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Mathematical Modelling for the Integrated Management of Water Resources in Hydrological Basins

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Abstract Mathematical models are tools that can facilitate the instrumentation of the Integrated Water Resources Management (IWRM). The first basin models to be developed were completely hydrological; today, due to the urgent need to plan the sustainable use of water resources, new models are needed that in addition to hydrology also incorporate social, economic, legal, environmental and other aspects. The objective of this work was to identify the characteristics that mathematical basin models must have in order to satisfy the requirements of IWRM. To achieve this, the conclusions of the main international conferences on water and the environment were analyzed; these were conferences in which IWRM was promoted as a strategy to face the challenges of both sectors. IWRM considers social participation as a key element in the decision-making process; consequently, the models must be accepted

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and applied, and their results interpreted, by those who participate in the process even if they are not modelling experts. This requires a change of perspective in the scientific community for the development of new IWRM models, in government institutions regarding their role as water administrators, and in water stakeholders regarding their role as decision-makers. The results of the analysis indicate that models for IWRM must be accessible to non-expert users, integrate different viewpoints, representing adequately the problem to be solved, in addition be flexible and have a structure focused on practical solutions.

Keywords Integrated management of water resources • Decision support systems • Mathematical basin modelling • Hydrological models • Water resource management

1 Introduction

Since the first International Water Conference was held in 1977 by the United Nations in Mar de Plata, Argentina, the number of gatherings at which the Integrated Water Resources Management (IWRM) is discussed has gradually increased as has the number of actions agreed upon by the participating countries. In a parallel way though with less intensity, the interest of the scientific community on this subject is manifested by the growing inclusion of this subject in national and international congresses and conferences, as well as articles in scientific journals. This denotes the importance that humanity has given to the current water crisis.

The concept of the Integrated Water Resources Management was recognized in Agenda 21 during the 1992 United Nations Conference on Environment and Development (GWP-TEC 2004). It was later proposed in the Implementation Plan of the 2002 World Summit on Sustainable Development in Johannesburg. It was identified during the United Nations World Summit in 2005 as a strategy to accomplish the United Nations Millennium Development Goals. Finally, the importance of IWRM was consolidated when it was integrated as a framework theme during the Fourth World Water Forum held in Mexico City in March 2006 (WWC-CNA 2006b).

Presently, IWRM tends to be integrated into development policies and national hydrological management plans by a greater number of countries in the world (WWC-CNA 2006b). According to the results of an evaluation performed by Global Water Partnership (2006) to determine the state of the IWRM planning process in 95 associated countries, 21% have established plans and strategies or are in the process of achieving this, 53% have already started the process to formulate the plans and strategies of IWRM, and the remaining 26% presents very limited progress. Many manifest their intention to advance but require help to achieve this. This evaluation included 38 countries in Africa, 23 in Asia and Oceania, ten in Europe, 16 in Latin America, and eight small island states from the Pacific and Caribbean (GWP 2006).

Under the IWRM approach, it is recognized that mathematical basin models are a valuable tool for their instrumentation (WWC-CNA 2006b). However, it is very important to know whether existing models satisfy the demands of IWRM in their present condition or need some modification. This paper has the objective of identifying the basic characteristics that mathematical basin models must gather in order to be used in an IWRM scheme.

2 The Integrated Water Resources Management and Its Instrumentation

The Integrated Water Resources Management is visualized as a strategic planning process, with the finality of promoting the development and coordinated management of water and related natural resources, in order to achieve a better economic use and social well-being in an egalitarian way oriented towards the conservation of the environment (GWP-TEC 2004). However, it is not limited to the management of the physical environment; it also refers to modifying social and institutional systems as necessary so that people can be benefited the most by the use of natural resources (GWP 2004).

According to the Global Water Partnership Technical Committee (2004), IWRM is not a static approach with predetermined rules, but a dynamic proposal with common sense based on the Dublin Principles (ICWE 1992). These principles establish that:

1. Fresh water is a finite and vulnerable resource, essential to life, development, and the environment.
2. The development and management of water resources must be founded on a participative proposal involving users, planners and decision makers at all levels.
3. Women have a central role in the provision, management and safeguard of water.
4. Water has an economic value in all of its competitive uses. It must be recognized as an economic and social good.

In order to instrument IWRM, it is fundamental to adapt these basic principles in view of local needs and, naturally, of the changing problems and conditions of each particular case. This is achieved by updating, expanding and making these basic principles more specific as necessary (GWP-TEC 2004).

