WORLD METEOROLOGICAL ORGANIZATION

OPERATIONAL HYDROLOGY REPORT No. 34

HYDROLOGICAL MODELS FOR WATER-RESOURCES SYSTEM DESIGN AND OPERATION

by A. Becker and P. Serban

WMO-No. 740

SECRETARIAT OF THE WORLD METEOROLOGICAL ORGANIZATION - GENEVA - SWITZERLAND

1990

ISBN: 92-63-10740-4

NOTE

The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the World meteorological Organization concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

CONTENTS

CONTENTS

FOREWORD

The Commission for Hydrology (CHy) at its seventh session in 1984 appointed Dr A. Becker as Rapporteur on Hydrological Models and requested him to prepare a report on the availability and use of hydrological models in water resources system design and operation, in particular in relation to the development of the Hydrological Operational Multipurpose Subprogramme (HOMS). A first draft of this report was presented in 1987.

Simultaneously, Dr P. Serban, the Rapporteur on Operational Hydrological Models of the Working Group on Hydrology of Regional Association VI (Europe), was asked to analyse the replies to a questionnaire on the characteristics of operational hydrological models circulated in the European region, and to present the results of this analysis in a technical report. This report, "Operational Hydrological Models Used in the Region", was issued in 1986.

Recognizing the value of combining these two reports into a comprehensive publication, the two rapporteurs kindly accepted to undertake this task with the assistance of the Secretariat. It is with great pleasure that I express WMO's gratitude to Dr Becker and to Dr Serban for the time and effort they have devoted to the preparation of this valuable publication.

G.O.P. Obasi
Secretary-General

SUMMARY

The mathematical representation of hydrological processes has a long history, but it is only within the last two decades that hydrological models have become sufficiently comprehensive and widely available for them to be accepted as operational tools.

Such models are now used for a variety of purposes, each purpose setting its own requirements. The result has been the development of a whole range of deterministic models exhibiting differences in basic structure, the processes they simulate and the manner in which this simulation is carried out. The principle features identified relate to time and space discretization and the modelling of:

- Precipitation and evapotranspiration;
- Canopy interception and infiltration;
- Soil water and sub-surface flow formation;
- Groundwater storage and outflow;
- Overland and channel flow.

These differences are used as the basis for a comprehensive classification system covering both surface water and groundwater models.

Particular attention is paid to the characteristics of models for use in real-time forecasting.

The great majority of hydrological models are used only within the context of research studies, but many have been successfully introduced into operational practice. An extensive international survey of such operational models is presented, cross-referenced to the classification system introduced earlier.

The field of hydrological modelling is one of great diversity and development. A review of recent trends and demands is therefore presented, highlighting developments in computer technology and water-quality and macroscale models, and the barriers to further progress.

The conclusions point to the number of well-developed models that are in operational use while, at the same time, noting the serious gaps in technology that still exist. Hydrological modelling is seen as being a strong growth area in the decades to come.

RÉSUMÉ

La représentation mathématique des processus hydrologiques a une longue histoire, mais ce n'est qu'au cours des deux dernières décennies que les modèles hydrologiques sont devenus suffisamment clairs et largement disponibles pour être considérés comme moyens opérationnels.

De tels modèles sont actuellement utilisés dans des buts différents, chacun d'eux définissant ses propres besoins. Par conséquent, toute une série de modèles déterministes s'est développée, soulignant les différences de structure de base, les processus qu'ils simulent et la manière dont cette simulation est produite.

Les particularités relevées ont trait à la différenciation dans le temps et dans l'espace et à la modélisation:

- de la précipitation et de l'évapotranspiration;
- de l'interception et de l'infiltration de la couverture nuageuse;
- de la formation d'écoulement d'eau près de la surface et de l'écoulement souterrain;
- de l'emmagasinement d'eau souterraine et du débit sortant;
- du ruissellement et de l'écoulement dans des canaux.

Ces différences constituent la base d'un système de classification compréhensible englobant à la fois les modèles d'eau de surface et d'eau souterraine.

Une attention toute particulière est portée aux caractéristiques des modèles à utiliser pour la prévision en temps réel.

La majorité des modèles hydrologiques sont uniquement utilisés dans les recherches, mais beaucoup ont été introduits dans les pratiques en matière d'hydrologie opérationnelle. Une longue étude est présentée avec des renvois au système de classification introduit au préalable.

Le domaine de la modélisation hydrologique est d'une grande diversité et est en train de se développer. Une revue des tendances récentes et de la demande est donc présentée, soulignant les progrès de la technique informatique, des modèles pour la qualité de l'eau et des modèles à grande échelle, et les obstacles ralentissant ces progrès.

La conclusion indique le nombre de modèles bien développés qui sont opérationnels tout en notant les lacunes importantes qui subsistent encore dans les techniques. La modélisation hydrologique est considérée comme étant un domaine dans lequel de grands progrès seront faits au cours des prochaines décennies.

РЕЗЮМЕ

Математическое представление гидрологических процессов имеет долгую историю, однако лишь в течение двух последних десятилетий гидрологические модели стали достаточно объемлющими и широко доступными, чтобы стать оперативным средством.

Такие модели сейчас используются для многих целей, каждая из которых предъявляет свои требования Результатом стало развитие целого ряда детерминистских моделей, различающихся структурой, процессами которые они воспроизводят, и способом их моделирования. К основным характеристикам относятся временная и пространственная дискретизация и моделирование:

- осадков и эвапотранспирации;
- задержания осадков растительным покровом и инфильтрации;
- влаги в почве и формирования подповерхностного потока;
- накопления грунтовых вод и оттока;
- поверхностного и руслового стока.

Настоящие отличия используются в качестве основы для разносторонней классификационной системы, охватывающей модели как поверхностных, так и грунтовых вод.

Особое внимание уделяется характеристикам моделей для использования в прогнозировании в реальном масштабе времени.

Большинство гидрологических моделей используется только в ходе исследовательских работ, но многие были успешно внедрены в оперативную практику. Представлен обширный международный обзор таких оперативных моделей, содержащий ссылки и на ранее введенную классификационную систему.

Сфера гидрологического моделирования является разносторонней и развивающейся. Поэтому в публикации излагается обзор новых трендов и потребностей, освещаются последние достижения в компьютерной технологии, моделях качества воды и макромасштабных моделях, обсуждаются препятствия на пути к дальнейшему прогрессу.

В выводах отмечается, что ряд хорошо разработанных моделей используется в оперативной практике, в то же время в технологии все еще имеются серьезные проблемы. Гидрологическое моделирование рассматривается ка область интенсивного развития в ближайшем десятилетии.

RESUMEN

La representación matemática de los procesos hidrológicos tiene una larga historia pero es únicamente en las dos últimas décadas que los modelos hidrológicos han llegado a ser lo suficientemente integrales y ampliamente disponibles para ser aceptados como instrumentos de tipo operativo.

Tales modelos se usan ahora para una variedad de propósitos, cada uno de los cuales tiene sus propios requisitos. El resultado ha sido el desarrollo de toda una gama de modelos determinísticos que presentan diferencias en su estructura básica, en los procesos que simulan y en la manera en que esta simulación se lleva a cabo. Las principales características identificadas tienen relación con la discretización en el tiempo y el espacio y la modelización de:

- Precipitación y evapotranspiración;
- Intercepción por las copas de los árboles e infiltración;
- Formación de agua superficial y de flujo subsuperficial;
- Almacenamiento y descarga de agua subterránea;
- Escurrimiento superficial y en los drenajes naturales.

Estas diferencias son utilizadas como base para un sistema de clasificación integral que abarca modelos para agua superficial y para agua subterránea.

Se presta especial atención a las características de los modelos para uso en previsión en tiempo real.

La gran mayoría de los modelos hidrológicos se usan en el contexto de estudios de investigación pero muchos han sido introducidos con éxito en la práctica operativa. Se presenta una amplia encuesta internacional sobre tales modelos operativos y se comparan con el sistema de clasificación presentado anteriormente.

El sector de los modelos hidrológicos es de gran diversidad y desarrollo. Se presenta por consiguiente una revisión de tendencias y demandas recientes, haciendo hincapié en el desarrollo de la tecnología de computadoras, modelos para calidad del agua y de macroescala y en los obstáculos para el desarrollo futuro.

Las conclusiones se refieren al número de modelos bien desarrollados que están en uso operativo notando, al mismo tiempo. las serias lagunas que aún existen en la tecnología. Los modelos hidrológicos se ven como un sector de fuerte crecimiento en las décadas futuras.

HYDROLOGICAL MODELS FOR

WATER-RESOURCE SYSTEM DESIGN AND OPERATION

1. INTRODUCTION

During the last two decades research in the field of hydrology has been increasingly concerned with the development of mathematical models and with their application for various purposes such as hydrological forecasting, data extrapolation in time and space, and the prediction and assessment of the effects of human influence on the natural hydrological regime. This development is clearly indicated by the increasing number of publications, symposia and other events devoted to hydrological modelling.

However, the more hydrological models were developed, the more it became obvious that a gap existed between theory and practice, that is, between the models and their practical application. WMO therefore initiated and organized a series of intercomparison projects, namely:

(*a*) Intercomparison of conceptual models used in operational hydrological forecasting (WMO, 1975);

(*b*) Intercomparison of models of snowmelt runoff (WMO, 1985); and

(*c*) Simulated real-time intercomparison of hydrological models (WMO, 1987).

It is also relevant to note that WMO's Hydrological Operational Multipurpose Subprogramme (HOMS) was initiated in order to facilitate the transfer of hydrological technology, and a number of mathematical models are included as components of HOMS. The first edition of the HOMS *Reference Manual* was published in 1981, the second in 1988 (WMO, 1988b); supplements are distributed every year.

All these projects, along with analogous efforts of other international organizations, in particular Unesco and IAHS, improved the possibilities of applying hydrological models for practical purposes. Nevertheless, the present situation is still characterized on the one hand by "inflation" of mathematical models in hydrology, while on the other hand the models and methods needed for the solution of important problems, as indicated under (*a*) and (*b*) below, are still missing or are unsatisfactory. It can be said that, in general, the development of resources still lags behind the development of needs.

Important influences on developments in hydrological modelling are:

(*a*) The demand for more comprehensive and more reliable information on hydrological processes and characteristics and on the availability of water resources (quantity and quality) in space and time on the basis of different space and time scales (micro-, meso-, macroscale; real-time, short-term, long-term);

(*b*) The increasing need for investigating the effects of different human influences and impacts on the hydrological regime and on water quality. Reference is made here in particular to land-use changes, climatic variability and climate changes, and intensified water and land-use practices;

(*c*) The widespread and rapid growth in the availability and use of computer power, in particular of microcomputers, not only by research institutions, water authorities and Hydrological Services, but also by individuals (the "revolution" in computer technology);

(*d*) The availability of remotely sensed data on important hydrological land surface-related parameters and characteristics, such as temperature, soil moisture, precipitation, evapotranspiration, snow storage and albedo.

Some of these developments and the resulting requirements in hydrological modelling will be considered in later chapters of this report, the general aims of which have been defined as:

- To characterize briefly existing hydrological models in terms of their general function, character, type and their availability for the solution of practical problems;
- To point out those fields in hydrology and water-resource systems management where models are available for application and other fields where they are still missing or do not fulfil the requirements;
- To define criteria for selecting models for specific applications.

One significant fact should, however, be pointed out early in this introductory chapter: No model can stand by itself in solving real world problems. Two components are always required as a prerequisite, the model and adequate input data and information. It is evident that models will fail (i.e. give inadequate or unreliable results) if the model inputs do not fulfil basic requirements regarding data reliability, accuracy and representativity, at least to the degree required for solution of the given problem. This is essential not only in model applications but also in model calibration, and it often affects substantially the selection and structuring of a model.

Thus, in addition to a suitable model, adequate and reliable input data and information are also essential. In many cases their collection and appropriate supply for model application need more effort and are more important for deriving the desired information and results than the particular structure and level of complexity of the model. This aspect will be considered in several sections later in the report.

2. MAIN FIELDS OF APPLICATION OF HYDROLOGICAL MODELS

2.1 Main categories of model use

Mathematical models have found increasing practical application in two main categories of problem in operational hydrology and water-resource system planning and management:

(*a*) Real-time forecasting and control;

(*b*) Prediction, planning and design.

A third category might be considered which would include research problems but may be more generally described as:

(*c*) Other problems.

This category concerns the use of hydrological models, in particular for improving our understanding of processes and our modelling capabilities, and for the estimation of model parameters and similar tasks.

The characteristic difference between the first two categories results primarily from the time horizon under consideration. *Real-time problems* are always related to the present situation, to given existing system structures and to initial conditions, and they are concerned with *forecasts* (WMO, 1988a) for a few hours up to two days (short-term); two to ten days (medium-term); months or years (long-term).

Planning and design studies are principally long term, that is, they need long-term *predictions* of the hydrological conditions and water-resource availability over time horizons of 10 to 100 years. They also have to take into account the long-term variations of the hydrological processes in their stochastic character, as well as different or changing system structures and conditions in the planning alternatives considered.

2.2 Real-time uses

In real-time monitoring and control of hydrological and water-resource systems the following general tasks are undertaken (Figure 1):

1. Collection, primary processing and storage of real-time data, observations and other information on the state conditions and the expected (forecasted) changes in input of the hydrological systems of interest (water stages, discharges, water quality, precipitation, snow data, temperature, etc.).

2. Real-time forecasting of hydrological variables (short-term, medium-term and long-term), in particular river discharges, water levels, water storages, water quality and ice conditions.

3. Real-time control of state conditions and processes in hydrological and water-resource systems, e.g. for

- Storage in and release from reservoirs, lakes, ponds, reservoir systems and other surface water systems;
- Water transfers within river basins or from one basin to another;
- Water withdrawals for different purposes;
- Waste-water treatment and release.to ensure water supply for different users, flood and environmental protection and other demands of the society.

Tasks 1, 2 and 3 are listed in hierarchical order. Activities under 1 are always necessary even when no forecasting and control computations will follow. Forecasting 2 requires activities mentioned under 1 as prerequisites, and control activities 3 require 1 and 2. The role which models play for tasks 1 and 2 in forecasting real-time hydrological systems is illustrated in Figure 1 (Nemec, 1986). This clearly illustrates the observation made at the end of the Introduction that input data availability is always a most important prerequisite for any model application.

The demand for applying mathematical models clearly increases from tasks 1 to tasks 2 and 3. Obviously, activities under 3 are only required and possible in systems where the ongoing processes and state conditions can be controlled by existing hydraulic structures. Well-known cases of such applications are flood control; water transport planning and control; optimum operation of reservoirs, in particular for hydroelectric power production, low-flow augmentation and water supply; water pollution control and irrigation system control. Accordingly, two categories can be distinguished in real-time applications of mathematical models:

(*a*) Forecasting without control (FO in Figure 2); and

(*b*) Forecasting with control computations (FC in Figure 2).

Reservoir control illustrates the importance of real-time control computations, because this activity nearly always leads to a conflict of interests between different water users. On the one hand is the requirement to keep reservoirs as empty as possible to ensure a high degree of flood protection, while on the other hand is the need to keep them filled so as to maintain an adequate water supply for users (e.g. power production) during low-flow periods.

It has been found that efficient real-time control of reservoirs can often result in a remarkable reduction in the amount of water released during water shortages; this can increase the volume of water retained in storage by an average of about 20 per cent (Serban, 1986; NERC., 1975). An efficient real-time forecasting and control system, including all the aforementioned activities (1, 2, 3), can also eliminate the need for additional investment in a higher reservoir storage capacity of the same order.

2.3 Prediction, planning and design

Any water-resource project, whether it serves for water supply, flood or environmental protection, energy production, irrigation, navigation or for other purposes, requires some degree of detailed investigation. A general comprehensive overview of the different stages in water-resource system and project planning is given in Figure 3 (after Haimes *et al.*, 1987). It illustrates well the complexity and the necessary sub-activities in this process, as well as the demand for mathematical model applications (the related sub-blocks in Figure 3 are marked by double-lined frames).

As a result of such factors as the multiple uses of water, the increasing influence of human activities on water resources, and the complex interrelations and interactions between the two, the planning process and water management in general are becoming increasingly complex. Moreover, while the demand for information used to be restricted to a

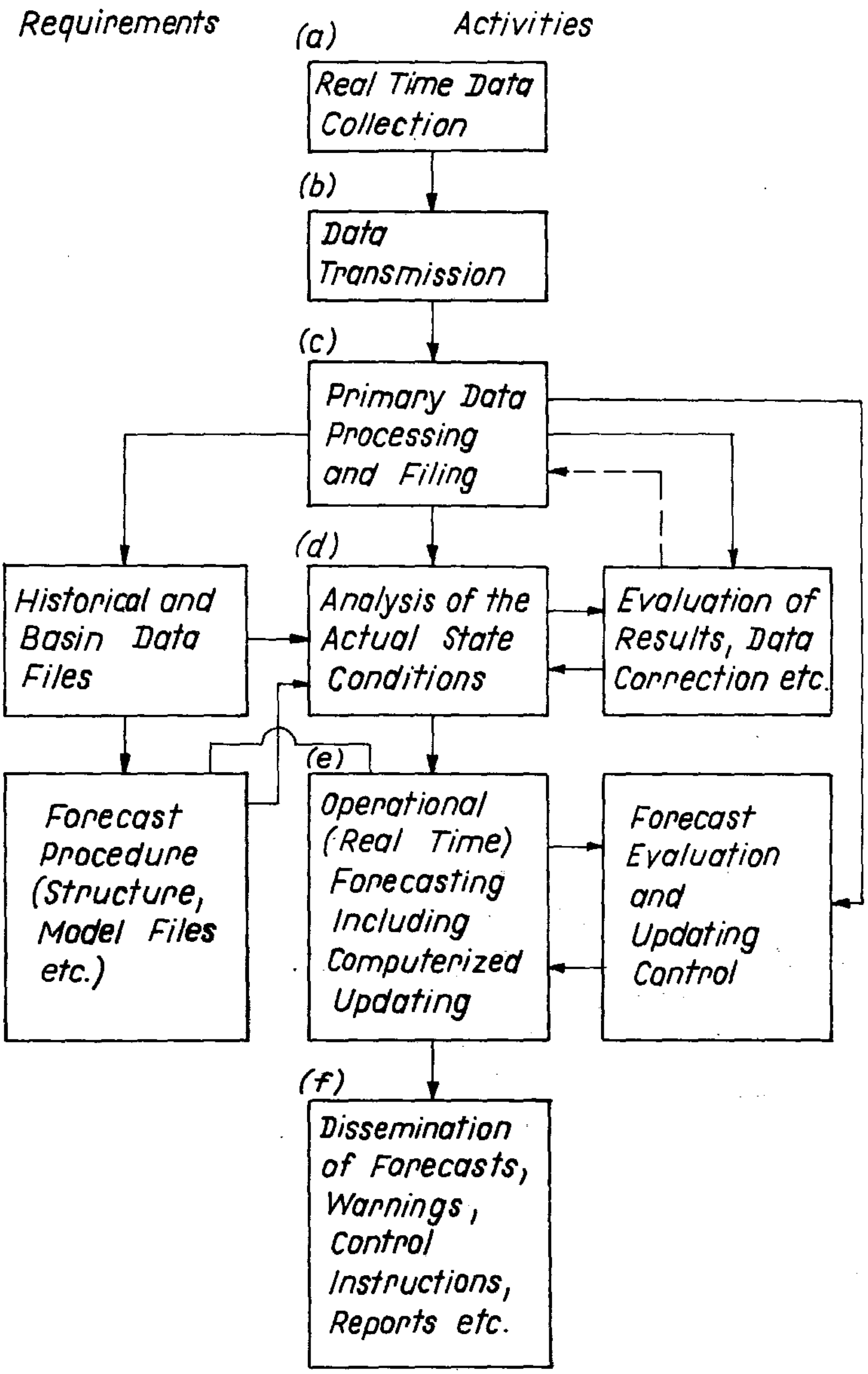


Figure 1 – General structure and components of operational hydrological real-time forecasting systems (developed from Nemec, 1986)

