rose very close to the top of the dikes, necessitating emergency sandbagging to prevent over-dike spilling due to wind setup. In other words, the performance of ring dikes reached a threshold that kept both the residents and the emergency workers on the edge, necessitating the MEMO to issue a mandatory evacuation order.

Although the WRB deserves credit for the early forecast of the impending ‘flood of the century’, repeated revisions of water levels during the operational phase of the flood introduced an element of uncertainty in flood warning. The emergency preparedness and response by three levels of government were coordinated quite effectively by the MEMO with a central goal of preventing loss of life. Since there was not a single loss of life directly from flooding, MEMO’s operation may be considered as a success from this perspective. However, there were major problems in communicating the meaning of the term “mandatory evacuation”. The results of our experimental study on emergency evacuation policies indicated that the respondents were willing to accept mandatory evacuation at a very high risk of flooding (i.e. at 99% or imminent risk). This implies that if the risk of hazardous flooding were explained adequately and in a trustworthy manner to the residents, perhaps they would be less resentful of the mandatory evacuation order. Following a post-flood review of its performance by a consultant, the MEMO is in the process of implementing several recommendations for improving its emergency management policies (Clayton 1999).

Prior to the announcement of the Canada-Manitoba floodplain management program, structural flood control, through such engineering interventions as dikes and floodways, have dominated flood alleviation measures in the Red River basin. The floodplain residents of the basin have also demonstrated a strong preference for structural measures, such as upgrading ring dikes and sandbagging, for the solution of their flood problems (Tables 5 and 6). Their dominant preference for floodproofing in lieu of relocation to flood-free zones is consistent with this reliance on engineering interventions. Although floodproofing is considered as a semi-structural measure (Alexander 1993), it involves certain amounts of engineering interventions. One of the problems of relying too heavily on structural measures is that they provide a false sense of security (Kumar et al. 2000, 8). Often the post-flood compensation policy promotes continued reliance on flood control infrastructures. For example, the Grande Pointe residents were permitted to submit claims in excess of the provincial limit of $100,000, since post-flood hydraulic modeling confirmed that abnormally high water levels in this community were contributed by the operation of the floodway. Similarly, in other areas, the 20% deductible for disaster assistance was waived. The main problem with such a policy of full compensation for flood losses is that it undermines floodplain land use regulations and promotes continued occupance of flood-prone lands. In particular, this policy penalized indirectly those landowners and municipalities that had implemented floodplain regulations at a cost to themselves (Shrubsole 200, 16).

In the wake of the 1997 flood in the Red River basin, the Province of Manitoba has established a new standard for floodplain development. Primary responsibility for implementation of the new development standard rests with municipal governments who may use their discretion in applying minimum building elevations into building by-laws (Morris-Oswald et al. 1998). Provincial agencies will not be able to ensure effective implementation of this standard. While new provincial legislation has been introduced to preclude disaster relief to development that fails to comply with the new standard, past experience suggests that this intent will likely not be followed (Shrubsole 2000, 16). As past lessons have shown, the effectiveness of programs to deal with flood hazards may be limited if they are not adhered to. Permitting increased occupancy by municipalities in designated flood risk areas is an example of such relaxation of land use regulations (Shrubsole et al. 1995 and 1997; Kreutzwiser 1988; Forget et al. 1999). There should be a broadening of municipal and individual responsibilities to include or strengthen their roles in floodplain management and flood hazard mitigation. This situation suggests the importance of social science research on the various aspects of short-term and long-term flood /floodplain management policies, which other authors have also suggested recently (Kumar et al. 2000; Shrubsole et al. 1997). So far in Canada very little research has been undertaken about individual behaviour in flood hazard risk mitigation and response. The case studies presented in this paper relied on public surveys and produced several important insights about individual residents' perceptions and tradeoff behavior.

Multivariate stated preference research approaches could make important contributions to decision-making about flood alleviation measures. Ultimately the success of both structural and non-structural measures depends on the adoption and correct response by the residents to these measures. Stated preference methods provide insights into how members of the general public will adjust to such measures and policies before they are built or implemented. The case study on emergency evacuation policies showed that randomly selected respondents could successfully respond to these tradeoff questions and provide insights that were not otherwise available. In contrast, the case studies on long-term floodplain management policies documented the limitation of a stated preference / choice approach, which appeared to be inappropriate in a situation when a policy had already been announced. In such a situation, respondents should be guided by several competing motives, which might be rational in their own way, such as rationalizing the decision they had taken already, as opposed to the rational response behaviour that the DCE would require.

Other survey methods play an important role in gaining insights about additional factors influencing tradeoff behaviour. For example, respondents' attractions for living on the floodplain appear to be such a value, and such information contributes to understanding actual behavior of floodplain residents, as well as their response behaviour to stated preference questions. We would argue that discrete choice experiments, and other methods for structuring tradeoff behavior are important tools for decision-making in floodplain management, because this kind of research provides a statistically rigorous analysis of public opinions and tradeoffs for technical and/or management options or outcomes. Therefore, we suggest that these more formal quantitative survey procedures should be regarded as an important complement to more qualitative social science approaches. In particular, these survey procedures provide essential information about affected stakeholder groups or the public and thus complement the technical nature and technical expertise that inevitably dominate flood /floodplain management.

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