Therefore, due to the socioeconomic asymmetry of the world, there will necessarily be a difference between the instrumentation of IWRM in countries with a great development of their hydraulic infrastructure and countries that are starting their development or are in transition stages (WWC-CNA 2006a). In countries of lower development, IWRM can serve as a mechanism for using water for growth and development, helping the reduction of poverty and hunger, increasing well-being and improving the environment. Countries in transition can identify IWRM as a strategy to optimize the management of their resources and guarantee the continuity of socioeconomic development. For developed countries, IWRM can serve as a base framework that can be modified to satisfy specific needs and expectations (WWC-CNA 2006a).

In the work done by Rahaman et al. (2004), the results of the following are presented: the International Conference on Water and the Environment held in Dublin in 1992, the Second World Water Forum held in The Hague in 2000, the International Freshwater Conference held in Bonn in 2001, and the World Summit on Sustainable Development held in Johannesburg in 2002. The last three were conferences of great international penetration and influence in which IWRM was promoted. In these conferences, to instrument a participative decision-making process involving users, stakeholders and the general society was identified as a key issue. This is further reiterated in Fourth World Water Forum and the preparatory work leading up to it (WWC-CNA 2006b).

The Training Manual and Operational Guide for the Establishment of Plans for the Integrated Water Resources Management (CapNet and GWP 2005) describes in further detail the four Dublin principles (ICWE 1992). From this explanation it is possible to say that this new focus demands, among other things:

1. A hollistic point of view that considers the behaviour of natural physical systems as well economic and social systems.
2. The hydrological basin is the basic unit for the management of water resources.
3. Social participation in the decision-making process, involving water users, administrators, non-governmental organizations and the society, in the design of plans and strategies for the management of water resources.
4. In particular, the participation of women in decision-making at all levels.
5. Cultural changes oriented towards increasing consciousness about the importance of water among decision-makers and society.
6. Generation and diffusion of knowledge that makes responsible participation possible.
7. Recognizing that water has an economic value but is also a social good. The economic value of water is important to decide how best to distribute it in productive activities. However, it is foremost a social good and as such it is necessary to ensure the right of every human being to have access to water in adequate quantity and quality.

Thus, IWRM implies the use of knowledge from several disciplines as well as the contributions from the different actors involved, with the objective of defining and implementing integral, efficient, technically feasible, socially acceptable and environmentally sustainable solutions (WWC-CNA 2006a). This is the reason why both the Dublin principles and the results of the international conferences that promoted IWRM identify the adoption of participation schemes as a key and priority issue for the establishment of this new approach.

Through mathematical modelling it is possible to analyze the functioning of hydrological, operative, social and economic processes, as well as others that can occur in a basin, with the objective of setting and evaluating management alternatives in the IWRM terms previously described. Existing models have proven to be excellent tools to approach the different problems (hydrological, hydraulic, related to water quality, etc.) for which they were designed. However, they are frequently limited because several factors: by the specific scale for which they were conceived, by a very specific purpose, by a non-modular structure, by a difficulty to update them or connect them to other models, and their lack of flexibility to perform more integral analyses that satisfy the present demands of IWRM (Ahuja et al. 2005).

3 Mathematical Modelling of Hydrological Basins

In the beginning, the mathematical modelling of basins was focused on trying to reproduce the hydrological behavior of the basin; because of this it was named hydrological modeling. Hydrological modelling began in the 19th Century in order to solve design problems in hydraulic infrastructure through the development of concepts, theories and models of individual components of the hydrological cycle (Singh and Woolhiser 2002).

It is possible today to identify, among others, two trends in the area of mathematical basin modelling: (1) hydrological models, which attempt to reproduce the behavior of components of the water cycle—through which rainfall transforms into runoff, and (2) Decision-making Support Systems (DSS), which attempt to reproduce the behavior of various physical, natural, social and economic processes that can interact in a hydrological basin.

4 Application Perspective and Current State of Hydrological Models

According to Xu (2002a), physically-based models are often used for research purposes in order to obtain greater knowledge of the hydrological processes occurring in a basin and also to determine how possible physical changes (e. g., changes in climate or soil use) can affect these processes. Statistical and conceptual models are used for operational purposes, in order to generate synthetic series of hydrological data useful for the design of hydraulic infrastructure or to evaluate future scenarios through forecasting. There is no conflict between these models; however, they represent a different level of approximation to reality. All three are useful and have their own effectiveness depending on the objectives of the study, the degree of complexity of the problem, the available data and the desired precision (Xu 2002a).