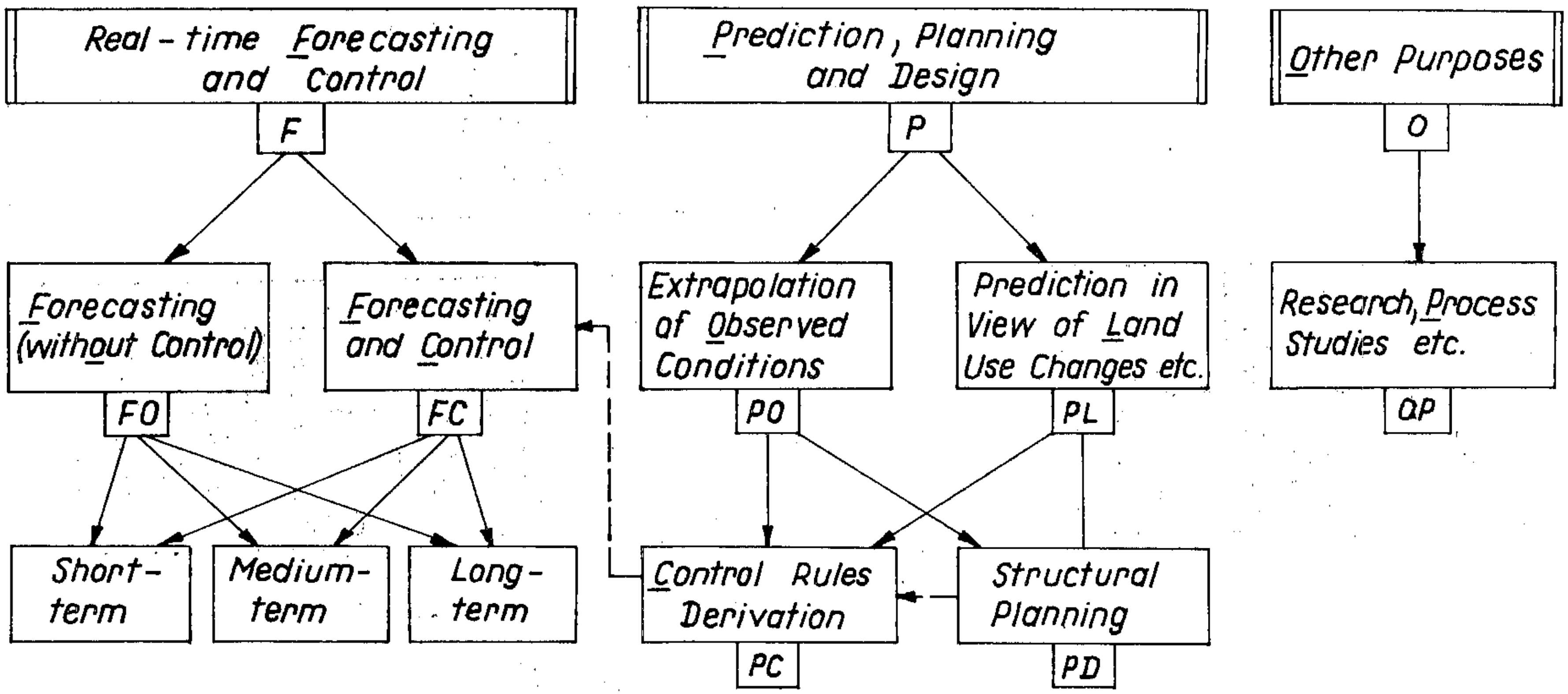


Figure 2 – Main purposes of using hydrological models

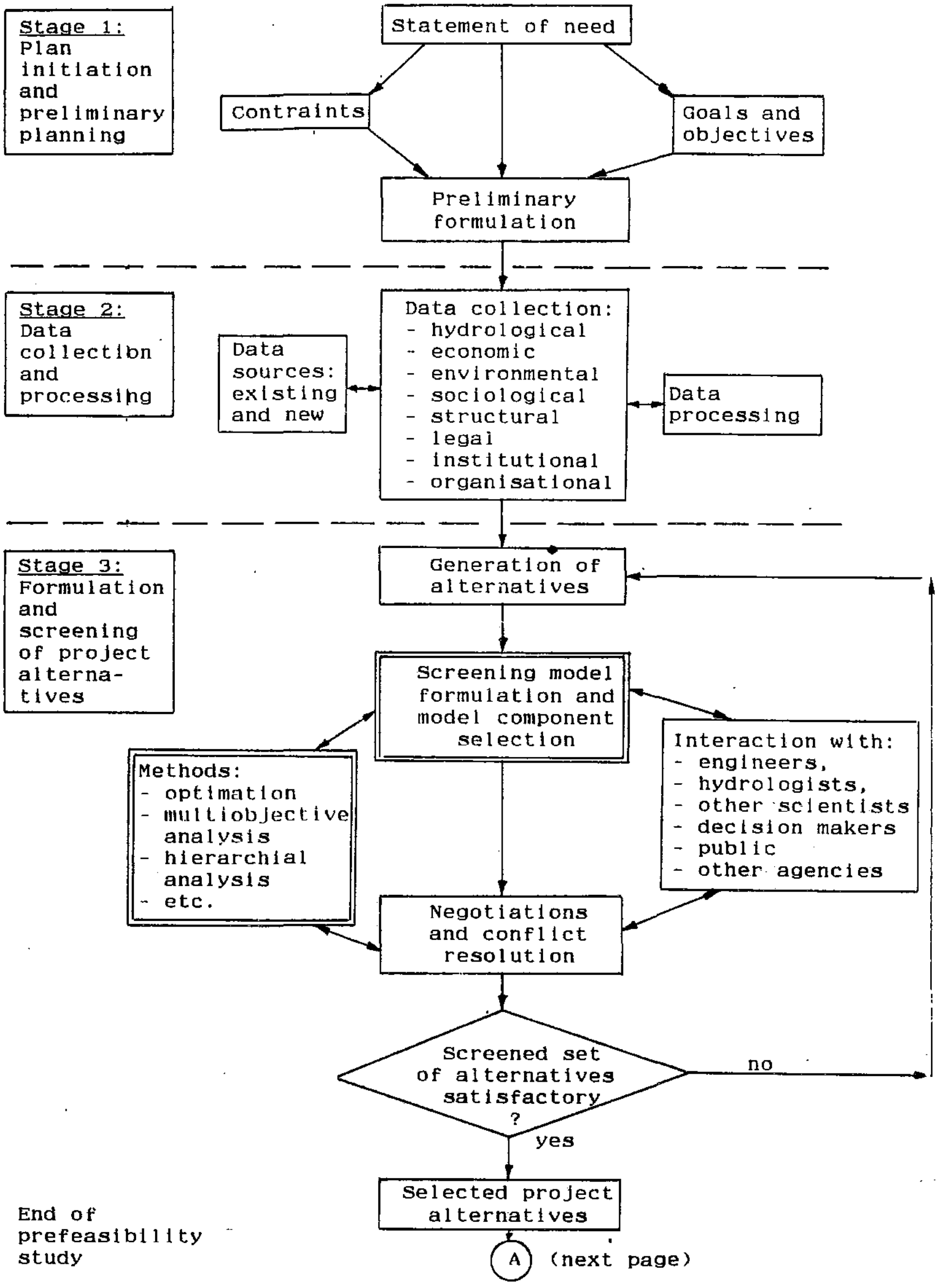


Figure 3, Part 1 – Stages in the water resources planning process

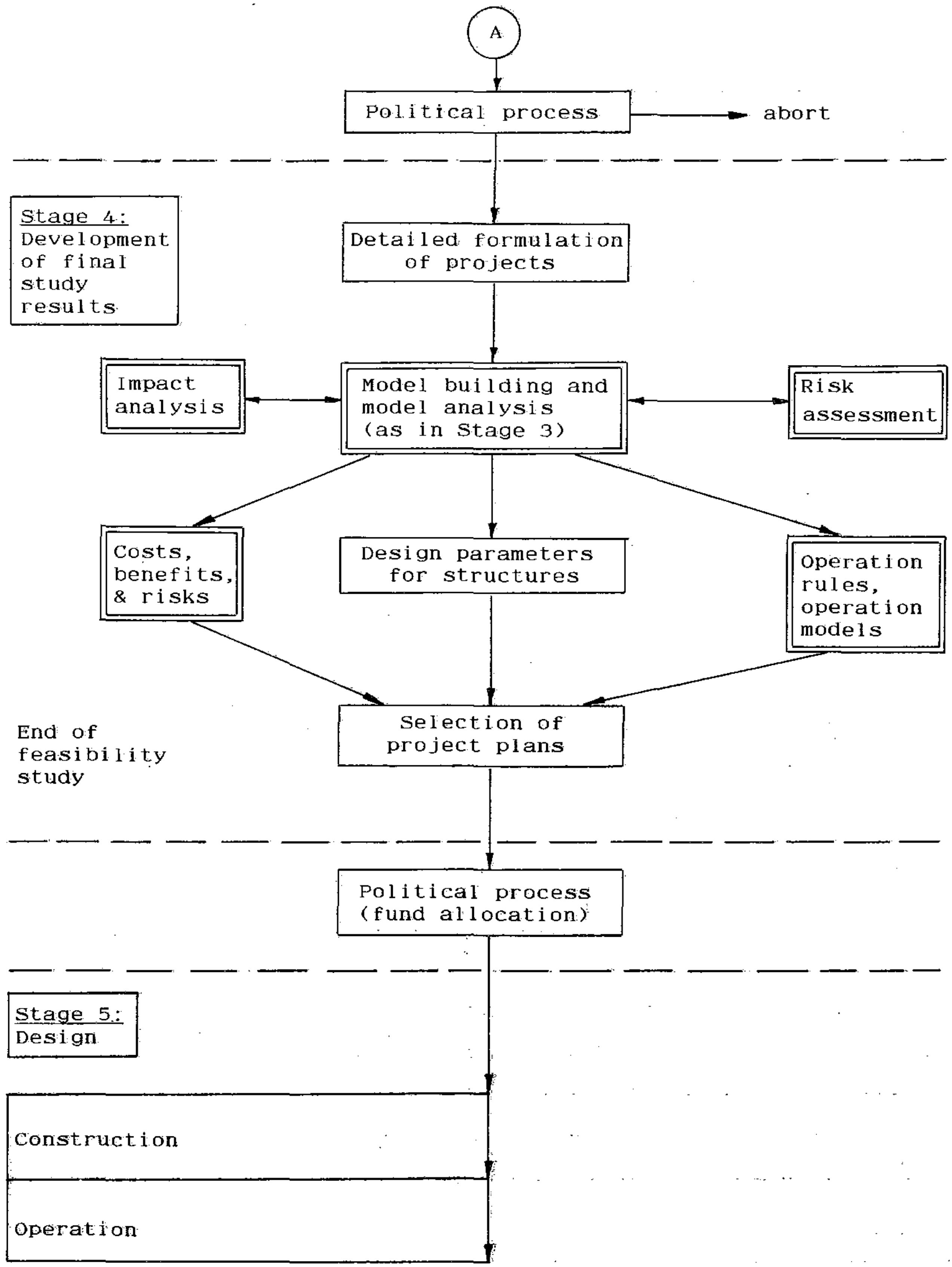


Figure 3, Part 2 – Stages in the water resources planning process limited number of localities and parameters which characterized the hydrological phenomena and regime, numerous elements and parameters are now demanded even for smaller rivers and land surface units. Furthermore, many rapid and significant changes are taking place in the environment over large areas as a result of hydraulic structures, the extensive use of water resources, development of forest areas (including de- and reforestation), the expansion of agricultural cultivation over previously bare or forested lands, the development of drainage and irrigation areas, increased use of chemicals in agriculture, and the growth of industrial complexes and urbanization. These activities are expected to continue in the future. It can be stated that human activities have reached a level such that the resulting environmental impacts often dominate the natural phenomena. Under these circumstances, significant modifications of the hydrological cycle components are liable to occur.

All these developments and their effects have to be taken into account in most planning and design investigations which consequently become more comprehensive and complicated and which increasingly require the application of mathematical models for deriving "optimum" or efficient planning and design alternatives and long-term water-resource management strategies (Haimes *et al.*, 1987). Figure 4 was prepared to illustrate this developing demand. It gives an overview of some important recent developments in the world, their influence on the availability of water resources (in quantity and quality) and on the most important interactions (Becker, 1988).

In considering these interactions and interrelations, two phases of the planning process may be distinguished, from the hydrological point of view.

First Phase

Long-term prediction of the hydrological parameters required in the planning process (in the form of continuous time series; characteristic parameters of extreme events, such as floods or droughts, with a given occurrence probability; etc.):

(*a*) For the given climate and hydrological conditions, i.e. by extrapolating the available hydrological information in time (for the planning period) and space (for ungauged sites, sub-basins, etc.) while preserving the statistical characteristics of the observation period (assumption of stationarity in climate and hydrological regime; block PO in Figure 2);

(*b*) For expected or planned changes in land use (PL in Figure 2);

(*c*) For expected or predicted climate changes and for extreme conditions or events (for example as observed in neighbouring areas, generated or expected; PL in Figure 2);

(*d*) For any other "scenario" of interest.

Second Phase

Planning and design of hydraulic structures or systems of such structures (PD in Figure 2) which have to serve for one or a number of the following purposes:

- Water supply for different users, user groups or categories of user (see Figure 4, centre right part), in particular for industrial, energy and agricultural production, including irrigation;
- Waste water treatment and release;
- Low flow control;
- Storm-water management;
- Flood control and protection;
- Environmental control and protection;
- Transportation and communication.

This planning process has to be based on the results of the "first phase predictions". It concerns in particular the construction of dams, weirs, levees, bridges, channels, water pipelines, water treatment plants, installations for water distribution, irrigation, artificial groundwater recharge and erosion control, and, increasingly, agricultural, forest and water management practices.

The derivation of efficient strategies and rules for water-resource use, allocation, management and protection for any given or planned system structure (PC in Figure 2) is always an important sub-task in planning water-resource systems.

In all cases the degree of complexity of an investigation, and consequently the use of mathematical models, is strongly dependent on:

(*a*) The specific conditions of the water-resource system concerned (structure of the surface and groundwater resource systems, number and location of water uses and control structures, etc.);

(*b*) The number of investigated planning alternatives (structural alternatives, scenarios for system management, input developments, land-use changes, etc.);

(*c*) The available input data and information.

The large variety of requirements, resulting in an increased demand for more powerful models and more flexible programme systems, has already been mentioned.

3. CLASSIFICATION OF HYDROLOGICAL MODELS

3.1 Classification principle

For various reasons it is useful or even necessary to classify hydrological models. This is helpful, for example, in selecting a model appropriate to the application and in assessing model availability. From the point of view of model users, a classification according to the following problem-related and user-oriented criteria is the most appropriate:

(*a*) Purpose of model application;

(*b*) Type of system to be modelled;

(*c*) Hydrological process or related variable (criterion, component) to be considered;

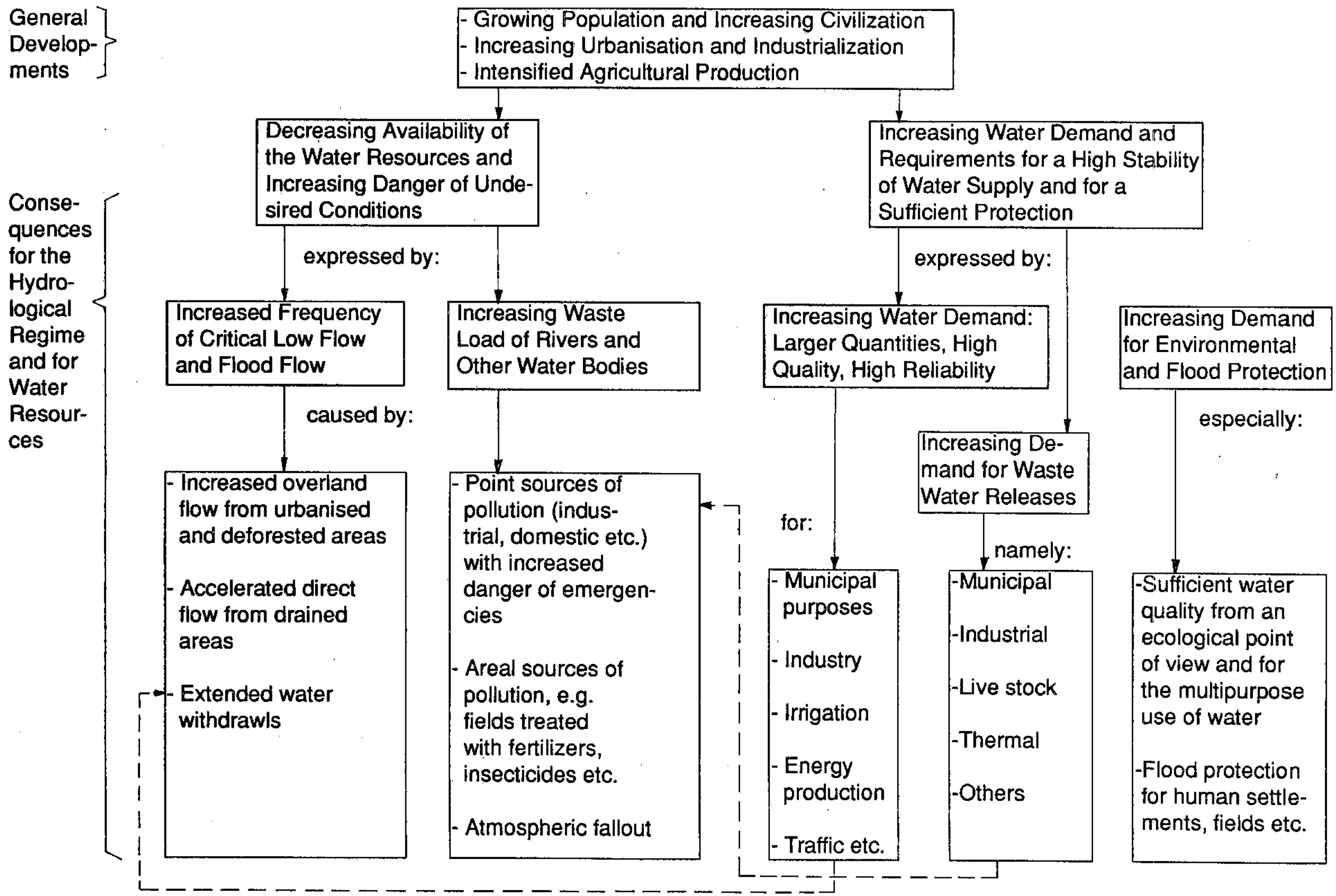


Figure 4 – General developments in the world and their effects on the availability and qualitity of water-resources

(*d*) Degree of causality of the process;

(*e*) Required time and space discretization.

Of these criteria, three require more detailed examination and general acceptance, namely (*a*), (*d*) and (*e*). An attempt is therefore made to clarify the situation on the basis of our improved understanding of the ongoing processes and demands for model applications. The suggested categories under these three criteria are explained in Tables 1 and 4 and Figures 2 and 5.

The purposes of model application (criterion (*a*)) have already been discussed in the previous chapter. The classification presented in Table 1 and represented in Figure 2 is therefore recommended for use.

TABLE 1

Scheme for classifying hydrological models in terms of the purpose of their application

(to be read in conjunction with Figure 2)

Number	*Purpose of application*	*Identifier**
1.	Real-time uses	F
1.1	Forecasting - without considering control aspects	FO
1.2	Forecasting - considering control aspects	FC
2.	Prediction, planning and design	P
2.1	Prediction - without considering land use and climate changes	PO
2.2	Prediction - considering land-use changes	PL
2.3	Planning and design (of hydraulic structures, etc.)	PD
2.4	Derivation of efficient or "optimum" control strategies, rules, etc.	PC
3.	Other purposes (research, model calibration, etc.)	OP

*These identifiers are used in the model availability evaluation procedure described later in this report.

In connection with this classification, it is important to explain the difference between a model and a procedure: While a model describes a definite process or system (independent of the specific purpose of the model application), a procedure is understood to be a combination (sequence) of sub-procedures including a model or some models as sub-routines, for instance:

- Procedures which handle a set of given input data and transform it into the form required by the model (input sub-routines);
- Computational procedures based on a hydrological model or a combination of models and approaches (including, for example, an updating procedure for real-time forecasting);
- Procedures for preparing and presenting the output in a user-oriented format.

In many cases models form the necessary core, or at least an important component, of a procedure. Procedures are required as a "frame" for running models for specific applications, and often they determine the "availability" or "non-availability" of a model. Therefore, although the models are the primary subject of this report, procedures also have to be taken into consideration.

It is now clear that the classification identifiers explained in Table 1 and Figure 2 denote primary procedures which should be directly useable for operational applications in the field of hydrology and water resources, in particular for real-time forecasting (FO, FC) or for prediction, planning and design (PO, PL, PD, PC).

3.2 Classification in terms of the type of system and hydrological process or variable

The classification in terms of these two criteria causes no major problems. It has been submitted for the purpose of this report and in view of the information that has been compiled on the availability of hydrological models.

Table 2 defines those water-resource systems and their important elementary sub-systems which are of primary interest in operational hydrology. A distinction is made between elementary systems (1) and complex or coupled systems (2).