Hydrological modeling has been successful in the application of physically-based and spatially distributed models in small basins and using data with fine resolution; however, their application at a regional scale with good results continues to be a challenge (Xu 2002b). The models currently being developed seek to obtain a system linking Soil–Vegetation–Atmosphere–Transference, groundwater, snow, and hydrodynamic routing models with Geographic Information Systems, Digital Terrain Models, Digital Elevation Models and General Circulation Models of Global Atmospheric Process (Xu 2002b).

Hydrological modelling continues advancing in the development of models that describe in greater detail the processes that participate in the generation of runoff from precipitation. However, there are still differences in opinion regarding whether or not the models developed today, are spatially distributed, physically-based or both in a true and complete sense (Beven 1989; Singh and Woolhiser 2002).

There are also problems of non uniqueness in the found solution and with uncertainty management that have not yet been satisfactorily solved (Beven 2001). This has prompted much argument in the international scientific community about the development, application and limitations of physically-based and distributed models (Beven 2001; Sokrut 2004).

5 Application Perspective and Present State of DSS

Decision-making Support Systems are used in search of an integral management focus. They can incorporate surface runoff generation, its interaction with groundwater, runoff routing models, estimation models for the water requirements of agriculture, precipitation, and soil humidity models, water quality and contaminant transport models, as well as socioeconomic factors that could affect decision-making (Lanini et al. 2004). In countries with a high development of hydraulic infrastructure and water management institutions, it is more common to apply DSS to the establishment of basin management plans.

The Water Director Work Frame established in the year 2000 in the European Union demands an integral focus, in order to achieve a good state of its water resources by the year 2015 (Blind and Gregersen 2005; Volk et al. 2007). This has increased the number of research activities, and because of this there exist today several work lines for the development of modelling generic frameworks as well as modular modelling systems (Krause et al. 2005; Berger et al. 2007; Croke et al. 2007). These generic work frames and modular systems have the objective of facilitating the construction of DSS and offer a high potential for the development of mathematical basins models with a holistic focus.

6 Integrated Water Resources Management, Identification of Water (Development) Use Policies and Mathematical Basin Models

The Integrated Water Resources Management is basically a process for the planning of water and other related natural resources (GWP-TEC 2004). This can be achieved through the definition and instrumentation of management policies and better practices for the use of these resources.

The identification of viable policies for the Integrated Water Resources Management in a given basin, demands participation and dialogue between the scientific community (hydrologists, sociologists, economists, etc.), water administrators (government institutions and user associations), stakeholders or end users (Bonell 2004) and the non-governmental organizations that generally concerns about the needs of the environment. This satisfies the demand of establishing participation schemes, identified as a key and priority issue for the establishment of IWRM. However, a change of attitude will also be necessary in the three sectors in order to insure not only participation and dialogue, but also understanding and consensus.

In order to facilitate understanding and consensus, it is necessary for the key actors in decision-making to get involved in the problem to be solved and in the alternatives that can be formulated (Falkenmark et al. 2004). For this, it is necessary that they acquire technical capabilities that will allow them to responsibly evaluate these alternatives and also communicate effectively amongst themselves. Water use policies, in addition to have emanated from a participative process, must also be compatible with other demands of IWRM.

Mathematical basin models are functional tools for the analysis of water resource management alternatives, as well as for the design of new water development policies. It is considered that mathematical modelling, data analysis, and the creation and maintenance of digital hydrological databases are all important activities for the generation of knowledge and the development of technical capabilities that make it possible to instrument IWRM (WWC-CNA 2006b).

7 Characteristics to Be Considered in IWRM Mathematical Basin Models

It is a fact that mathematical models do not solve the problems of a basin; it is people that do that (BDMF 2000). Because of this, these models must facilitate the communication and positions represented by those who participate in the decision-making process in the basin (Heinz et al. 2007). For this, tools are needed that without losing their scientific foundation can also meet the following basic characteristics:

1. Multisector integrality
   IWRM cannot be instrumented by recurring only to hydrology; it requires a holistic focus for the study of the complex systems and processes that occur in a hydrological basin. Because of this, DSS are more frequently used for this purpose. However, the integration of different models creates a challenge mainly due to the differences in scale and technical modelling, as well as the specific nature of the applications for which they were designed (Kralisch et al. 2005).
   An area of opportunity for the development of basin models that is currently visualized as a challenge for the instrumentation of IWRM is the fact that there still is no good communication between water users, governmental administrators and the scientific sector. Hydrologists frequently have difficulties in order that those who do not belong to their discipline understand their expositions (Bonell 2004). Many hydrological models and most DSS have been designed by scientists or engineers, who had very little or no contact with the people that use the water, those who administer it and those who operate the hydraulic infrastructure. Because of this, these models offer a solution alternative only from a theoretical point of view and their practical application for planning purposes is frequently discarded. A model originated in a participative multi-sector process would have a level of acceptance and credibility much higher that of a model developed by one sector alone (Olsson and Anderson 2007; Croke et al. 2007).
2. Representativity of the problem
   The loss of trust in models by water users and decision makers is mainly due to: (1) ignorance of the modelling principles, (2) inconsistencies in the way the models are developed and applied, (3) gaps in the model and incomplete data (BDMF 2000). The first point refers to the need for generation and diffusion of knowledge, as well as for the skill acquisition of those involved in the decision process. The second point corresponds to the unacceptability of developing a model for one purpose and trying to apply it to a different one. The third point, finally, mentions that a model is also unacceptable if it fails to represent one or many of the processes considered important for the analysis to be performed. This also applies to models that depend on inexistent data.
   Thus, a model that does not adequately represent the processes that are of interest to the water users (e. g., water distribution and the operation of hydraulic infrastructure) will yield results that are not practically applicable. In this sense, a change of vision is necessary in the scientific community with respect to the identification and conceptualization of the processes that occur in the basin. Many basins with an important development of infrastructure for water use also have hydrometric records that are currently used for decision making. Even though mathematical basin models are not used, analyses of the historical records of hydrological data are performed, for example, when locally deciding the use that is to be given to the water volume available in a storage dam (CNA 2000). The time series, methods and procedures established at a local scale can be very useful for the development of a basin model that integrates several dam systems and the users depending on them.

Considering this can lead to relatively simple conceptual models of the functioning of the basin, that nevertheless from a pragmatic point of view are much more representative of the operative processes happening in it. This can facilitate the construction of mathematical basin models that will be accepted, understood and used by decision-makers including the water users themselves. A mathematical model with this characteristic could promote and facilitate the participation of water users and administrators, which satisfies the demand of IWRM regarding the promotion of participative schemes.

3. Flexibility

   It is also necessary that the scientific community visualize possible scenarios with respect to the agreements reached by the decision makers. Perhaps the management alternative initially adopted will not be mathematically optimal; however, it will represent an important advance if it is politically, economically, and technically better than the management taking place presently. Adopting and reaching the best solution will depend on time, on the results of the initial alternative and others subsequently adopted, and on the levels of synergy and commitment established among those who participate in the decision-making process.

   Considering this can conduct to more flexible and practical modelling structures that make possible to advance through stages towards the optimal alternative, according to the possibilities and real conditions existing in every basin. A flexible structure oriented towards practical solutions is another characteristic of a model that makes it compatible with the demands of IWRM.

4. Accessibility

   Generally, those who participate in the decision-making process are not modelling experts; however, they are willing to use tools such as mathematical models as long as these tools offer an adequate level of trust, transparency and accessibility in their opinion.

   Most of the time, mathematical basin models incorporate a high degree of complexity in their application. DSS in water resources area also frequently lack the flexibility and accessibility that would enable their generalized application (Koutsoyiannis et al. 2003). However, with the increase in capacity of computer systems and programming languages, in the past few years the attempt has been made to adapt DSS as tools for non-experts (Lanini et al. 2004). Being friendly and offering comprehensible results are characteristics of a mathematical basin model that aids the generation of knowledge and fosters the participation of decision makers.

Considering these characteristics in the development of mathematical models for IWRM would lead to greater compatibility with this new planning scheme, which must be visualized as a dynamic process that must evolve through time. As the IWRM focus is consolidated, the dialogue and understanding between the main actors as well as the level of application of the models and the decisions that are taken will improve.

8 Conclusions

The fundamental demand of Integrated Water Resources Management in hydrological basins is the creation of a participative work frame for decision making where all the water-using sectors, including the environment, are represented. In order for mathematical basin models to be compatible with this social participation framework, they must be versatile and represent not only the hydrological behaviour of the basin but also the operative aspects of the infrastructure therein and the social, economic, environmental, normative and legal aspects that can affect the definition of management schemes. In addition to having this holistic approach, they must really facilitate communication and provide a level of trust, transparency and accessibility satisfactory in the opinion of those participating in the decision-making process.

The DSS developed today have characteristics compatibles with the needs of IWRM, and it is to be expected that their characteristics will improve as a result of the work of research lines currently being developed. A generalized work platform (a computer program) that facilitates the development and construction of DSS tailored for the specific problem to be addressed has a high potential to be applied for purposes of IWRM.

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