TABLE 2

Types of hydrological system, as used in this report in the classification of hydrological models

Number	*Type of system to be modelled*	*Identifier*
1.	Elementary systems:	
1.1	Hydrotopes (elementary "uniform" unit areas, plots)	HU
1.2	Non-uniform small or medium-sized land surface areas (combinations of some hydrotopes)	SA
1.3	Aquifers (groundwater systems)	AQ
1.4	River reaches or channel reaches	RR
1.5	Reservoirs or lakes	RL
2.	Complex (coupled) systems:	
2.1	Surface water systems consisting of several river reaches, eventually with lakes, reservoirs, etc.	CS
2.2	River basins or other larger land surface units	CB

With regard to the coupled systems, it should be noted that under CS (complex surface water systems) only the surface water system itself, consisting of rivers, channels, lakes, reservoirs, etc., is understood to be modelled while the "feeding" land surface parts of the river basin, aquifers, etc. are not explicitly considered. Their outputs are treated as given boundary conditions of the surface water system

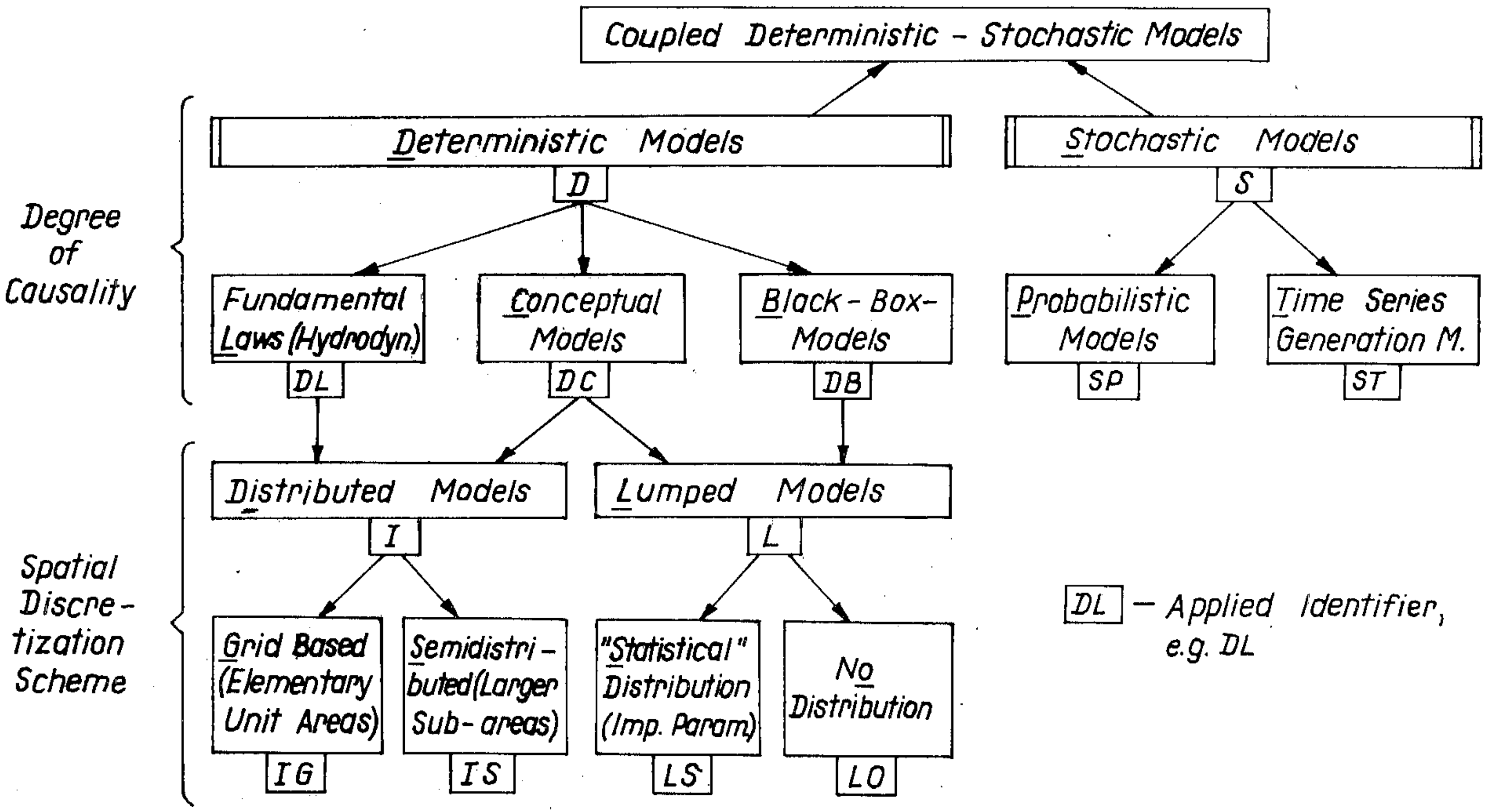


Figure 5 – Classification of hydrological models in terms of purposes of application, degree of causality and appplied spatial discretization

(CS); however, they form an important part of CB (river basin) models for those areas.

The classification in terms of hydrological process or related variables is presented in Table 3. While in general very wide fields are defined (e.g. water quality (6), soil moisture and evapotranspiration (1)), a sub-division of category 3 (river discharge and water level) into two sub-categories (time steps greater than one day or smaller than/equal to one day) seemed to be appropriate for this report. This indicates already that, within or in accordance with the general frames defined by the main types of hydrological systems and processes or variables as listed in Tables 2 and 3, any required alternative or sub-classification can be introduced.

TABLE 3

Hydrological processes or related variables to be considered in the classification of hydrological models

Number	*Hydrological variables to be considered*	*Identifier*
1.	Soil moisture, evapotranspiration (including other related variables)	ES
2.	Groundwater storage, level, discharge	SG
3.	River discharge and water level:	
3.1	– in small time steps ($\leq$ 1 day	QF
3.2	– in larger time steps (> 1 day)	QM
4.	Water temperature, ice conditions and other related variables	TW
5.	Sediment yield and related variables	QS
6.	Water quality criteria	WQ

3.3 Degree of causality

Causality is expressed in the form of cause-effect relations. They are best reflected in deterministic models (D in Figure 5) which relate given dependent variables y (effects, outputs or dependent state variables of a considered system) to a set of independent variables x (causes, inputs or other state variables of the system such as initial and boundary conditions):

$$y = f(x, a) \tag{1}$$

where a are coefficients or parameters describing the system behaviour.

There is a large variety of deterministic models. They are different in their basic structure, physical "soundness", dimensionality, etc., depending on the purpose of the modelling system and the process to be modelled. Aspects of dimensionality, space and time discretization will be considered in the next chapter. Here the three main categories of deterministic models are introduced (Figure 5):

(DL) Models based on the fundamental laws of physics (in particular hydro- and thermodynamics), chemistry, biology, etc. (white-box models);

(DC) Conceptual models reflecting these laws in a simplified approximate manner and involving in general a certain degree of empiricism (grey- box models);

(DB) Black-box models which do not explicitly take into account the governing laws but only the cause-effect relation of system inputs to outputs, in a very general and purely empirical manner.

The other main group of hydrological models which primarily do not consider the principle of causality are the stochastic models (S in Figure 5). One sub-category of these models—the so-called *probabilistic models* (SP)—are generally represented by probability distribution functions of the hydrological variables of interest such as, for example, maximum and minimum discharges (flood peak flows, low flows, etc.) and water levels or storage volumes. They are often described in terms of parameters such as averages, standard deviations and co-efficients of skewness. A fundamental assumption which forms the basis for these models is that no causal relation should exist between the different elements of the considered process (variable).

The second sub-category of stochastic models is the *time series generation models* (ST) which can be used for extrapolating in time a sequence of recorded variables or events while preserving their statistical parameters. The well-known ARIMA model belongs to this category.

It becomes clear from the above that stochastic models are usually related to a definite hydrological variable (process) at a given observation station (e.g. gauge), and only in an "integrated", more general manner to one of the systems indicated in section 3.2. Therefore, the type-of-system criterion cannot always be applied in connection with stochastic models in the evaluation procedure used later in this report except where there is a clear relation to a definite system. Conversely, deterministic models are clearly related to definite systems, as listed in Table 2, and thus to their inputs, state conditions and outputs.

It should be mentioned that hydrological processes always include deterministic and stochastic elements (coupled deterministic-stochastic models at the top of Figure 5). This is true not only for prediction, planning and design models where at least the "prediction part" often needs a stochastic model component as a decisive element, but also for real-time forecasting models, where the updating procedure and all system input forecasting procedures (precipitation, snowmelt, etc.) represent or require a stochastic model component.

Another well-known fact is that, in a deterministic model of a complex hydrological system, we are often unable to take into account all variables and factors (parameters) which influence the output. Therefore, in model applications, a certain error $E_y(n)$ will occur which decreases as the number n of independent variables and parameters is increased up to a definite number n_t of these variables, as illustrated in Figure 6. This error, which can be described by a stochastic model, includes two types of error: the model error itself and the measurement error (represented as E_M in Figure 6).

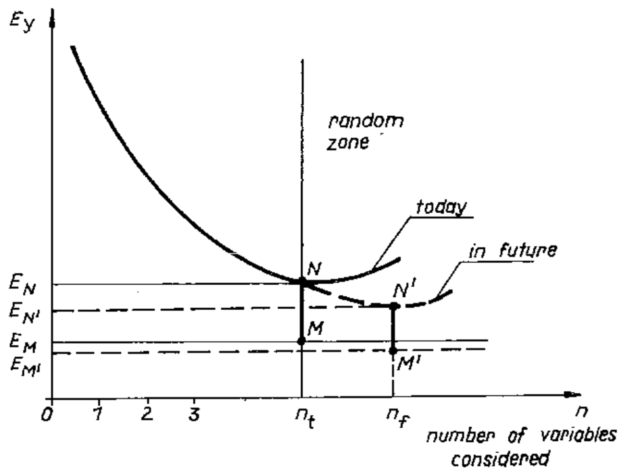


Figure 6 – Modelling error as a function of the number of elements considered

3.4 Time and space discretization in hydrological modelling

The appropriate time step in a modelling task is mostly determined by the purpose of the model application. For flood studies, erosion studies and a number of water quality studies, time steps of one hour to one day are normally required, while for other purposes longer time steps up to one month can often be accepted. Some recently developed models are designed in such a way that different time steps can be applied. This aspect is essential in the selection of an appropriate model for a specific application.

Similarly essential but more difficult in modelling is the space discretization, sometimes characterized as "topological modelling". There are two basic categories of space discretization (Figure 5 and Table 4): distributed models (I) and lumped models (L). In discussing these types of discretization and related sub-types, we will use river basins or land surface areas as a first example (CB and SA in Table 2).

TABLE 4

Categories of space discretization in hydrological modelling of large areas, river basins, etc.

Type of model	*Identifier*	*Input, output, state variables*	*Characteristics, parameters**
1. Distributed models considering	I		
– elementary unit areas (grid based)	IG	$u\ (x, y, z, t)$	$k\ (x, y, z)$
– larger sub-areas of approximately similar behaviour (semi-distributed)	IS	$u_{i,j}(t)$	$k_{i,j}$
2. Lumped models	L		
– black-box or conceptual	LO	$u_j\ (t)$	k_j
– considering a statistical spatial distribution of important parameters	LS	$u_j\ (A_p/A, t)$	$k_j\ (A_p/A)$

*Some parameters may be a function of time.
i - number of hydrological sub-areas; j - number of layers (levels) considered; A_p - part of the total catchment area A.

If the understanding of the process and the measuring technique can be improved (in the future) then this error $E_N = E_y\ (n_t)$ will be reduced to $E_N = E_y\ (n_f)$. The error reduction (N -> N') as indicated in Figure 6 would then be composed of two parts, arising from:

(*a*) The reduction of the measurement error (M -> M');

(*b*) The increase of n up to n_f.

Accordingly, the role of the stochastic sub-model for the model error function will decrease.

In summary, it can be said that stochastic models form a substantial part of each prediction, planning and design study. In real-time applications their role increases significantly with increasing lead time of the forecast. In short-term forecasting they represent an element of secondary importance which is included in the updating procedure, while in medium- and long-term forecasting they reach rather quickly the same level of significance as in planning and design studies.

According to Table 4 distributed models in their basic form take into account the spatial variability of model inputs, outputs, state variables and parameters in a detailed form (IG), for instance by sub-dividing a land surface area into elementary unit areas determined either by a detailed regular grid (as in Figure 7, part c) or otherwise. In many cases, especially in microscale considerations, the grid areas are chosen small enough to ensure the validity of the governing fundamental physical and other laws. This means, in terms of the scale definition presented in Figure 18, that they should not be greater than about 1 km^2.

The application of distributed models for river basins or other land surface areas is required in view of the following facts:

- The spatial variability of precipitation and other meteorological factors important for hydrological modelling;
- The non-uniformity in space of watershed characteristics (topography, vegetation, soils, etc.);

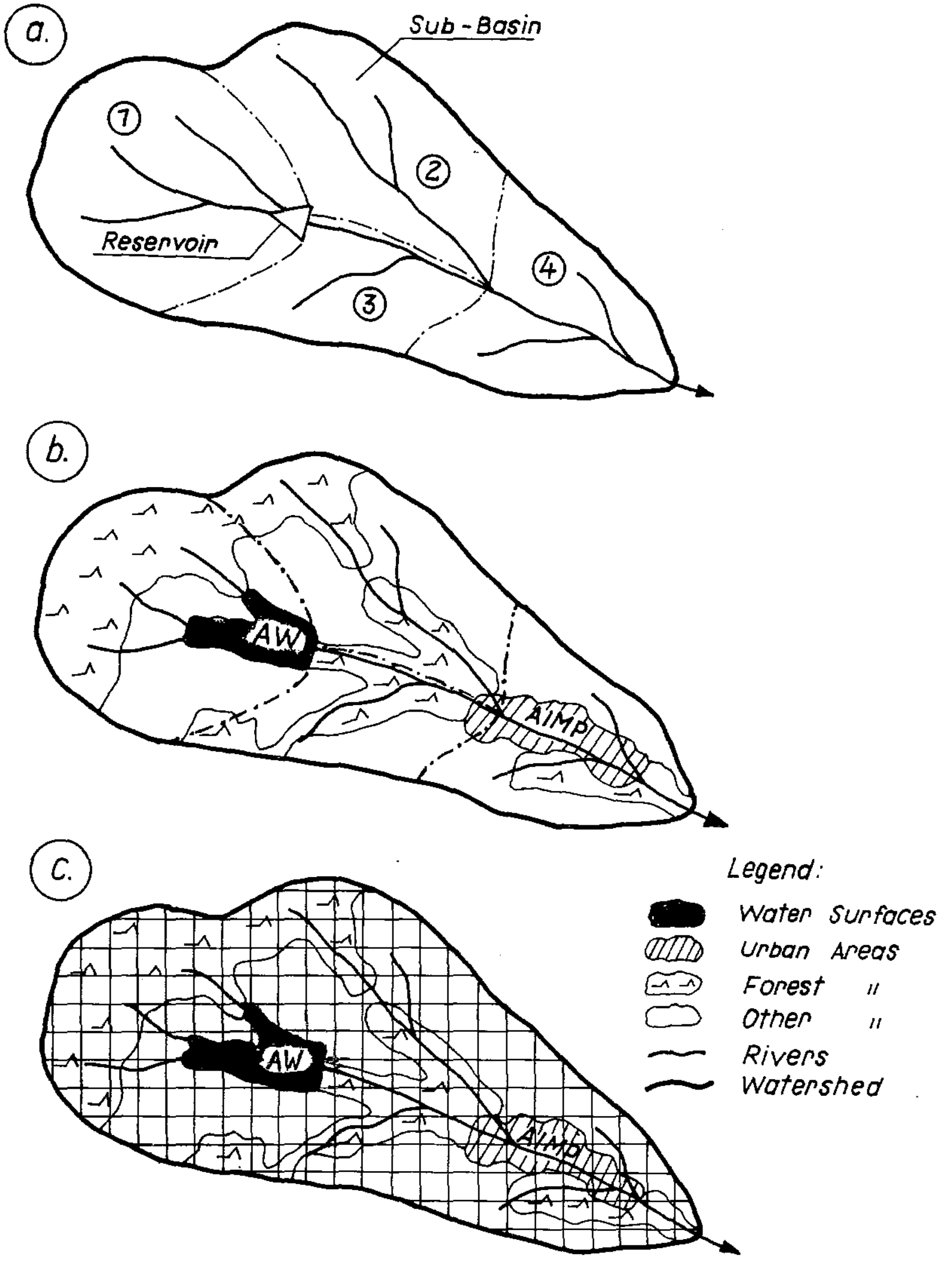


Figure 7 – Representation of different space discretization schemes in river-basin modelling:
(a) Lumped (4 sub-systems)
(b) Semi-distributed
(c) Distributed (grid-based)

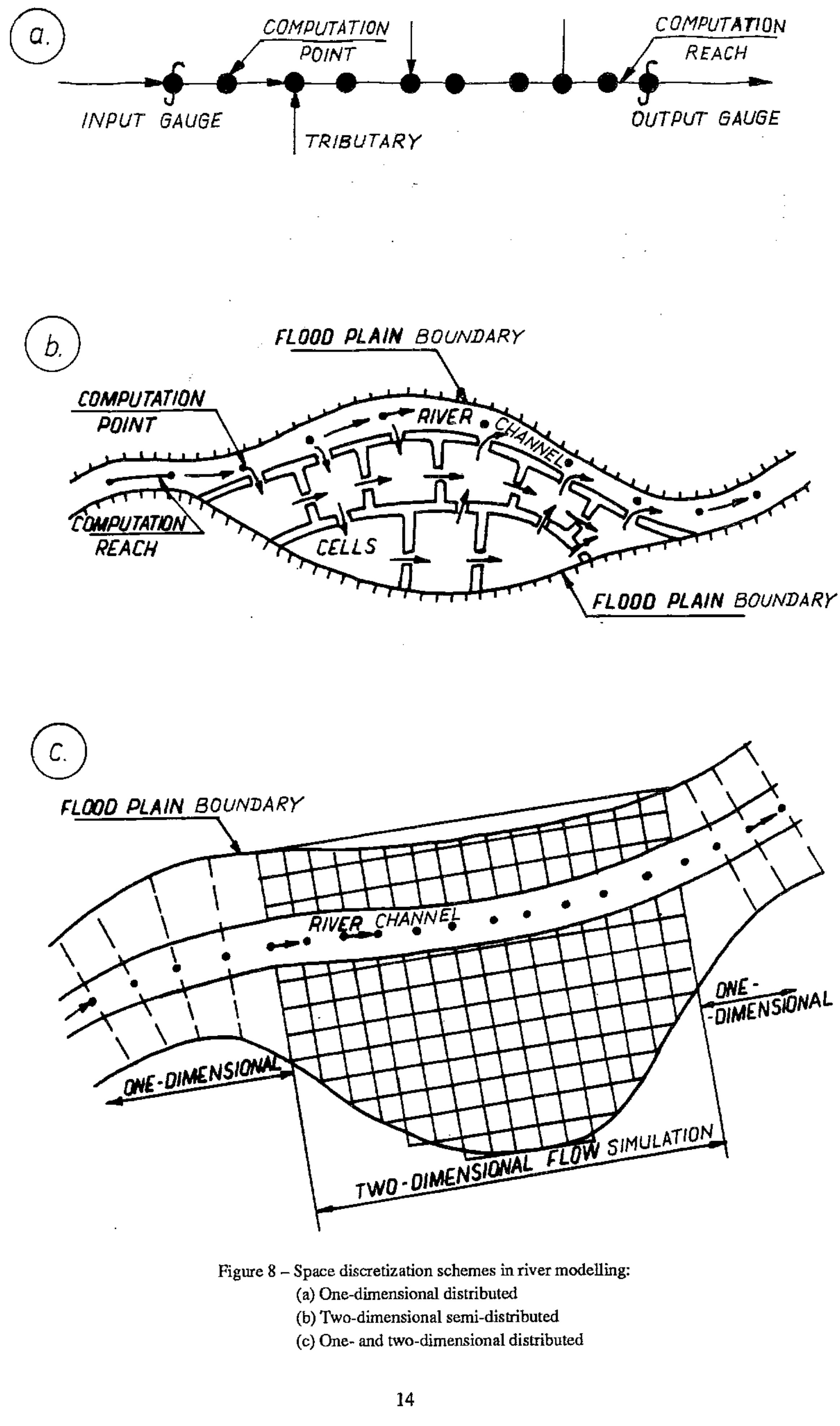


Figure 8 – Space discretization schemes in river modelling:
(a) One-dimensional distributed
(b) Two-dimensional semi-distributed
(c) One- and two-dimensional distributed

- The spatial differences and non-linearities of the mass and energy transfer processes taking place in a watershed;
- The non-uniformly distributed influences of human activities on the components of the hydrological cycle and on their interaction.

Lumped models (L), as the other extreme, do not take into account the areal distribution of the above-mentioned characteristics, and are therefore much simpler and are easier to handle. Despite or even because of this simplicity, they are most widely applied for a number of purposes, in particular in simple design studies and in real-time forecasting of discharges.

Between the two extremes there are compromise solutions which try to overcome the limitations of the lumped models (LO) and to avoid the computational demands and large amount of input data and parameters required for grid-based distributed models (IG). A very early attempt in this direction was the introduction of "statistical distribution functions" for essential parameters (sub-category LS in Table 4). Examples are the use of a linear distribution of the soil capacity for infiltration and evapotranspiration within a river basin (the so-called "source-area" method used by Crawford and Linsley (1966)) or a linear distribution of the soil storage capacity for capillary water in the rooted soil layer as introduced by Becker in 1975 (see Becker and Nemec, 1987).

A further step involves sub-dividing the land surface or river basin area into larger sub-areas (zones) of approximately equal inputs and hydrological behaviour (Figure 7, part b). This sub-category (IS) of distributed models is denoted in Table 4 as semi-distributed, after Refsgaard (Knudsen *et al.*, 1986). At present this category of model is being increasingly accepted and applied because it avoids a number of the problems associated with the application at larger scales of distributed grid-based models. These problems have been pointed out in recent publications and relate, for example, to an appropriate assessment of feedbacks, areal variabilities and spatial integration features within larger areas (Dooge, 1985; Becker and Nemec, 1987). This category of model is also better able to work in the general situation with respect to the availability of model input data.

The following criteria should be taken into account when a river basin or land surface area is sub-divided into sub-areas (category IS):

(*a*) The areal distribution of the most important meteorological inputs to hydrological systems, in particular precipitation and potential evapotranspiration (taking into account the available measuring system and observation data);

(*b*) The areal distribution of land characteristics which significantly determine the general hydrological conditions and regime such as

- Topography;
- Soil and land use;
- Hydrogeology;
- Others.

In this connection it should finally be pointed out that a sub-division of a river basin into sub-basins according to Figure 7, part a, must not be misinterpreted as a semi-distributed model. It is a combination of lumped models adapted to the sub-basins concerned.

In the case of surface water systems (RR, RL and CS in Table 2) the discretization procedure is slightly modified and is principally related to the dimensionality of the model which may be one-, two- or three-dimensional.

For simple flow routeing through river reaches without extended flood plains, reservoirs, lakes, etc. a one-dimensional description is generally sufficient. An overview of available models of this type is given in Table 7 (see section 4.6 below). In applying these models, the river system is sub-divided into sub-reaches according to the existing gauging stations and also to the position of major confluences of tributaries with the main river. Whereas with a conceptual or black-box model these reaches are each modelled as a single model element, the application of a distributed hydraulic model offers the possibility of sub-dividing the river reach into shorter "computation reaches" in accordance with Figure 8, part a.

Whenever extended flood plains exist, it is more appropriate to apply a two-dimensional distributed or a semi-distributed model. However, even here a fine grid representation as shown in Figure 8, part c is only necessary in very detailed and specific investigations, e.g. in planning and design of hydraulic structures. In many other cases it is also possible to apply the much simpler but often equally efficient solution of a semi-distributed conceptual model based on a "quasi-two-dimensional" description of the river reach. The river channel itself is then represented as a separate primary conceptual model and secondary conceptual sub-models are introduced for the inundation plains; these are routeing models with different parameters for the river channel and the storage elements for polders, etc. These secondary sub-models are activated only after a certain threshold discharge— the inundation discharge—is exceeded. Such a semi-distributed model is illustrated in Figure 8 part b. Specific forms of these are the so-called multi-linear models (Table 7 and section 4.6).

It is necessary to state that relations exist between the model types explained in section 3.3 and the space distribution schemes mentioned before. These relations are represented in Table 5. They must be taken into account in selecting a model and its appropriate space discretization scheme.

Finally, some general aspects should be listed which influence the space discretization in both river basins and surface water systems:

(*a*) The purpose of the model application and the required accuracy of the model outputs;

(*b*) The amount and quality of available input information and data;

(*c*) The specific requirements and constraints to be fulfilled for applying a selected mathematical model (stability and convergence of the solution, etc.);

TABLE 5

Relation between model types and spatial discretization schemes

Model type	*River basin spatial discretization:*			*Rivers, lakes, reservoirs*		
	distributed	*semi-distributed*	*lumped*	*one-dimensional*	*two-dimensional*	*three-dimensional*
Hydrodynamic fundamental laws	+	(+)	-	+	+	+
Conceptual	(+)	+	+	+	+	-
Black-box	-	-	+	+	-	-

\+ = possible
\- = not possible
(+) = possible under certain conditions

(*d*) The type and control effect of existing or planned hydraulic structures, land-use and land-management practices.

Some explanations which may help in finding the appropriate type of model and discretization scheme are given in the next chapters, especially in Tables 6 to 8.

4. FUNDAMENTALS IN DETERMINISTIC HYDROLOGICAL MODELLING

4.1 Basic structure and requirements of deterministic simulation models

In the previous chapter hydrological models were classified in accordance with the full spectrum of required models and the purposes of their application. The main aim of this chapter is to supply some more specific information on basic approaches in deterministic modelling of hydrological processes and systems with specific reference to the most fundamental hydrological processes: water storage and discharge. These variables characterize the quantitative availability of water resources in river basins and in their relevant sub-systems. Information on them is required in almost any hydrological or water-resource system investigation and they are, therefore, of general interest.

The principal purpose of using deterministic hydrological models is to simulate ("imitate") the behaviour of the hydrological system under study, that is, to compute system outputs from given inputs (boundary conditions) and initial state conditions (Figure 9). The system output might be a set of time-dependent output or state variables $Q(t)$, such as runoff or discharge, real evapotranspiration, water level, water storage or soil moisture. These hydrological characteristics may be related to a drainage basin or its sub-systems, such as aquifers or surface water bodies. The system input $P(t)$ is a set of climatological factors (precipitation, potential evapotranspiration or related meteorological factors) and, for some sub-systems (rivers, aquifers...) water inflow.

The model equations used in computations represent specific expressions or solutions of the governing fundamental physical or other laws, in particular the continuity and dynamic equations (conservation of mass and momentum or energy) which are, in modified forms, valid for any system under consideration. The coefficients in these equations (the "model parameters"), or at least most of them, characterize the "nature" or the specific behaviour of the prototype system under study. They are dependent on relevant prototype characteristics, such as topography and other factors (Figure 9).

After a model has been calibrated, that is, all parameters have been determined (often on the basis of a relatively small number of data collected from a real hydrological system), it is possible to compute "effects" (system outputs) for longer and for other periods (than the calibration period) for which the "causes" (system inputs) are given. These may be observed, forecasted or generated, for instance by means of a stochastic input time series generation model. The "stochasticity" of the process is here included through the system inputs, while the system model itself is generally considered to be deterministic.

If the system model is "physically based", then the model parameters are identical with or related to the respective prototype characteristics (e.g. storage capacities, roughness coefficients, transmissivities). Physically based models provide a number of important advantages and are therefore increasingly in demand. Important advantages are (Klemes, 1985):

(*a*) These models are geographically and climatically transferable. Geographical differences can be taken into account by adjusting model parameters and climatic differences or climate change by system input data modification;

(*b*) The parameters of the models can be derived from assessable (measured or estimated) catchment characteristics, even for ungauged and hydrologically insufficiently explored river basins and land surface areas;

(*c*) Observed, planned or predicted land use or other changes of the system behaviour and conditions, in particular those caused by human impacts and influences, can be taken into account in the planning phase by changing the respective model parameters (for assessment, prediction or planning purposes).

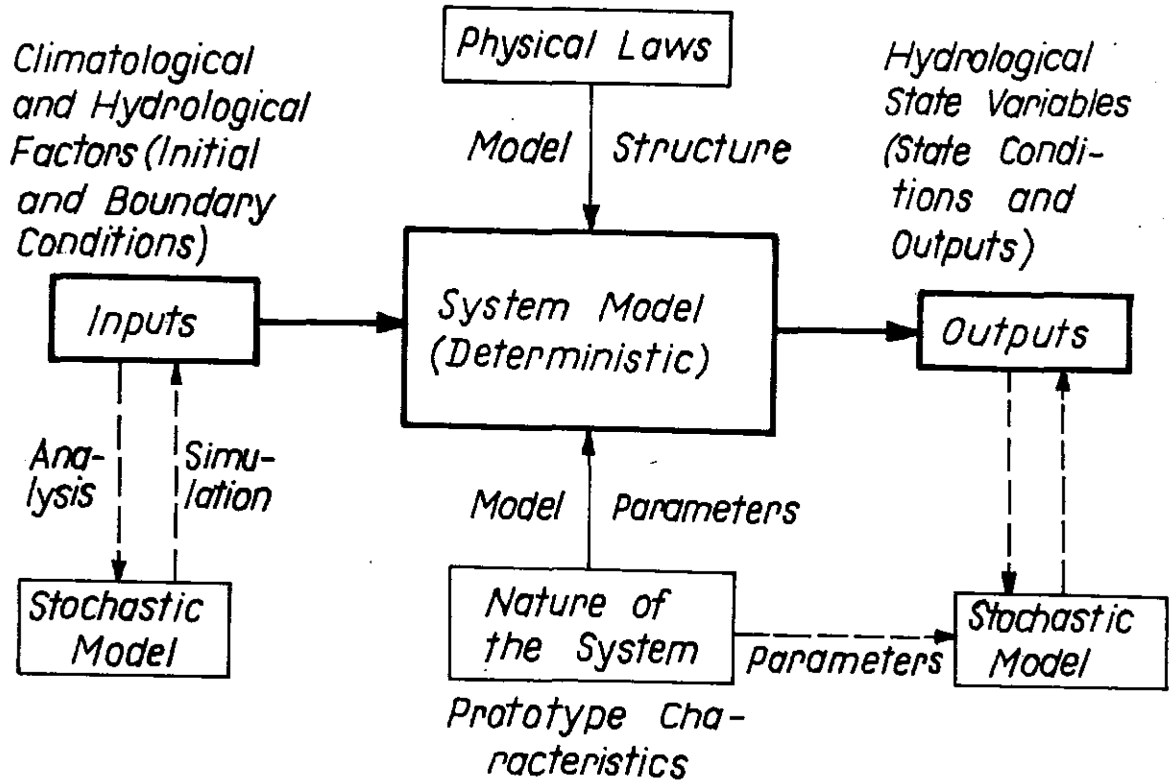


Figure 9 – Schematic representation of the role and character of determinisic hydrological models

In addition to the requirement for physically based hydro-logical models, the following general requirements should always be taken into account:

- The model should reproduce the process as accurately as possible;
- It should be understandable and "attractive" for the user in practical applications;
- It should have a modular structure so that sub-models (components) can be easily exchanged according to the specific demand, purpose of use and availability of sub-models;
- The amount of input data and information required for model calibration and application should be as small as possible.

Considering the fact that some of these requirements are contradictory, it is always necessary to find an optimum balance between the demand for a very detailed and comprehensive model (in order to reach a certain degree of accuracy in simulating the prototype behaviour) and the desire to maintain model simplicity.

Within the last decade remarkable progress has been achieved in the field of deterministic modelling of hydrological systems. A variety of successfully applied models are available which are well reflected in the different surveys and inquiries of WMO, the results of which will be presented in Chapter 5 of this report.

4.2 Time and space discretization and their dependence on the purpose of model application and input data availability

What structure a hydrological model should have, in particular which time and space discretization scheme should be used, is strongly dependent on the purpose and objective of the model and on the availability of input data. Following the rules outlined in the previous section, and recognizing the need to design a model as complicated as necessary but at the same time as simple as possible, some general recommendations are given in Table 6 for choosing appropriate time and space discretization schemes for well-known cases of river basin modelling (Becker, 1988).

It can be seen in Table 6 that in six of the eight listed cases lumped or semi-distributed models are considered as sufficient; the lumped models are used primarily in the simpler cases or for "quick solutions". In the remaining two cases a semi-distributed model (using a zoning approach), and especially in case 8, a distributed approach (considering elementary unit grid areas) is required. Naturally, the distributed approach can also be applied in other cases where the required input information and data are available.

It should be pointed out here that input data availability in model application and calibration substantially influences the selection and structuring of a model, including the time and space discretization to be used. Consider, for instance, a real-time rainfall-runoff forecasting system for which only daily totals of rainfall

TABLE 6

Appropriate time and space discretization in river basin modelling in relation to purposes and objectives of model applications (Becker, 1988)

No.	*Purpose/objective of model applications*	*Time step DT*	*Horizontal distribution*
1.	Real-time analysis and short-term forecasting and control, including flood forecasting and control	1 to 6 hours (in flatlands: up to one day)	Lumped or semi-distributed (zoning into larger sub-areas)
2.	Long-term hydrological forecasting in real time and derivation of control policies, particularly for expected low-flow periods	1 month 1 decade	
3.	Extrapolation of given discharge series (prediction)	1 day, or as 2. above	
4.	Computation of design floods	As 1. above	
5.	Larger-scale planning of water-resource use and management including planning of new structures, development of control strategies, etc.	1 month, 10 days, possibly 1 day	
6.	Development of flood-control strategies for reservoirs and reservoir systems	As 1. above	
7.	Assessment and prediction of effects of large-scale land-use changes, climate changes and different human activities on water resources	As 5. above	Semi-distributed, possibly unit grid area distribution
8.	Assessment and prediction of effects of small-scale land-use changes on water resources and hydrological processes, in particular on direct runoff, erosion, matter transport and related processes	As 1. above	Distributed (e.g. unit grid areas) or semi-distributed

can be supplied as model input (see Figure 1). It would be unreasonable in that case to use computation time steps smaller than one day even when, according to the current understanding of processes, it would be considered necessary for the simulation of infiltration and flood formation to apply much smaller time steps.

Equally, it would make no sense to apply a distributed model when neither the model inputs (precipitation, temperature, etc.) nor the required land surface and underground characteristics (parameters) can be obtained with adequate areal resolution for the area concerned. This fact very often also favours the application of simpler lumped or semi-distributed models, as indicated in Table 6.

As far as time discretization is concerned, it is clear that for different purposes and depending on the input data availability, different time intervals are to be applied. This means that sub-models which are valid only with time steps in a certain range should be exchangeable and a modular structure should be established for the program system. On the other hand, it also means that modelling principles and sub-models which can be applied with different time and space discretization schemes are preferable whenever a multi-purpose use of the integrated model is intended.

4.3 Main processes to be considered in modelling the land phase of the hydrological cycle

Modelling of the land phase of the hydrological cycle is one of the most complex problems in hydrology. For the solution of several tasks in operational hydrology and water-resource management, all components and sub-processes listed below and represented in Figure 10 are to be taken into account in their space and time variability:

(*a*) Precipitation P (rain and snowfall);

(*b*) Meteorological parameters and variables which determine

(i) Heat and moisture exchange between soil, vegetation and atmosphere, in particular real (ER) and potential evapotranspiration (EP);

(ii) Snow accumulation and snowmelt, etc.;

(*c*) Canopy interception and initial ground surface wetting (WO) during rainfall events;

(*d*) Infiltration F, depression storage and overland flow formation RO (excess rainfall);

(*e*) Soil water (recharge, movement, percolation, depletion by evapotranspiration, capillary rise; etc.) with consideration of the two forms of soil water content:

(i) Capillary water WS (below field capacity; unmovable part of soil water, but available for plant evapotranspiration);

(ii) Gravity water SF (from field capacity up to total porosity; dynamic component of soil water and source of sub-surface flows, such as percolation, flow through micropores and interflow);

(*f*) Sub-surface flow formation (interflow formation RH, groundwater recharge PG);

(*g*) Groundwater storage SG and outflow RG (base flow), if in different horizons (base flow components with various delay times);

(*h*) Overland and channel flow Q, including surface water storage in the channel network, lakes, reservoirs, etc.

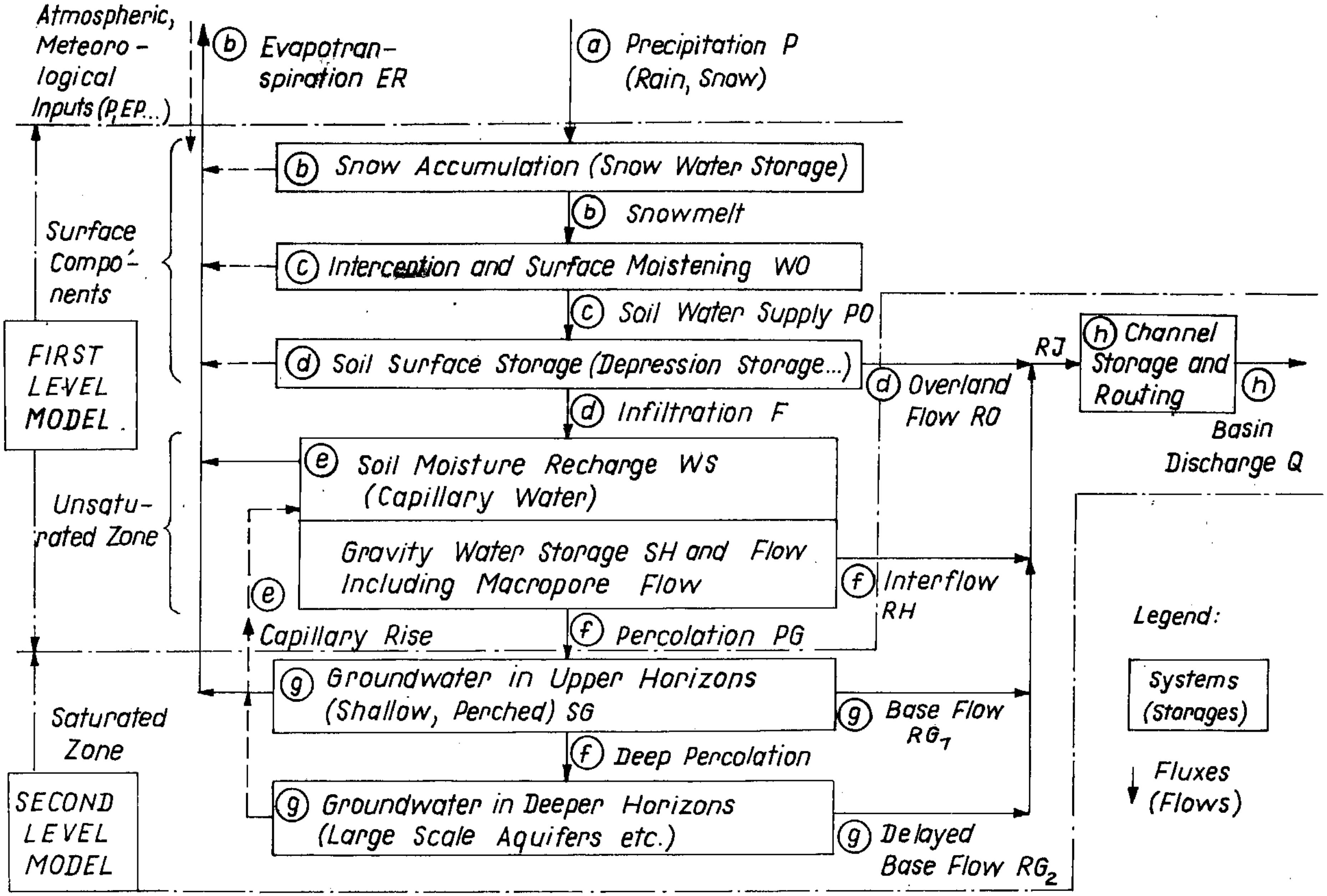


Figure 10 — Components and sub-processes of the land phase of the hydrological cycle

This sequence clearly reflects the vertical structure of the natural system (see Figure 10) and any model of it. Accordingly, and with concern for the principle differences in the character of the above-mentioned processes, the elements can be sub-grouped as follows (as shown in Figure 10):

- (*a*), (*b*) – Atmospheric (meteorological) system inputs;
- (*c*), (*d*), (*e*) – Losses (moisture recharge and evapotranspiration), infiltration and runoff formation at any place (elementary unit area) within the catchment or reference area;
- (*f*), (*g*), (*h*) – Flows (surface and sub-surface flows), areal flow concentration and outflows from the catchment.

This sub-classification directly supports the idea of a so-called "two-level modelling approach" as recently introduced (Becker and Nemec, 1987). It suggests the inclusion of sub-processes (*a*) to (*e*) in a first-level model which concerns all vertical processes of moisture exchange, recharge and flow and can be related to any land surface area (small plot, unit grid area, river basin, sub-basin or any sub-areas of them).

Accordingly, the first-level model can provide all information that is required for coupling hydrological land surface models and climate models.

The second-level model is concerned in general with the lateral flow processes (*f*), (*g*) and (*h*): surface flow, interflow and groundwater flows. It has to take into account existing water divides and is therefore more closely related to river basins, aquifer systems and the like.

An important advantage of this approach is that the requirement for a physically based model can be met separately for the first-level model which is needed for any part of the land surface whether or not it is gauged, and whether or not the available streamflow records are intended to be used for model performance testing. It should be developed even for the ungauged areas, where realistic estimates of areal evapotranspiration are demanded as an essential component of the water balance of land surface areas and as a required input for climate models.

In contrast, in a number of the larger-scale hydrological investigations (except in aquifer management, matter transport and related studies), the second-level model can be simpler. This stems from its main purpose, which is to supply time series of total storage volumes in different larger-scale flow systems together with computed river basin outflows which can then be compared with measured river discharges. A sufficiently good fit of computed and measured river basin discharges can also be considered as an indication of the reliability and correctness of the results of the first-level model.

Naturally, if specific information on the areal distribution of water movement and storage, in particular on groundwater movement and storage and on the different flow components, is of interest or is needed, then distributed physically based second-level models are also required.

As regards the flow models (second-level sub-models), it can be said that in the past, river basin modelling very often considered only two flow components: direct flow and base flow. As our understanding of processes has improved, and in view of the increasing demands, it has been found necessary to take into account at least three components and their sub-components, if possible in their areal differentiation (Figure 10):

(*a*) Overland flow RO consisting often of three sub-components

- RO_I = flow from impervious sub-areas (AIMP);
- RO_S = flow from saturated sub-areas (AS);
- RO_E = infiltration, excess rainfall and/or snowmelt from other sub-areas (AF);

(*b*) Interflow RH (quick return lateral sub-surface flow through permeable soil horizons or zones and macropores, especially in hill slope areas);

(*c*) Base flow RG (groundwater outflow), often separated into at least two sub-components

- RG_1 = short-term base flow from upper ground-water systems (near to the surface), highly permeable aquifers, perched groundwater, etc;
- RG_2 = long-term base flow from large-scale aquifers, fissure and crack systems in bedrocks, etc.

Similarly, the areal and vertical differentiation of other processes (soil moisture, evapotranspiration, precipitation, etc.) are also increasingly required. A primary task in modelling is therefore always to decide, in relation to the purpose and objective of the modelling, which sub-processes and components can be neglected or modelled in a simplified way and which must be modelled in a more detailed form.

4.4 Special aspects and problems in sub-process modelling

Almost any of the sub-processes mentioned in the previous section are highly variable in space and time, dependent on such factors as the areal variation of inputs, land surface and other characteristics and human activities. Therefore, they have to be and are modelled by means of sub-models of varying complexity. It is beyond the scope of this report to deal with all these sub-models. This subject is dealt with in relevant textbooks and special publications. Here, only some principal aspects and problems of modelling sub-processes (*c*) to (*e*) will be outlined, with special reference to larger-scale modelling. Separate sections are devoted to sub-systems (*f*) to (*h*) (i.e. to modelling the behaviour of ground and surface water systems: sections 4.5 and 4.6), and to the composition of the different sub-system models in integrated river basin models (section 4.7).

The *canopy interception* (including initial ground surface wetting; ((*c*) in Figure 10) should be taken as an example for the rather general approach of sub-process modelling in integrated river basin modelling. Here, the interception sub-model is very often represented by a simple storage reservoir with a given storage capacity (WOMAX). During rainfall events the reservoir is considered to be filled initially to this storage capacity.

Further rainfall overflows and supplies the soil surface as input PO. In subsequent dry periods, the interception storage evaporates at a rate equal to potential evapotranspiration. Often WOMAX is taken as a constant lumped parameter (e.g. 5 mm), for the sake of simplicity. In more detailed models WOMAX is introduced as a time-varying parameter, in distributed models as a space variable according to the state of the vegetation in the prototype system; sometimes it appears even in a more detailed version (e.g. Rutter *et al.*, 1975). However, this simple model, even in its improved form, can only be considered as satisfactory when computation time increments of one day or less are used. For larger time intervals, empirical or other relations are applied.

More critical, and also more difficult, is the modelling of *excess infiltration, overland flow formation and unsaturated flow and matter transport in the ground* ((*d*) and (*e*) in Figure 10). All the classical physically based models and relations for computing these processes (e.g. Nielsen *et al.*, 1986; Van Gnuchten and Jury, 1987) as well as field observations during overland flow-producing rainfall events indicate that

(*a*) Rainfall excess is strongly time variant with rainfall intensity; this would require, in the majority of rainfall events, computations in time intervals of one hour or even less (e.g. 10 min.);

(*b*) Rainfall excess is highly variable in space and depends on rainfall intensity, soil and vegetation conditions, topography, etc. and their areal distribution.

From these facts, it can be concluded that to correctly apply the classical infiltration models would require working with time intervals (DT) of 10 minutes up to a maximum of one hour. Accordingly, one can hardly claim that unsaturated flow and infiltration excess computation models are available for operational application with larger-scale lumped or semi-distributed models where time intervals of 3, 6, 12, 24 hours or even larger are usually applied. With such time intervals, most of the infiltration sub-models currently used for practical purposes lose their physical significance and become generally nothing more than "stochastic" models or empirical relations, the parameters of which are "adjusted" (somehow calibrated) or estimated (from experience).

Quite different ways of thinking and approaches are required if we are to model on a physical basis larger-scale unsaturated flow and infiltration or excess rainfall. This thinking has to take into account our improved understanding of the ongoing processes influenced by the heterogeneity of soils, macropores, etc. (Kirkby *et al.*, 1978; Yeh *et al.* 1985; Beven and Clarke, 1986). It may start from a knowledge of source areas (AS) of infiltration excess in river basins which, after an initial filling period during heavy or long-lasting rainfall, become saturated up to the surface producing direct overland flow at a rate equal to that of the falling rain (PO):

$$RO_S = PO.AS \qquad (2)$$

After an initial filling these source areas (AS) often grow dynamically with increasing moisture supply, that is, with increasing total soil water storage volume in the upper soil layers (Dunne *et al.*, 1975). This dependence can be used for estimating the time variation of the source areas, AS, (see, for example, Becker, 1988) which could provide a better physical basis and be more suitable for areal extrapolation in the larger-scale modelling of infiltration excess than the classical infiltration equations, even if the latter are modified for longer time intervals and areas.

The other important sub-process to be considered here is evapotranspiration. The estimation of areal evapotranspiration is very difficult because three different and complex factors are involved:

- The controlling atmospheric factors (radiation, temperature, wind, etc.);
- The type and state of the vegetation cover;
- The soil moisture distribution.

Each of these is variable in time and space (see, for example, Brutsaert, 1982). It is therefore easy to understand why no satisfactory methods and models for estimating areal evapotranspiration have as yet been developed. This was well reflected in the presentations and discussions in a workshop on the subject, during the XIX General Assembly of the IUGG in Vancouver, Canada in August 1987. The results of this workshop may be summarized briefly as follows (Black *et al.*, 1987):

(*a*) At present the following methods and models (relations) are more or less widely applied for practical purposes:

- Estimation methods based on measurements and estimates of potential evapotranspiration (e.g. Penman, Priestly-Taylor equation);
- Combination equations with resistence expressions (e.g. Penman-Monteith);
- The Bouchet-Morton complementary relationship;
- Energy balance methods (including those using the Bowen ratio);
- Planetary boundary-layer methods (using boundary-layer profile of gradient data);

(*b*) Unfortunately, most of these methods cannot be applied directly for larger-scale estimations, and only the first two equations offer the opportunity to predict (at least to a certain degree) the effects of expected land-use changes and other factors on areal evapotranspiration;

(*c*) The large-scale oriented models of the planetary boun-dary layer are still in the research phase, particularly in view of the given time and space variability of important processes, the incomplete mixing and the like.

Considering this unsatisfactory situation, WMO has initiated a project, "Intercomparison of methods and models for estimating area evapotranspiration", whose aims are to better understand the practical applicability of the existing estimation techniques and to promote ongoing research activities (Becker, 1987).

4.5 Groundwater flow models

Groundwater flow in aquifers is very often described by equations obtained by combining Darcy's law, as a dynamic equation with the continuity equation, adapted to the specific hydrogeological conditions of the system being investigated. The most frequently employed forms of the combined equations for two-dimensional flow modelling in acquifers are:

- For steady flow:

$$\frac{\partial}{\partial x}(K_x\frac{\partial \Phi}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial \Phi}{\partial y}) + q = 0 \tag{3}$$

- For unsteady flow:

$$\frac{\partial}{\partial x}(K_x\frac{\partial \Phi}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial \Phi}{\partial y}) + q = S_s\frac{\partial \Phi}{\partial t} \tag{4}$$

where K = hydraulic conductivity;
ϕ = groundwater head;
S_s = specific storage coefficient;
q = discharge (sources and sinks);
x,y = horizontal co-ordinates.

In its early days, groundwater-flow modelling was based mainly on analog model techniques. The introduction and wide use of high-capacity computers caused the rapid development of numerical models with a wider scope for application. Groundwater-flow models became more widely operational during the period 1966-1968.

At present there is a wide variety of operational models, from the one-layer two-dimensional models up to the multi-layer models and three-dimensional models; the range also covers monophase models and polyphase models to handle fresh water-salt water or water-air systems (water movement in the unsaturated zone), migration models (for approaching the subjects of matter transport in groundwater and groundwater pollution) and heat-transport models to be applied to the study of systems under significant thermal influences.

Accordingly, it may be said that groundwater-flow modelling has become a domain of distributed modelling, with grid-based (as in Figure 7 part c) or finite element representations of the aquifer or river basin under study. For more specific details see, for example, Bredehoeft *et al.* (1982) or Engelen and Jones (1986).

Nevertheless, in a number of larger-scale river-basin-oriented investigations with integrated river basin models, it has been found acceptable to approximate the outflow behaviour of all groundwater systems of the basin (with time delays for discharges within a certain range) by a single, rather simple and quasi-one-dimensional storage element, namely, a linear or nonlinear reservoir.

In this case the basic equations are:

- Continuity equation: $dS/dt = p - q$ (5)
- Dynamic equation: $S = k.q^m$ (6)

where S = storage (total storage volume);
p = input (total groundwater recharge per time unit);
q = output (total groundwater discharge or base flow);
m = exponent.

For the linear reservoir ($m = 1$) a very simple and useful solution of equations (5) and (6) can be derived (with $p = p_m$ = constant during a computation time step from $t - \Delta t$ to t):

$$q(t) = \underbrace{c.q(t-\Delta t)}_{\text{recession term}} + \underbrace{(1-c).p_m}_{\text{"convolution" term}} \tag{7}$$

where $c = \exp(-\Delta t/k)$. (8)

It should be pointed out, however, that this simplified approach can only be applied if the overall storage and total discharge alone are of interest, but not the internal groundwater flow and matter transport processes within the different aquifers of the basin. For groundwater systems with clearly different time delays (in different levels, or in flat or mountainous sub-areas of the river basin), different models with different parameters k and $c = c(k)$ should be applied.

4.6 Flow-routeing models for rivers and channels

A complete account of unsteady fluid flow in three dimensions is provided by the equation of mass continuity and the Navier-Stokes force-momentum equations (Cebeci and Bradshaw, 1977). For most flow-routeing cases the full equations are more complex than is warranted by requirements and data availability; a one-dimensional, gradually varied flow version is therefore applied. First derived by Saint-Venant, the resulting equations are often quoted in a form similar to Cunge *et al.* (1980)

- Continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \tag{9}$$

- Momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\frac{Q^2}{A}) + gA(\frac{\partial h}{\partial x}) + gA(I_f - I_o) = 0 \tag{10}$$

kinematic waves
diffusion waves
dynamic waves

where Q = discharge;
A = cross-sectional area of flow;
h = water depth (water surface elevation);
I_f = friction slope;
I_o = bottom slope;
x = distance along the river channel;
t = time;
g = gravitational acceleration;
q = lateral inflow.

The friction slope I_f is calculated from a resistance formula such as the Darcy-Weisbach equation

$$I_f = \frac{Q^2 f}{8gdA^2} \tag{11}$$

where d = depth and f = the Darcy-Weisbach resistance coefficient.

In the above, equation (9) expresses conservation of mass while equation (10) relates rate of change of momentum to applied forces. Derivations of the equations are presented by Cunge *et al.* (1980), among others.

Assumptions implicit in the equations include the following (Bathurst, 1988):

1. Wave depths vary gradually, meaning that the pressure distribution along a vertical should be hydrostatic, or that vertical accelerations should be small: There should be no evidence of rapidly varied flow such as hydraulic jumps.

2. Longitudinal changes in cross-sectional shape, channel alignment and frictional properties are continuous.

3. Friction losses in unsteady flow are not significantly different from those in steady flow.

4. Variation in the distribution of velocity across the channel does not significantly affect wave movement.

5. Wave movement can be considered to be two-dimensional, with the effects of lateral differences in surface elevations at cross-sections being negligible.

6. Average bed slope is small enough so that $\theta \cong \sin \theta \cong \tan \theta$ and $\cos \theta \cong 1$, where θ = angle between the channel bed and the horizontal.

7. Fluid density is constant.

8. Channel geometry does not change with time.

These assumptions are generally satisfied in most instances of flood routeing, although assumptions 3, 7 and 8 may require careful consideration when sediment transport is significant.

The Saint-Venant equations form the basis of most channel-flow models, the so-called hydrodynamic or hydraulic models. In their full form they are nonlinear and there is no known general analytical solution. In order to facilitate solution, therefore, various simplifications have been introduced, in which terms in equation (10) are neglected.

Solutions involving equation (9) and parts of equation (10) are known as simplified hydraulic routeing methods. According to equation (10), they include the kinematic wave model:

$$I_f - I_o = 0 \tag{12}$$

and the diffusion wave model

$$I_f - I_o + \frac{\partial h}{\partial x} = 0 \tag{13}$$

The kinematic model should be applied only where the depth-discharge rating curve is single valued and where backwater effects are insignificant. The diffusion model allows for the attenuation of a flood wave and for backwater effects, but should otherwise be limited to slowly or moderately rising flood waves in channels of generally uniform or quasi-uniform geometry.

Some authors have shown that the initial terms

$$(\frac{\partial Q}{\partial t} \text{ and } \frac{\partial}{\partial x}(\frac{Q^2}{A}))$$

of the momentum equation (10) are, in numerous practical cases, two orders of magnitude smaller than the bottom slope I_o (cf. Bathurst, 1988).

Solutions involving the full Saint-Venant equations are known as the complete hydraulic or dynamic wave model. This is the most general model, within the assumtions noted above, allowing for backwater effects and the upstream propagation of waves. It is the most efficient and versatile of the flow-routeing models, but is also the most complex.

Hydraulic models generally require numerical solution. Summaries of some of the techniques involved together with more detailed reviews of the characteristics of flow-routeing models are given, for example, by Cunge *et al.* (1980), Fread (1985) and Dooge (1986). These techniques require high-capacity computers and large amounts of calibration data referring to riverbed and flood-plain characteristics, in partic-lar river cross-sectional profiles, roughness coefficients, etc. They are essential for a number of applications as mentioned in Table 7.

Another way of approaching flow routeing has been introduced by hydrologists who describe the routeing process by simpler mathematical relations which result in more robust models known as hydrological or conceptual models. These models are based on a special form of equation (9) which is valid for a longer river reach:

$$dS/dt = Q_I - Q_o \tag{14}$$

where S is the total storage volume in the reach and Q_I is the inflow to and Q_o the outflow from the reach. The momentum equation (10) is replaced by a more-or-less empirical relation between S and Q_I and/or Q_o:

- Muskingum model introduced by McCarthy in 1935 (Cunge, 1969):

  $$S = k.[x.Q_I + (1-x).Q_o] \tag{15}$$

  with x taking values from 0 to 1;
- Kalinin-Miljukov model (1958): cascade of n linear reservoirs with:

  $$S = k.Q_o \tag{16}$$
- "Lag and route" model consisting of a linear reser-voir coupled with a pure translation element (SSARR, 1972).

More attractive than these "empirical" models is the solution of the diffusion wave equation (13) or the full Saint-Venant equation (10) derived under certain assumptions (Dirac im-pulse as input, or linearization; see, for example, Dooge, 1986).

However, the application of all these models is limited to systems behaving, at least approximately, in a linear manner. They fail in rivers with inundation plains which, in the case of overbank flow, behave in a strongly non-linear manner. For simulating such events and conditions, multi-linear models have proved to be very useful and efficient. They describe nonlinear systems by means of two or more different linear models operating in parallel. The inflow to the river reach is first distributed into sub-inflows to different linear sub-models. The computed outflows of these are then recombined in order to get the total outflow of the reach (Figure 11). The first version of such a model, consisting of two linear models in parallel with amplitude distribution of the input, was introduced in 1969 by Becker and Glos (the so-called "threshold model"). For more details see Becker and Kundzewicz (1987).

TABLE 7

General characteristics and fields of application of one-dimensional streamflow routeing models for gradually varied flows

Model category	*Specific models*	*Major fields of application*	*Advantages*	*Special requirments and problems*
Hydraulic (hydrodynamic) models with distributed parameters	Full Saint-Venant equations (dynamic wave model) Diffusion wave model	Water level and flow computation in any type of river or canal, even those with significant backwater effects (subcritical flow) Basis for investigations of sediment transport, water quality, effects of planned system changes, hydraulic structures, etc.	Most adequate description of gradually varied streamflow in any type of river, even for changing system conditions Most parameters and prototype characteristics are identifiable	Large amounts quality data on channel and flood plain geometry, roughness, etc. High-capacity computers required Extended efforts in programming and programme operation
Hydrologic (conceptual) models with lumped parameters	Kinematic wave model Special solutions of the above-listed models (linearized) Lag and route model Muskingum model Kalinin-Miljukov model Multilinear models, e.g. non-linear threshold model	Streamflow computation in rivers without backwater effects (esp. for supercritical flows) Real-time hydrological forecasting (exepts in backwater-affected reaches)	Adequate description of flows for the listed fields of application Small amount of input data for model calibration Easy to handle and to operate on small computers Model parameters have physical significance and are related to prototype chacarteristics	Significant simulation errors in case of applications beyond the given limits Parameters are not identical to prototype characteristics No application for predictions in case of planned system changes

In several applications to rivers with overbank flow (see e.g. Becker and Kundzewicz, 1987) it has been proved that multilinear models are nearly as simple as linear models and therefore as accurate as hydrodynamic models, at least in cases where the constraints outlined in Table 7 for their application are fulfilled. They represent an important alternative to hydraulic models.

4.7 Composition of integrated hydrological models for river basins

The composition of a hydrological model for a land surface area is dependent on the applied space distribution principle. In the case of lumped modelling, the required sub-process models can be arranged simply in a cascading manner in the sequence listed in section 4.3 and represented in Figure 10 (see sections 4.4 to 4.6). The output of one sub-system is input to the subsequent system (or vice versa). Areal variabilities are neglected or approximately taken into account by statistical distribution principles (LS in Table 4). Feedbacks are similarly treated.

This composition approach has been applied in a large number of river-basin models, beginning from the first applications of the unit-hydrograph, a lumped black-box model, in combination with a simple computation procedure for estimating "effective rainfall" (direct runoff) as input to the unit-hydrograph application.

Later, simple conceptual models were introduced as sub-system models, in particular those based on a series of storage reservoirs or tanks with a certain storage capacity and outflow characteristics (e.g. according to equation (6), generally called Nash-cascade models). Specific arrangements of such sub-models resulted in a number of well-known conceptual river-basin models of "tank-cascade type". These include the Stanford Watershed Model, represented in Figure 12 (Crawford and Linsley, 1966), the SSARR model (1972), the HBV (Bergström, 1976), the IRMB (Bultot and Dupriez, 1976), the Sacramento model (Burnash and Ferral, 1980), the Tank model (Sugawara *et al.*, 1984) and others.

The most important performance characteristics of these models and the limitations on their use are briefly outlined in Table 8 (lower part). A more extensive discussion of these limitations, in particular the problems associated with the "time and space extrapolation" of the model for application to unobserved conditions, has been presented by Klemes (1985). This clearly underlines the

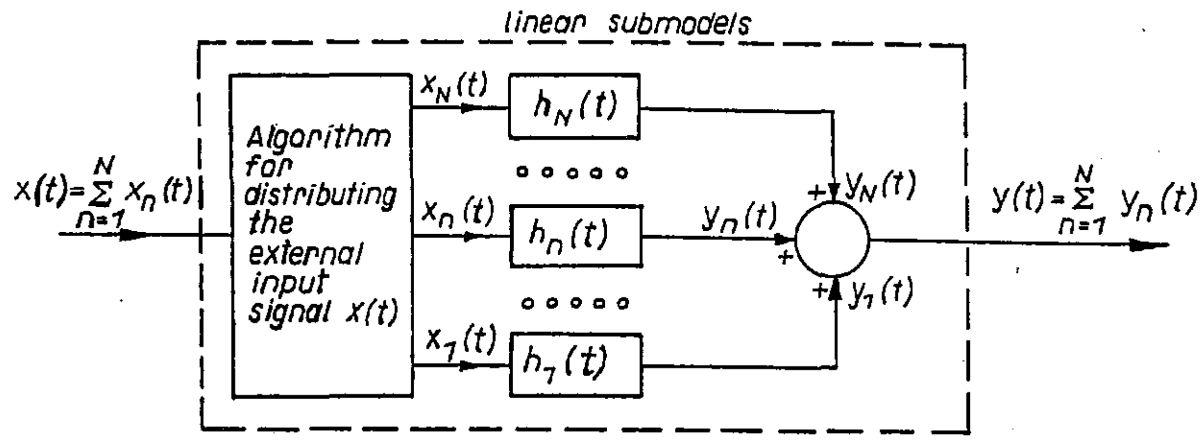


Figure 11 – Concept of a multilinear model

need for models which have a more correct physical basis, the parameters of which are identical or clearly related to measurable prototype characteristics, as already mentioned in section 4.1.

Because of these requirements and in view of the limitations of lumped models, the development of distributed and semi-distributed river-basin models was initiated. The SHE-modelling system jointly developed by the Institute of Hydrology (UK), the Danish Hydraulics Institute and SOGREAH (France) offers one version of a detailed distributed modelling system for river basins and other areas of interest (Abbott *et al.*, 1986). Its general structure is schematically represented in Figure 13. It is based on a refined space discretization of the catchment and on the numerical integration equations for momentum and mass conservation describing the physical processes in the catchment. Accordingly, it fulfils all requirements of a distributed physically based model and involves all the advantages and problems explained for this model category in the upper part of Table 8. A quite similar model was developed by Kutchment *et al.* (1983). The CEQUEAU model also belongs to this category (Girard *et al.*, 1981).

Taking into account the enormous efforts required and problems involved in adapting and applying well-founded distributed models to a real river basin, the semi-distributed modelling approach using larger sub-areas of similar hydrological behaviour as modelling units becomes an attractive proposition. When considering the sub-zoning, it is necessary to define first the different types of sub-area to be separately modelled. One version of an appropriate differentiation scheme is presented in Table 9 (Becker and Pfützner, 1986). This considers important areal differences in the hydrological regime, with particular concern for evapotranspiration and direct runoff formation.

The application of this classification to the river basin cross-sectional representation presented in Figure 14 results in the sub-zoning indicated in the upper part of that figure. The explanation of symbols is given in Table 9 and in Figure 10.

The composition of a river-basin model which takes this sub-zoning into account would result in a semi-distributed model as schematically represented in Figure 15. It can clearly be seen that different vertical "cascades" (sequences) are arranged in parallel (sub-areas AG, AH, AN, AIMP, AW) and are treated separately, though with due consideration for existing horizontal interactions.

Other important criteria for sub-zoning are:

(a) Significant differences in meteorological inputs (e.g. the dependence of precipitation and evapotranspiration on elevation);

(b) Different land uses (forests, agricultural fields, pasture, etc.);

(c) Soil and vegetation types;

(d) Morphological parameters.

An example of the sub-division of a river basin according to (*b*) is shown in Figure 7.

Existing examples of semi-distributed river-basin models are specific version of the TANK model represented in Figure 16 (Sugawara *et al.*, 1984), the EGMO model (Figure 15; Becker and Pfützner, 1986) and the WATBAL model (Knudsen *et al.*, 1986).

Fortunately, for a number of tasks (problem solutions), some of the sub-processes listed in Figure 10 can be neglected or simulated in a simplified manner. This concerns, for instance

- Groundwater flow, in the case of flood studies;
- Infiltration and direct flow formation in low flow and/or groundwater flow investigations, etc.

Thus, according to Table 6, the structure and composition of a river-basin model is strongly dependent on the purpose and objective of its application.

TABLE 8

General characteristics and fields of application of hydrological models for river basins and other land surface areas

Model category	*Main fields of application*	*Advantages*	*Special requirements and problems*
Distributed, grid-based and physically based (IG)	Detailed investigation of hydrological processes, including erosion, matter transport, water quality in their real areal distribution Study and prediction of effects of human activities, i.e. of land use practices and changes (small or larger scale) on the hydrological regime and water resources	Application of fundamental laws of hydro- and thermodynamics, etc. Applicability to gauged or ungauged basins or areas Model parameters are identical with prototype characteristics Direct useability of available areal information, e.g. remote-sensing information (satellite images, etc.)	Enormous effort in model development and operation Large amount of required input data (basin characteristics, system inputs, etc. Problems in assessing areal interactions, feedbacks, etc. Demand for high-capacity computers Difficult to operate
Semi-distributed physically-based or conceptual (IS)	As above, but for larger-scale investigations Real-time hydrological forecasting	Use of larger sub-areas as elementary modelling units Applicability to gauged or ungauged basins or areas Some parameters are identical with, others are related to prototype characteristics Relatively easy to understand and user friendly in application "Acceptable" amount of input data for model calibration and operation on "small" computers	Limited possibilities of applying fundamental laws of hydro- and thermodynamics Derivation of several parameters by empirical relations or regionalization Limited areal resolution, i.e. not useable for small-scale investigations
Lumped conceptual or black box (LS, LO)	Extrapolation of time series and "quick", approximate predictions of basin discharge Real-time hydrological forecasting	Easy to understand and to operate, even on "small" computers Small amount required input data	Very limited range of application (only gauged basins) Possibility beyond the limits defined by the calibration

When larger river basins are considered, it is necessary to use a combination of a model for the river or surface water system itself (CS in Table 2) with river-basin models for the inflowing rivers and those catchments (SA or CB).

4.8 Assessing human influences on the natural hydrological regime by means of mathematical models

An overview of the effects and influences of general developments in the world on water resources and on the hydrological regime has been given in section 2.3 (Figure 4). It clearly indicates the negative side effects on water resources and hydrological processes of ongoing activities, in particular urbanization, deforestation and intensified agricultural production.

Extensive deforestation often leads to an increase in water yield, particularily in direct runoff and hence in sediment transport (Fleming, 1975). This brings about rapid siltation of existing reservoirs which consequently lose their capacity to meet the requirements for which they were designed (water supply, irrigation, power generation, flood control, etc.). Soil erosion leads to the loss of fertile soil and hence to lower agricultural productivity.

Irrigation also provides an example of human influence on the hydrological regime. The irrigation of large areas without careful scientific support and permanent control will lead to larger agricultural yields only initially. It will later lead to higher groundwater levels and increased evapotranspiration. The latter may bring about higher ground salinization which gradually reduces agricultural productivity. In order to prevent soil salinization, drainage systems are built and operated in conjunction with the irrigation systems.

These are only two of the many examples of human activities which may influence hydrological processes and their interaction.

In long-term predictions for planning and design or for long-term management of water resources, it is very important to simulate in advance the effects of different human activities on water resources and to derive measures to preserve and protect the latter against pollution. This can only be done by using mathematical models for the systems under study.

Two different problem areas can be distinguished here when considering human influences on water resources:

(*a*) Human activities at the land surface, e.g. land-use changes (urbanization, deforestation, etc.);

(*b*) Water-resource use and management, including the control of hydrological processes in surface and groundwater systems.

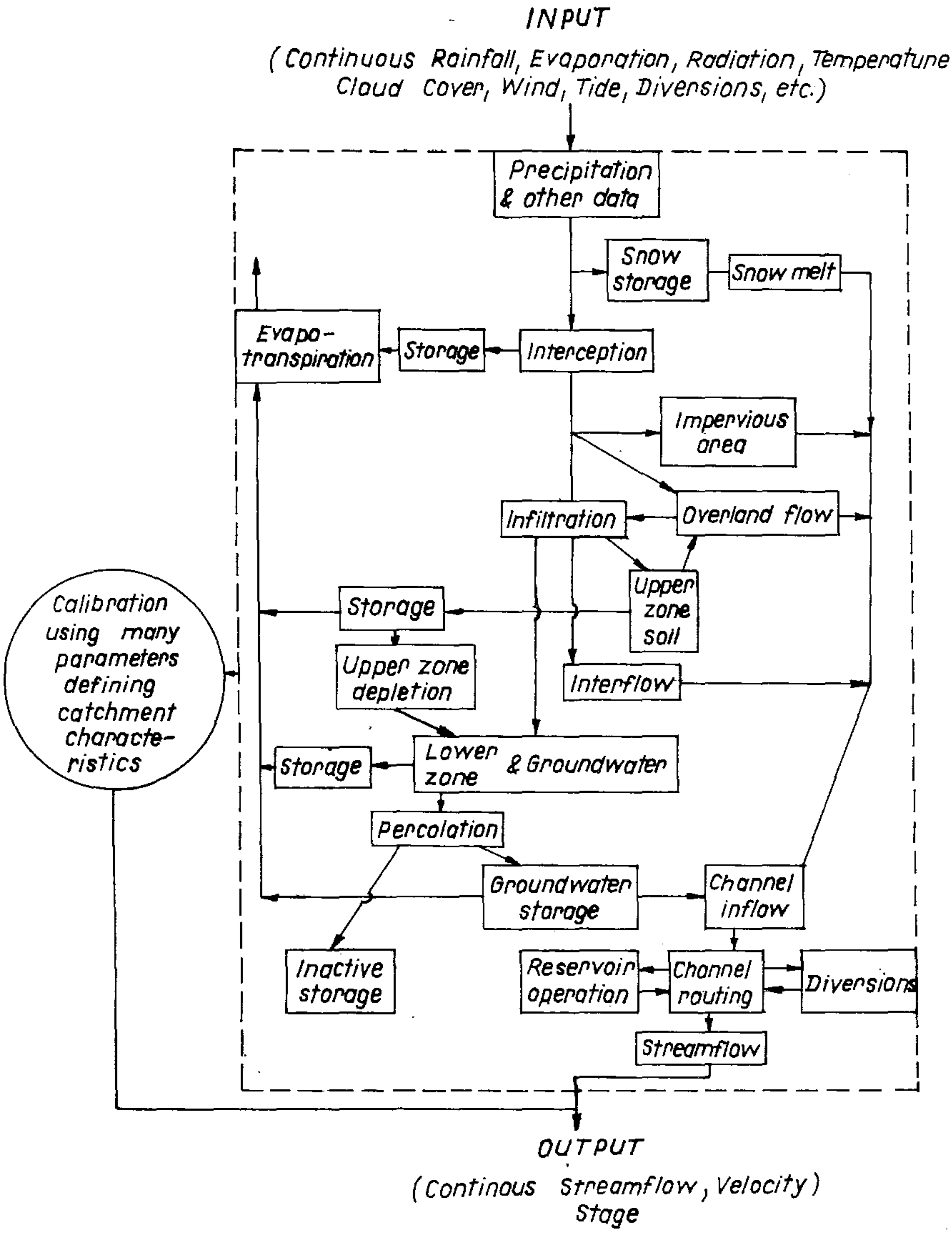


Figure 12 – The Standford watershed model IV

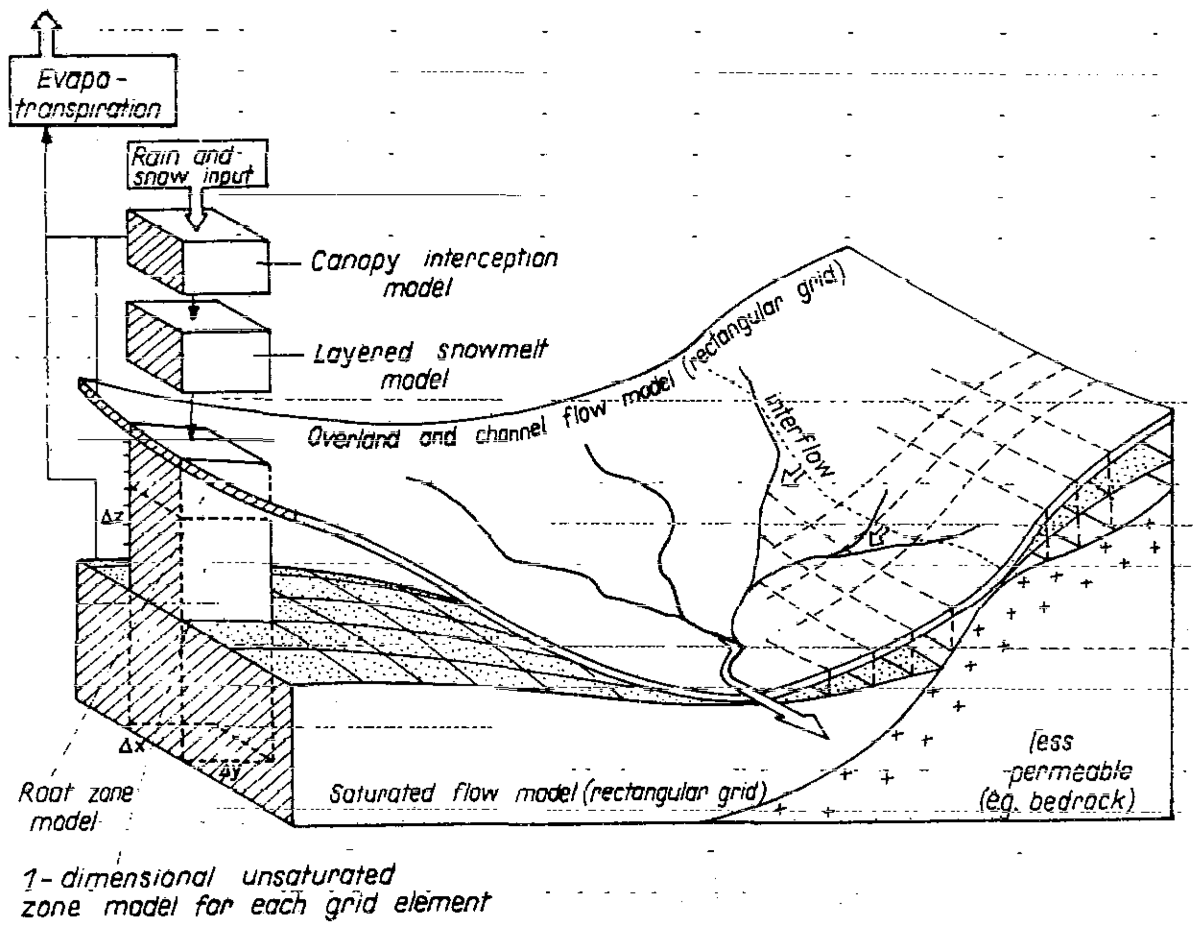


Figure 13 – Structural scheme of a river basin with indication of important sub-system

TABLE 9

Sub-areas of a river basin with significantly different hydrological regimes

Sub-area type	*Symbol*	*Evapotranspiration*	*Direct runoff generation*
Open water surfaces	AW	Potential	Equal to total precipitation (100%)
Impervious areas (rocks, paved, etc.)	AIMP	Only during rainfall, i.e. near zero	Near total precipitation (near 100%)
Flat areas with:			
– deep groundwater	AG	Soil-moisture dependent	Near zero
– shallow groundwater	AN	Generally potential	From saturated sub areas AS (which vary moisture dependent), near total precipitation
Sloped areas with:			
– deep permeable underground	AF	As for AG above	As for AG above; infiltration excess in case of heavy rainfall or frozen ground possible
– shallow soils, highly permeable subsoils	AH	As for AG above	Interflow (quick return) and infiltration excess or AS overland flow (as for AN above)

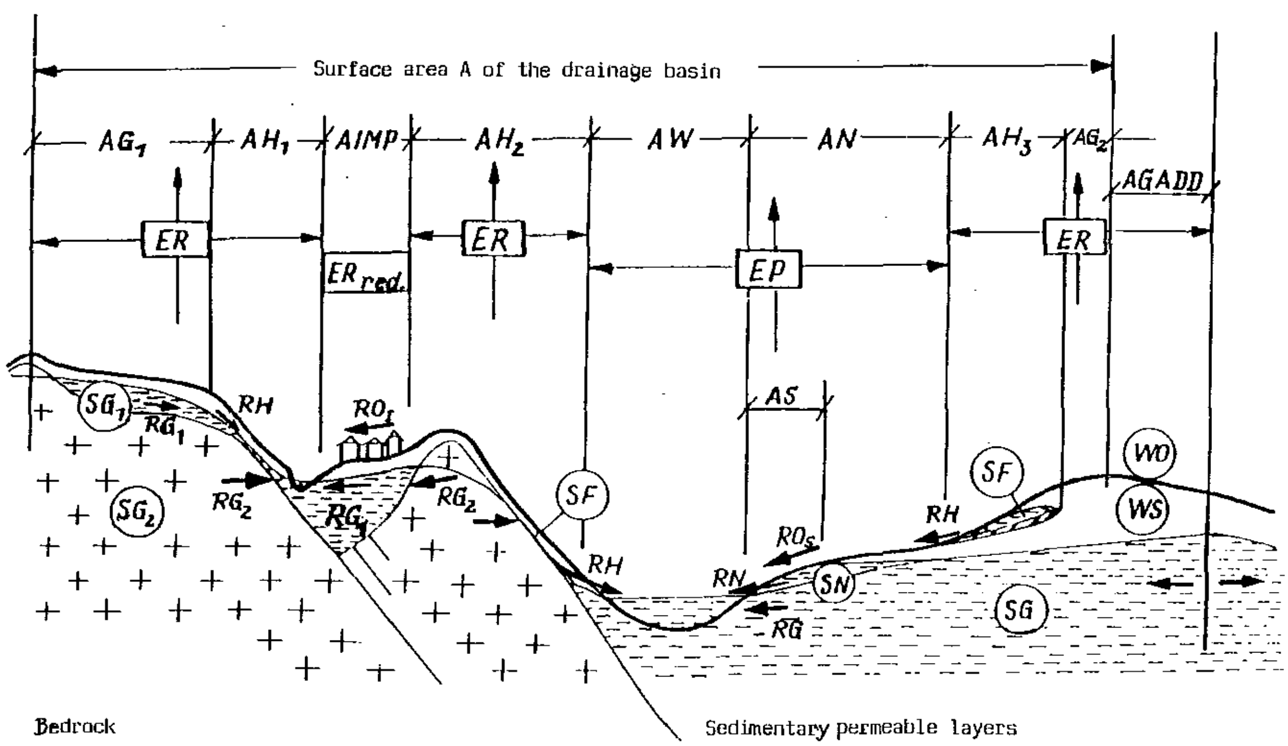


Figure 14 – River basin cross-section with indication of sub-areas of different hydrological regime

Typical activities of the aforementioned types are listed in Table 10 and grouped according to (*a*) and (*b*). The hydrological processes which are affected to a greater or lesser extent are listed on the right of the table.

Taking account of activities of types (*a*) requires a distributed or semi-distributed physically based model of the respective land surface area. The parameters of this model must be identical with or clearly related to the characteristics of the prototype system (see Tables 4 and 8). It is then possible to adjust the relevant model parameters according to the expected land-use change (e.g. root depth, infiltration capacity, moisture storage capacities, etc.) and to predict the consequences on the hydrological processes and on the water resources with given system inputs as observed or predicted. These predictions were introduced in section 2.3 as activity (*b*) (PL in Figure 2) in the first phase of the planning process.

Activities (*b*) in Table 10 together represent one of the main subjects to be investigated in the second phase of the planning process (see section 2.3). They are of interest not only in the structural planning (PD), but also in the derivation of efficient management strategies and control rules for hydraulic structures (PC in Figure 2). In all cases, it must be possible to make specific structural modifications of the modelled water-resource systems in line with the relevant structural planning, and this has to be considered in the choice and development of a model. This also ensures that different management or control strategies can be investigated.

4.9 Particularities of real-time forecasting procedures

Models which simulate a definite process, for example flow routeing or river-basin models as described in sections 4.6 and 4.7, are also useable in principle for real-time forecasting. They compute system states and outputs from given inputs and initial conditions, as shown in Figure 9.

As no model can perfectly represent the real system, simulation errors occur in any model application. In real-time forecasting applications, considerable efforts are made to minimize these errors using so-called updating procedures which take into account the last observed values of the forecast variable (e.g. discharges or water stages) or, more strictly, the differences between the "simulated" and last observed values of the forecast variable (see e.g. Anderson and Burt, 1985). Thus, a real-time forecasting model is generally a combination of two components (Figure 17):

- A simulation model;
- An updating procedure.

Updating procedures are continuously applied in real-time forecasting. They do not involve the periodic recalibration of a simulation model, which is necessary only after important events (e.g. major floods) or system changes (e.g. due to human influences). How updating generally affects a forecast hydrograph is illustrated in the lower part of Figure 17 (Serban, 1988).

Considering the different possible origins of simulation errors:

- Errors in the input data;
- Errors due to imperfect model structure, limited number of calibration data, changing system conditions;
- Rating curve errors

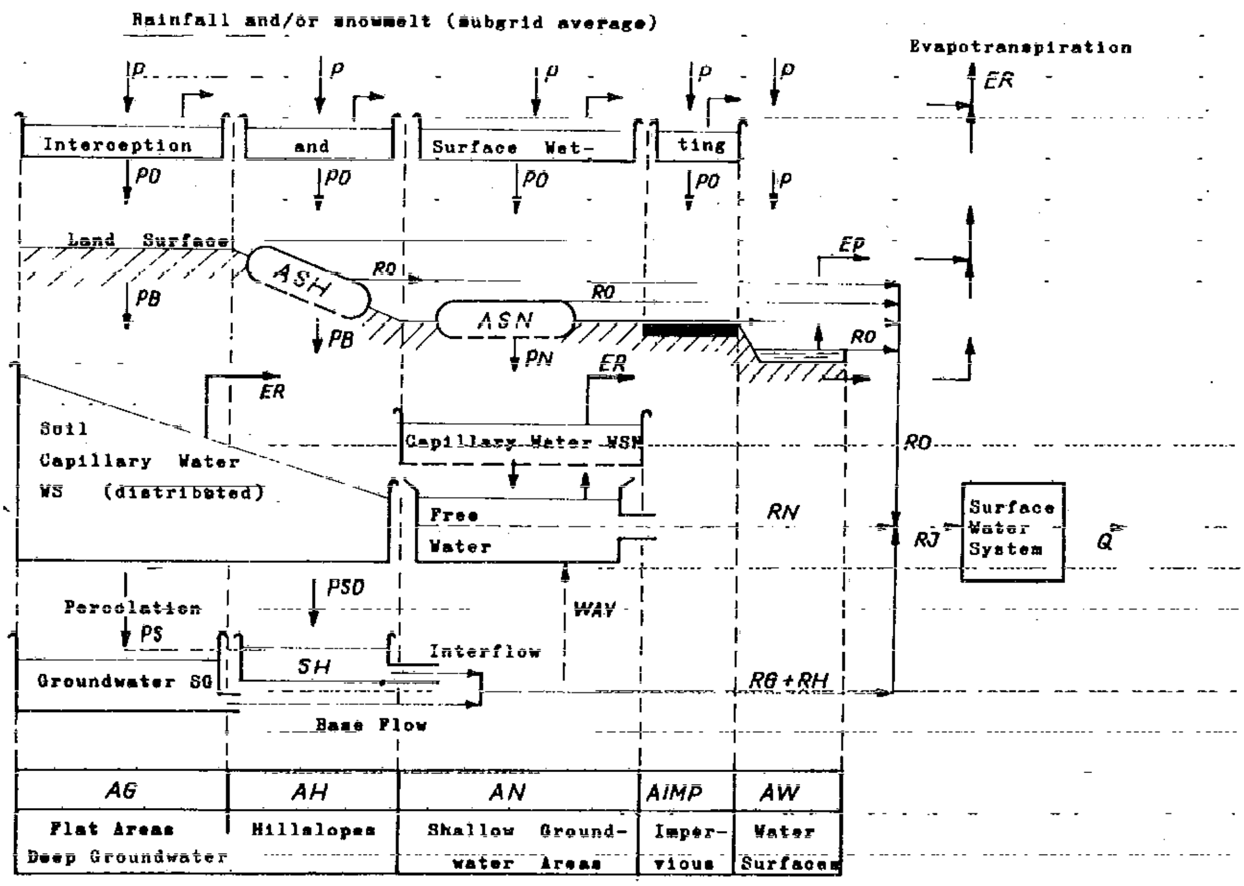


Figure 15 – Compositions of a semi-distributed river-basin model on the basis of a zoning conception (Model EGMO after Becker and Pfützner, 1987)

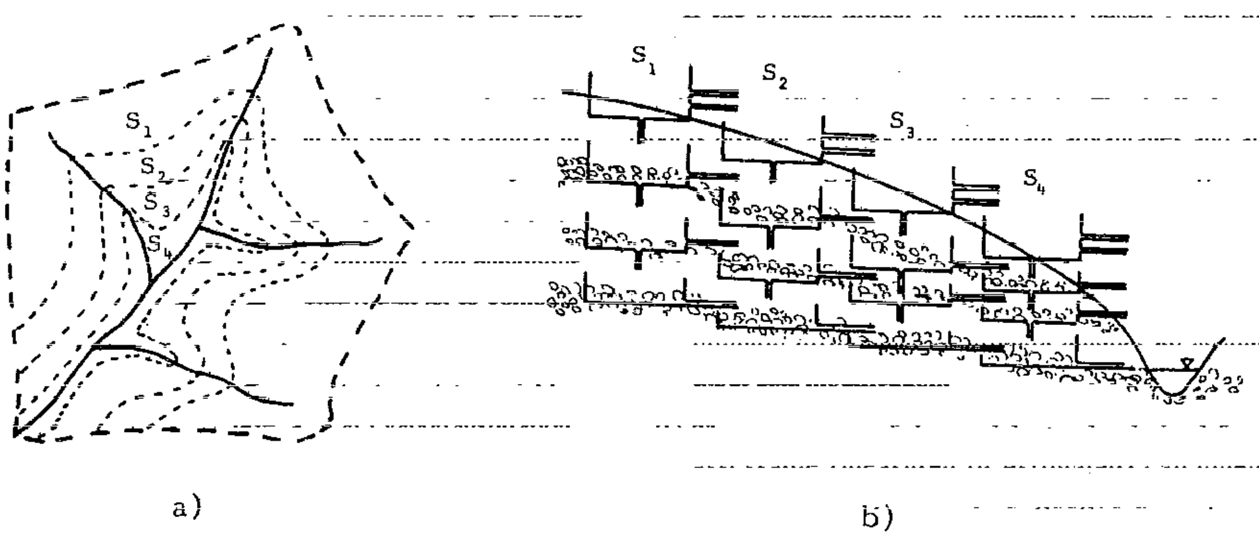


Figure 16 – "Zoned" TANK model (after Sugawara et al., 1984) as a special version of a semi-distributed river-basin model

a) Sub-areas with different water storage behaviour

b) Related Tank model (zoned)

TABLE 10

Different types of human activity which influence hydrological processes and water resources

Basic type	*Human activities*	*Processes influenced*
(a)	AGRICULTURE	
	Irrigation	ET/WS/SG
	Drainage	RO/WS/SG
	Soil erosion conrol	RO/QS/WS
	Agrophytotechnology	RO/QS/WS/ET
	Agrochemistry, Phytopathology } pollution	WS/SG
	SYLVICULTURE	
	Afforestation	ET/RO/QS
	Deforestation	ET/RO/QS
	Torrent alleviation	Q/QS
	URBANIZATION AND INDUSTRALIZATION	
	Urbanization	All processes
(b)	Groundwater use	SG
	Surface water use	Q
	Sewage discharge (pollution)	Q/(wG/SG)
	RIVER ENGINEERING WORKS, CONSTRUCTION OF	
	Reservoirs	Q/QS
	Dykes	Q
	Diversions	Q

Note: ET - evapotranspiration
RO - overland flow
WS - processes in the unsaturated zone
SG - processes in the saturated zone
QS - erosion-deposition-transport
Q - channel flow

three different sets of variables are taken as the subject of updating:

(*a*) Input variables (in particular rainfall and/or snowmelt);

(*b*) State variables (water storages);

(*c*) Output variables (discharges or related variables).

Certain models make use of updating procedures for both input and output variables, whereas others use the updating of both the state and output variables. As a rule, model parameters are not updated because in most models they are not independent of each other and the modification of one parameter would call for the modification of other parameters. Manipulation of parameters and studies of the relation between them should preferably be carried out during calibration and not on a continuing basis during forecasting operations.

The updating procedures can be classified according to their means of application as follows:

I - Automated procedures;

II - Manual-interactive procedures.

Automated procedures are reproduceable and fully objective. This point is sometimes used to justify their use in preference to manual procedures.

The manual-interactive procedures are based on the practical experience of the forecaster, and so include a certain amount of subjectivism. In applying manual procedures, interactive programmes are required which allow for a real "man-machine" dialogue.

Some models use both automated and manual procedures. In these cases the automated adjustment schemes are used only as instruments for assisting the user to adjust the model to the observed conditions. After applying the automated procedures, the forecaster reviews the model state and compares it to the data measured over the basin. If there are errors the user subjectively changes certain variables and runs the automated procedure again.

Input variables to be updated are precipitation (rainfall, snowmelt), air temperature and the snow-covered area. In some cases snowmelt is updated as an intermediate variable (snowmelt model output being a rainfall-runoff model input).

Most procedures which update input or state variables are iterative and of the "trial-and-error" type, as with many models it is difficult to solve the reverse problem: to estimate model input when model output and parameters are given.

The most important stages in this type of procedure, which are carried out at each forecasting step j, are:

(*a*) Computation of the error e_j (difference between the measured and simulated system output at time j);

(*b*) Comparison of e_j with the allowable threshold error;

(*c*) Adjustment of the selected input variable(s) taking into account the defined adjustment increment for each variable and the maximum number of increments of change allowed at any computation step;

(*d*) Re-running of the model with the adjusted input variables.

State variables to be adjusted are: water equivalent of the snow cover and levels of water storage at the surface, in the unsaturated and saturated zones and in the riverbed. One justification for updating state variables is the fact that errors in model inputs are primarily accumulated as errors in the water storages of the simulation model, which then directly cause the errors in the output variables.

The amount of water stored is often updated by means of a Kalman filter. In applying the linear Kalman filter, the following is required (Gelb, 1974):

- A description of the system dynamics by means of a system of linear equations of the form

$$X_j = \phi X_{j-1} + IU_{j-1} + W_{j-1} \tag{17}$$

- A definition of the measurement equation relating the measurements which are generally carried out on the system output to the considered state variables:

$$Z_j = HX_j + V_j \tag{18}$$

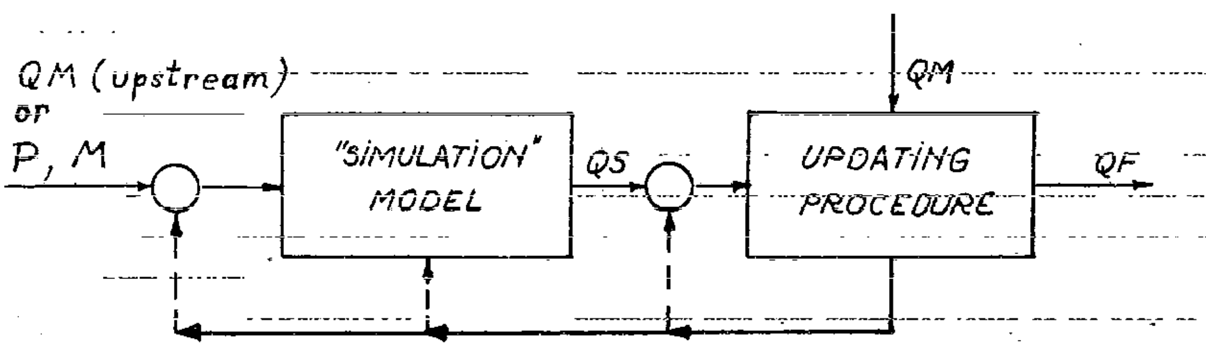
where X = vector of the state variables, describing the system evolution;
U = a control vector containing the input variables;
ϕ = transition matrix;
I = input adjustment matrix;
W = modelling error vector;
Z = measurement vector;
H = measurement selection matrix;
V = measurement error vector.

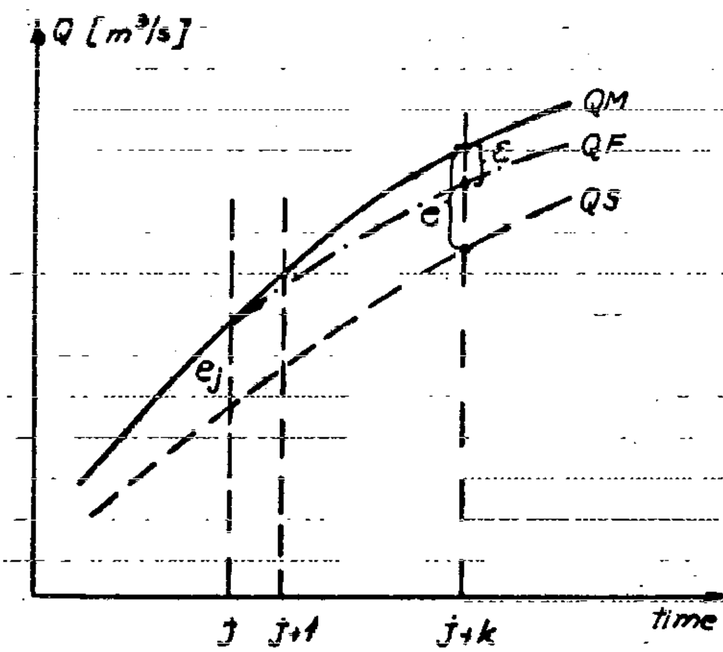
The matrices ϕ, Q and H defining the characteristics of the modelled system can be constant or variable in time.

The V and W errors are considered as independent and normally distributed.

The use of the Kalman filter helps in the consideration of the most significant error sources (input and output variables, non-optimal parameter values) and it is on this account that the discharges can be computed together with their confidence limits.

Output variables to be updated are discharges, water-levels, flood volume, hydrograph shape or related variables. The discharge-updating procedures most widely used in practice are based on auto-regressive models that simulate the errors between the computed and measured hydrographs.





P - rainfall
M - other meteorologcial factors
QS - simulated hydrograph
QM - measured hydrograph
J - forecasting moment
QF - forecasted hydrograph
e - simulation error
ε - forcecasting error

Figure 17 – Block scheme of a forecasting procedure and of the principle effect of updating

Some models use an efficient procedure for discharge updating based on a recursive relation of the type

$$QF_{j+1} = k_r QM_j + \Delta Q \qquad (19)$$

where QF_{j+1} = forecasted discharge at moment j+1;
QM_j = measured discharge at moment j;
k_r = recession coefficient varying as a function of discharge;
ΔQ = inflow due to rainfall and water released by snowmelt at time steps j and j+1.

Forecast updating procedures are generally efficient over lead times smaller than the system memory.

Updating procedures of the "trial-and-error" type for the input variables are efficient both on the rising and on the falling limb of the hydrograph and they yield the best results for snowmelt floods.

Updating procedures for the state variables based on a Kalman filter imply model linearization and its rewriting in state space form. The programming is difficult and, in addition, the memory occupied by the program is large and the program takes quite a long time to run. This procedure is optimum from a mathematical standpoint and yields satisfactory results with short lead times. Its efficiency, however, is still open to discussion for longer lead times and with respect to the flood crest, because the hydrological conditions may differ greatly from those at the conditions at the time of forecasting.

The updating procedure based on a Kalman filter is advantageous inasmuch as it allows the determination of the confidence limits of the forecast discharges, which are very useful in assessing the uncertainty in forecasts.

Updating procedures applied to model output variables and based on autoregressive models are easily programmed and applied with a short computation time. Their efficiency depends on the degree of error persistence between the measured and computed hydrographs. Accordingly, updating procedures based on the autoregressive model yield very good results along the falling limb of the hydrograph. Unfortunately, in the vicinity of the flood crest, error persistence is least and errors may show a tendency to oscillate.

5. EVALUATION OF THE AVAILABILITY OF HYDROLOGICAL MODELS

5.1 Criteria and sources used for evaluating model availability

An enormous number of different models exist within the model categories considered in the previous chapter. Most of these were and are the subject of research and have been applied only in a research mode. Others have been successfully introduced into practical applications and are now used routinely for practical purposes. The primary emphasis of this report is on the latter models. Therefore, the practical use and applicability of a model is taken as the primary criteria for evaluating its availability. Three main sources of information were used as a basis for the evaluation in this respect:

(*a*) The HOMS *Reference Manual* (WMO, 1988b), sections J, K and L of which include hydrological models and procedures which are generally available as components of the Hydrological Operational Multipurpose Sub-programme (HOMS);

(*b*) The results of different surveys (enquiries) of the WMO Regional Associations;

(*c*) Other specific publications.

HOMS was approved in May 1979 by the Eighth WMO Congress and initiated as a means of facilitating the transfer of available hydrological technology operationally used in the fields of network design; hydrological observations, collection, processing and storage of data; and hydrological modelling.

As one of the first activities within this sub-programme, a standardized format was designed for use in compiling brief descriptions of the components made available through HOMS by the various institutions and organizations concerned (see Annex 1). Each component can be requested by any other institution or organization in the world which is interested in using it. Thus any model or procedure included in HOMS can be considered, by definition, to be available for practical application. All descriptions of HOMS components received by the WMO Secretariat and approved by the competent bodies of the WMO Commission for Hydrology are included in the HOMS *Reference Manual.*

The first edition of the *Manual* was published in 1981 (WMO, 1981) and the second edition was issued in 1988 (WMO, 1988b). It is in the form of a loose-leaf collection which can easily be supplemented, "updated" or otherwise revised. For the present report, all descriptions available in sections J, K and L of the *Manual* in July 1988 were analysed and classified according to the criteria defined in Tables 1, 2, 3 and 4 in Chapter 2. The result, which is presented in Annex 3 and summarized in Tables 11 and 12, is analysed in the next chapter.

The series of enquiries mentioned above under (*b*) was initiated by Regional Association VI (Europe) at its eighth session (Rome, 1982). A questionnaire on the characteristics of operational hydrological models used in RA VI was prepared; a copy is reproduced as Annex 2. It sought the following information:

- Name of model, author, institution, country, place of application;
- Model objective, algorithm and outcomes;
- Modelled processes, including human influences;
- Required data for calibration and application;
- Data acquisition, transmission and processing.

The 63 replies to the questionnaire were carefully analysed and the results of the analysis presented in a comprehensive report by Serban (1986). Important parts of that report are included in the present report. The summarized outcome of his analysis is attached as Annex 4 and will be commented upon in the next chapter.

Similar enquiries were also initiated by other WMO Regional Associations, the summarized results of which are presented in Annexes 5 to 7. These results and the other publications referred to above under (*c*) will also be discussed in the next chapter.

5.2 Hydrological model availability according to different surveys and sources

As already mentioned, the results of the analysis of sections J, K and L of the HOMS *Reference Manual* and of the replies to the enquiries in Regional Associations I (Africa), II (Asia), III (South America) and VI (Europe) are presented in Annexes 3 to 7, and in summarized form in Tables 11 and 12.

In Annexes 3 to 7 the following information is presented for each model or procedure:

1. Country of origin of the model;
2. Name of the model;
3. Model index (composed of the official ISO abbreviation of the country's name and a running number);
4. Purpose of the model application characterized by the identifiers given in Table 1 and Figure 2;
5. Type of system modelled (identifiers of Table 2);
6. Process or variable considered (identifiers of Table 3);
7. Degree of causality according to Figure 5;
8. Applied space discretization scheme according to Table 4 and Figure 5.

A simple summary of equal identifiers in columns 3 to 8 of Annexes 3 to 7 provides a general overview of the availability of hydrological models with regard to the classification criteria defined in Chapter 3. This overview is presented in Tables 11 and 12.

Table 11 contains all available information on surface water resources systems and processes (RR, RL and CS, column 1 of Table 11), and on the source areas (SA) and basin areas (CB) of these systems. The main part of Table 11 is related to water discharges and levels as hydrological variables of fundamental importance and interest (columns 3 to 14). This is caused not only by the relatively advanced level of model development in this field of hydrology, but also by the form of the circulated questionnaires mentioned above in section 5.1.

The information is sub-divided horizontally in terms of the following criteria:

(*a*) Purpose of application (columns 3 to 8), in accordance with the sub-categories defined in Table 1 and Figure 2;

(*b*) Basic types of the models (columns 9 to 11) in accordance with the sub-categories defined in Figure 5;

(*c*) Space discretization scheme applied (columns 12 to 14) according to the sub-categories defined in Table 4 and Figure 5.

Furthermore, the information under each type of system considered is sub-divided in terms of the origin of the information, as specified in column 2, namely:

(*a*) HOMS – from descriptions in the HOMS *Reference Manual;*

(*b*) RA – from replies to the inquiries in Regional Associations I (Africa), II (Asia), III (South America) and VI (Europe).

The information presented in columns 15 to 17 of Table 11 on models for variables other than discharges and water levels is more or less accidental and not representative from a general point of view. It is only supplied because of its availability from the sources of information considered. The identifiers included with the numbers in columns 15 to 17 relate to the purpose of application of the respective model.

In addition to the information presented in Table 11, some information on the availability of groundwater models was derived and is reflected in Table 12. Although this information cannot be considered as complete, it indicates that groundwater models are available for different practical purposes, in accordance with Annex 10.

In principle, both tables are self-explanatory. It is clear that conceptual lumped models are best represented and widely applied for the solution of practical problems in hydrology, for real-time forecasting as well as for prediction, planning and design purposes. However, physically based distributed and semi-distributed models are also becoming increasingly available.

Another independent source of information on the availability of hydrological models is a publication of the Office of Technology Assessment of the Congress of the United States (US OTA, 1982). The relevant information is presented in Annexes 8 to 10. It was prepared by a group of leading experts which assessed the capability of surface water flow and supply models (Annex 10). They were rated according to two criteria: reliability of the model and credibility of the model results. Models were considered reliable if they accurately described the physical, chemical or other processes for which they were designed. Credible results require both a reliable model and sufficient and reliable data with which to run it.

The rating system used in the evaluation of the models is explained at the bottom of each table annexed. The tables can therefore be easily understood without additional explanation. As a general conclusion of the evaluation, it can be said that most of the available models were ranked in classes C up to A ("adequate for most purposes" up to "good"). This was also confirmed by Haimes *et al.* (1987).

5.3 General evaluation of the availability of hydrological models

The evaluation of the availability of hydrological models includes the following three aspects:

- Availability of the models themselves;
- Availability of methods, techniques (procedures) and data for calibrating hydrological models;
- Availability of programmes (procedures) and input data for applying the models for different purposes.

These aspects are considered in separate sections.

Hydrological models of elementary systems are listed in Table 2 and can be considered as being generally available. Tables 11 and 12 and Annexes 3 to 10 deal further with the availability of models and concern in particular:

TABLE 11

Availability of hydrological models for surface water bodies and systems, surface areas and river basins

Variables:		*Surface water levels or discharges Q*												*Others*		
		Purpose of application						*Model type*			*Space discretization*					
		Forecasting		*Prediction (P)*												
Type of system	*Evaluation source*	*Without control* FO	*With control* FC	*Observed conditions* PO. OP	*With land-use changes* PL	*Planning and design* <1D PD	>1D	*Fundamental laws* DL	*Conceptual* DC	*Black box* DB	*Distributed* IG	*Semi-distributed* IS	*Lumped* L	*Temperature* TW	*Erosion, sediment* QS	*Water quality* WQ
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Small area	HOMS	13		6	3	1	1	2	18	8		5	21		1	
SA	RA	23		11	7		1		30	11	3	1	39		(PL)	
River reaches	HOMS	7	1	8		8		15	9	2	13	2	11			3
RR	RA	16	1	3		6		8	13	3	8		16			PO
Reservoirs,	HOMS		1			5	6	3	9		3	2	7	1	1	1
lakes RL:	RA		2			2	1	1	7		1		7	(PD)	(PD)	(FC)
Surface water	HOMS		1			4	5	5	4		5	2	2		1	
systems CS	RA		6			2	1	2	6		3		5		pd	
Large river	HOMS	8	4	2	3	6	1		20	2		10	12	1		2
basins CB	RA	8	16	2	1	4			31			3	28	(FO)		(PD)

TABLE 12

Availability of groundwater models according to the HOMS *Reference Manual* and results of enquiries in RAs I, II, III, and VI of WMO

Source	*Groundwater*				
	Level/Storage				*Quality*
	FO	PO	PD	OP	
HOMS	1	3	3	1	4
RAs	1	9	3		

(*a*) Elementary mathematical sub-models and basic relations such as regression relations, empirical relations, convolution equations, differential or difference equations, approximate analytical solutions, equation solvers, etc.;

(*b*) Elementary hydrological land surface sub-systems models, for example for interception, infiltration, rainfall excess, soil moisture accounting, evapotranspiration, sheet flow, snowmelt and others;

(*c*) River-reach and channel-reach models, which include streamflow-routeing models (conceptual linear and non-linear models, hydraulic models with distributed parameters, etc.) and elementary sub-models for single water structures, lakes and reservoirs, etc.;

(*d*) Groundwater models;

(*e*) Transport, mixing, stratification and density-flow models (salt water intrusion, thermal plumes, etc.) for large water bodies (rivers, lakes, reservoirs, groundwater systems etc.);

(*f*) Water-quality models which take into account the water chemistry, biology and ecological aspects of water-resource systems;

(*g*) Erosion, sediment transport and sedimentation models.

Among these model groups (sub-categories), (*c*) streamflow-routeing models, including models for backwater curve analysis and models for reservoirs, lakes and single water structures, and (*d*) groundwater models are the most widely available, including well-developed and documented program packages (United Nations, 1986). This is discussed in sections 4.5 and 4.6.

Also available are (*b*) elementary hydrological land surface sub-system models. Specific aspects of and problems in modelling some of these sub-processes are considered in section 4.4.

Still under development are (*f*) water-quality models, (*g*) erosion and sedimentation models, and (*e*) transport and mixing models.

Clearly documented in Tables 11 and 12 and in Annexes 3 to 10 is the availability of model combinations for river basins (CB in Table 2), river systems (CS), complex groundwater or aquifer systems and other complex water-resource systems. Their structure and hence their computer programs are often specified with regard to the real systems to be modelled. This means that they are not directly transferrable. On the other hand, program packages do exist in a generalized form (e.g. in Haimes *et al.*, 1987). They are, however, not generally available, for example as HOMS components.

Rainfall-runoff models and the related software can be classified as well developed according to the above-mentioned UN Technical Report (1986). This concerns, however, only those models which are constructed from classical conceptual sub-models, and other simplified sub-process models (for infiltration, moisture accounting, streamflow routeing, etc.) as characterized in sections 4.2 to 4.5, 4.7 and in Table 8. Semi-distributed or distributed physically based river basin and other hydrological land surface models, in particular those that allow for an investigation of effects and influences of human activities on the hydrological regime and on water quality, are still in the research and development stage. This is discussed in sections 4.7, 4.8 and 6.5.

In principal, while they are not yet widely available or used, physically based meso- and macroscale models for land surface units are required within the World Climate Programme (WCP) in connection with Atmospheric Global Circulation Models (AGCM) and for other purposes. This is discussed in Chapter 6.

Further research and development work is also needed in the field of coupled water quantity and quality modelling and in integrating these models in comprehensive land surface area, aquifer, catchment and river-basin models.

5.4 Procedures for model calibration and testing

One of the most widely used approaches for identifying hydrological systems (calibrating hydrological models) is to "optimize" the model parameters using computer-aided minimizing of the deviations between recorded discharges and discharges computed from the corresponding observed system inputs (discharge, precipitation, etc.). For this purpose several optimization techniques and computer-aided trial-and-error procedures (programs) are available which will not be considered here. For estimating catchment model parameters, the Rosenbrock optimization procedure is often recommended (e.g. in Kraijenhoff and Moll, 1986).

System identification on the basis of such techniques is useful and acceptable if reliable input and output data sets are available and if the models are considered to be used for real-time forecasting purposes or for simulation, planning and design under the given system conditions. However, the calibrated models are not directly useable for investigating the effect of climate or land-use changes on the hydrological regime and water resources, and they are not geographically transferrable. This has clearly been pointed out by Klemes (1985). The alternative approach is model synthesis using physically based models, the parameters of which are estimated from available real-world characteristics. This approach is now under development (see section 6.5).

Another important aspect is the verification of models and their intercomparison. WMO has played a leading role in initiating and organizing international projects for intercomparing hydrological models, namely (*a*) Intercomparison of conceptual models used in operational hydrological forecasting (WMO, 1975);

(*b*) Intercomparison of models of snowmelt runoff (WMO, 1985);

(*c*) Simulated real-time intercomparison of hydrological models (WMO 1987).

In connection with those projects, generalized techniques for model testing have been developed and criteria characterizing their performance have been introduced and applied. These can be recommended for general use.

5.5 Procedures for real-time forecasting and control

The progress achieved in this important field of model application is well documented in Table 11 and in Annexes 3 to 9. This concerns nearly all sub-categories of real-time forecasting procedures as listed below:

(*a*) Stage and flow forecasting in rivers using hydrological data as boundary conditions, i.e. upstream, downstream and intermediate inflows, outflows, stages, etc.;

(*b*) Basin runoff (discharge) forecast from hydrometeorological input data (including urban runoff);

(*c*) Seasonal flow forecasting, including low-flow forecasting;

(*d*) Forecasting of soil moisture conditions (including water demands for irrigation);

(*e*) Forecasting of groundwater levels and flows;

(*f*) Forecasting of freezing and break-up of ice in rivers, lakes, reservoirs, etc.;

(*g*) Forecasting of sediment yield;

(*h*) Forecasting of water quality;

(*i*) Realtime control of hydrological processes and water-resource use and management (quantity and quality).

According to the state of model availability as characterized in sections 5.2 and 5.3, procedures for forecasting water stage and discharge ((*a*) to (*c*) above) are the most advanced and are in routine use in many countries. This is confirmed by reports recently published on discharge forecasting from precipitation (Zhidikov and Romanov, 1989). A number of routinely used procedures also exist for soil moisture accounting and forecasting. However, this is not reflected in HOMS.

A characteristic and essential feature of most procedures for real-time forecasting, in particular short-term forecasting, is their updating capability. This was considered in section 4.9 (see also Anderson and Burt, 1985). As stated there, some models used in real-time forecasting have an updating capability inherent in their structure, because the observed data of the forecast variable are used as input variables in the model (e.g. difference-equation-type models, ARMA models and others). Other models use a separate procedure for updating the forecasts (e.g. a Kalman filter).

Still under development are forecasting procedures for water quality parameters, sediment yield and ice conditions in surface waters, although a number of procedures already exist and are applied for operational purposes.

5.6 Procedures for planning and design

A situation similar to that for real-time forecasting and control is found in the planning and design of water structures and water-resource systems. This situation is adequately reflected in Tables 11 and Annexes 8-10, and also by some recent United Nations and Unesco publications (United Nations, 1986; Haimes *et al.* 1987; Zuidema *et al.*, 1987; Lowing *et al.*, 1987). According to these publications and to generally available information, it can be said that adequate procedures for operational use do exist for nearly all the following sub-categories of procedure for planning and design:

(*a*) Basic purposes of planning and design, such as generation of hydrologic time series, opti-mization, economic evaluation, etc.;

(*b*) Long-term prediction of available water resources;

(*c*) Planning of watershed management taking into account effects on water balance components, the hydrological regime and water quality;

(*d*) Estimation of flood parameters (peak, volume, exceedance probability, design flood, etc.);

(*e*) Flood control planning, flood plain management and urban storm-water management;

(*f*) Planning and design of irrigation and drainage systems;

(*g*) Determination of design parameters and management strategies for reservoirs, in particular multi-purpose reservoirs;

(*h*) Deriving of structural developments and man-agement strategies for complex and large-scale water-resource systems, in particular for river basins with reservoirs.

Some of these procedures and techniques can be considered as "well developed", in particular for water supply networks and sewer design, urban storm-water management and floold control planning ((*e*) and (*d*) above), planning and design of irrigation and drainage systems ((*f*)), reservoirs((*g*)) and water-resource use and management in river basins ((*h*)).

Further development work is required in two directions:

- The involvement of new, more comprehensive and complex models with improved physical bases, as characterized in sections 4.7 and 4.8;
- the development and introduction into practical application of computerized interactive decision support systems, expert systems, etc. that combine, in a user-friendly manner, data-base management, simulation and optimization techniques, heuristic qualitative approaches and possibly also artificial intelligence methods (Loucks and Fedra, 1987).

5.7 Summarizing remarks

The most significant progress in the field of hydrological modelling has been achieved

(*a*) In the physical (hydrodynamic and hydrologic) modelling of closed larger water bodies such as rivers, lakes, reservoirs, estuaries and aquifers;

(*b*) In the microscale modelling of elementary hydrological processes such as interception, infiltration, soil moisture recharge and movement and sheet flow;

(*c*) In the approximate (mostly conceptual) macroscale modelling of the most important hydrological processes and relations (e.g. rainfall runoff, snowmelt runoff, water balances of field plots, sub-areas and river basins;

(*d*) In the operational application of these models, particularily (*a*) and (*c*), for practical and research purposes, in real-time forecasting and control of hydrological processes, as well as in planning and designing of water structures and water-resource systems.

On the other hand, a growing demand exists for the development of new meso- and macroscale models that are better physically based, more complex and comprehensive and take into account:

- Water quantity and quality, including the complex interrelation involved in water and matter transport, transformation processes and balances in land surface areas, river basins and aquifers;
- The interaction, especially heat and moisture exchange, between the ground (soil and vegetation) and the atmosphere on different scales as a function of the control- ling factors and conditions. This includes meteorological, land-use, soil and vegetation parameters that define the available water, energy and nutrients, transpiration capability of the vegetation (e.g. canopy density, concentration of CO_2 and other greenhouse gases in the atmosphere, etc.) and other "exchange" conditions at the land surface;
- Specific flow and transport processes (vertical and lateral) through the soil matrix, macropore systems and permeable soil layers, and at the surface (including erosion and sedimentation);
- The long-term non-stationarity of climate and land-use conditions resulting also in a non-stationarity of hydrological conditions.

Such advanced and improved models are needed in particular for investigating the growing influence and impact of climate and land-use changes on the hydrological regime and water resources.

6. RECENT TRENDS AND DEMANDS IN THE FIELD OF HYDROLOGICAL MODELLING

6.1 Developments in computer technology

The rapid development of computer technology, particularily microcomputer technology, has strongly promoted the development, use and hence the availability of mathematical models in hydrology and water-resources planning and management. It has resulted in

(*a*) A variety of different computers with a wide spectrum of performance capabilities (inexpen-sive personal computers, supercomputers, computer networks, etc.);

(*b*) Improved facilities for direct communication between the computer and its user (not only alphanumerically but also graphically, with coloured pictures and graphs);

(*c*) New user-friendly software that can also be used by non-specialists in programming and modelling after relatively little training.

This computer "revolution" (Wallis, 1987) has touched almost every facet of hydrology and water-resource research and has stimulated enormously the development of new models, including model and software systems for the solution of scientific and practical problems which some years ago could not even have been conceived.

A very important characteristic of the new generation of computers and their associated software is the shift towards a more personalized, computer-aided, flexible, interactive approach which can be mastered by non-specialists as well as by specialists. This interactive approach is particularly useful in water-resourse decision-making: different alternatives for system design and management can be investigated in a dialogue mode, one after the other, the resulting consequences analysed, and other alternatives immediately created and investigated. Decision Support Systems and their relatives, Expert Support Systems and Decision Insight Systems, are under development. These represent a philosophy of man-model-machine interaction that is particularly appropriate for the microcomputer environment (Loucks and Fedra, 1987).

In real-time forecasting and control the interactive approach has its advantages because

- Computed forecasts can immediately be compared on the screen with new incoming observations;
- Errors in the real-time input data and serious forecast errors can be more easily detected and immediately corrected, and different scenarios of system control investigated (e.g. with alternative precipitation inputs, whether forecast or assumed).

As well as microcomputers, large supercomputers with parallel processors and multiple terminals are becoming more widely available. They are especially well adapted

(*a*) To solving large finite difference or finite element representations of groundwater and surface water flow and contaminant transport equations;

(*b*) To applying dynamic programming for multiple reservoir systems requiring the solution of numerous recursive equations;

(*c*) To simulating (stochastically and dynamically) water-resource characteristics, in particular flow, over longer time periods, and to deriving efficient (optimum) planning alternatives and management strategies;

(*d*) To solving other complex problems (Loucks and Fedra, 1987).

It is clear that further developments in computer technology are still in progress and that new software solutions and packages will take advantage of the increased possibilities.

6.2 General problems in software transfer

Applications software is at first always of the research type, developed for a particular problem or project, often inadequately documented and not generalized for various applications. Nevertheless, the software is often given away free of charge or at minimal cost. This can easily lead to frustration for the user because the implementation is generally difficult, time-consuming and not without danger. Basic assumptions underlying each model or program may be misunderstood, or "local specifications" not transferable. To detect such specifications in somebody else's source code and to replace them by others is often very hard or impossible, in particular if one has only an executable program version and little documentation.

In such cases it is often necessary, or at least very helpful, if the original developer of the model or a very experienced user is able to assist in the model transfer to the specific location of interest, and if that person participates in the model adaptation and calibration.

In other cases well-developed programs are acquired by "software houses", promoted and then sold under different brand names and in slightly different versions. The advantage of these programs is that they are more likely to be fully operational and can be backed up by the supplier. There is definitely no guarantee, however, that the programs are really "good", and that the underlying models sufficiently represent reality (United Nations, 1986).

This means that in the evaluation of model availability it is always necessary to consider the status of the model and of its program documentation and support, i.e. to distinguish between "well-developed" and "research" software.

Other problems in software transfer and general application which may reduce model availability are (Loucks and Fedra, 1987):

- The increasing dependence of users on available problem-solving software packages in the fields of hydrology, water resources and environmental management, in connection with the often insufficient level of the users' understanding of the theory behind the program and model, so that erroneous results cannot be recognized by the user when they appear and the necessary corrections made;
- The persisting difficulties in transferring application software from one computer system to another due to different hardware configurations, operational systems, graphics software, etc.;
- The existing variety of magnetic storage media in the form of at least four different sizes of floppy disc, incompatible tape and disk drives, multiple formats used on such media, etc.

All the above conditions and constraints can seriously limit the availability of models, even if these models are well established and tested. They therefore have to be considered in the evaluation of model availability.

6.3 Existing barriers in hydrological modelling

There are barriers which currently hamper developments in hydrological modelling and which are likely to remain in areas of importance for future hydrological research. These are excellently summarized by Kundzewicz, Afouda and Szolgay (1987):

1. One factor that makes hydrological modelling difficult is the high level of noise and uncertainty in hydrological systems as compared with other dynamic systems. Hydrological systems, being of natural origin, are irregular and non-homogenous. The signal-to-noise ratio in hydrology is significantly lower than in most technical systems. However, many signals are often neglected and regarded as noise in order to focus attention on "pet" hydrodynamic signals within the concept of the hydrological cycle as a big hydraulic machine.

2. A characteristic property of hydrological systems is the limited possibility of performing active experiments. The chance to design active experiments hardly exists. Typically, geo-physical, including hydrological, experiments are performed by nature and the scientist can merely passively observe them. After having observed different events, those appropriate for further study (e.g. those most suitable for model identification) can be evaluated.

3. The passage from the descriptive to the causal stage, seen as the mark of reaching maturity, has not been generally achieved as yet in hydrology. As no solid causal foundations have been developed, many methods have been introduced from other disciplines and used to redefine hydrological problems rather than to solve them. One can expect more significant efforts to be located in the areas where descriptive hydrological methods are not yet superseded by causal reasoning. For example, the empirical regionalization equations obtained via multidimensional regression analysis that are still used cannot be regarded as a satisfactory representation of hydrological processes.

4. The choice of a probability density function (p.d.f.) for describing hydrological variables is still affected by subjective reasoning. None of the existing p.d.f.s result from genetic (physical) onsiderations, and it is a case of matching abstract formulae with existing hydrological data. This is particularly apparent in the analysis of rare events. As the existing lengths of records are rarely satisfactory from the statistical viewpoint, conclusions concerning extremely rare events remain largely uncertain. Depending on the choice of the p.d.f. used for extrapolation, different values of a 1 000-year flood may be obtained and this can have important economic consequences. It seems desirable to strive towards the development of p.d.f.s which take into account the physics of the process (e.g. via physically sound stochastic differential equations).

5. There are at present two inherent limitations to the development of causal models in the hydrological sciences.

On the one hand, the available data may not suffice for the construction of cause-effect relationships, whereas on the other, known theoretical causal laws may be insufficient for construction of an exact model because of the complexity of feedbacks and interrelations in natural systems. Progress in causal modelling cannot be based on more manipulation with our present limited hydro-logical knowledge. This has obviously been the case in the history of mathematical modelling in many areas of hydrology.

6. The identification and verification barriers are still very apparent. This is particularly true for the interface between point and areal hydrology due to the strong spatial variability in natural characteristics.

7. Another important barrier is the separation between probabilistic and deterministic approaches. A pure deterministic relationship pertaining to concepts rather than to events can be realized only under strictly controlled conditions. Although this was recognized by hydrologists more than two decades ago, scientific methodology of this complex type is still far from being well shaped and tested. It is not yet certain what the most effective combination of deterministic terms and uncertainty elements is.

8. Another impediment to progress in hydrological modelling relates to scale and conceptualization. This is considered in the following section.

6.4 The scale problem in hydrology and the need for physically based macroscale hydrological land surface models

The scale problem in hydrological land surface process modelling was recognized and investigated only relatively recently, especially in connection with global climate modelling. Figure 18 (after Dyck, 1983; Becker and Nemec, 1987) illustrates what the different scales mean in hydrology and meteorology. On the right-hand side of this figure it is indicated that investigations and modelling activities in hydrology are mostly related

(*a*) To small space and time scales (i.e. areas from a few square metres to about one hectare, and time steps of less than one hour up to a maximum of one day); or

(*b*) To larger space and time scales (areas greater than 10 to 100 km² and time intervals greater than several hours to one month).

Different categories of causal models are accordingly applied, namely

(*a*) Physically based models for the different elementary hydrological processes;

(*b*) Simplified models, for example conceptual, black-box or other models.

Models of category (*a*), which in general are based on the fundamental differential equations of hydro- and thermodynamics, can conserve real-world validity only on a microscale, where the conditions of continuity, internal homogeneity, etc. are sufficiently fulfilled. This is the case, for example, for small sites, elementary unit areas or plots, hydrotopes or hydrologically "homogeneous" sub-areas. For larger areas and scales their application becomes questionable and critical. The reasons were extensively discussed in a number of publications. The following selected quotations characterize the problem:

Fiering (1982):

> One of the assumptions frequently made is that our understanding of the microscale elements and processes (in the hydrologic cycle) can, with minor modifications, be extrapolated in principle to the understanding of the macroscale environment, thus enabling reliable predictions to be made by linking the solutions to form a causal chain. Unfortunately, it seldom happens that way. Sooner or later, at some scale or characteristic dimension, mechanistic explanation breaks down and is necessarily replaced by unverified causal hypotheses or statistical representations of the processes.

McNaughton and Jarvis (1983):

> There are no general laws of plant response to environment. Plant form and function are both highly variable. Our basic knowledge consists of a collection of empirical examples, all different but with some common trends which can be interpreted using some unifying conservation principles. Models, if they are to claim generality, must necesarily be approximate.

And later:

> Many parts of a (complex physically and biologically based) reasonably complete model (with many parameters), such as Sellers', would have (on larger scales) conceptual value only, signifying real processes but not describing them in any interpretable fashion. What is (for instance, in a larger scale) the conceptual significance of a root resistance or a stomatal response to saturation deficit? Surely something simpler is indicated.

Becker and Nemec (1987):

> The microscale is in our opinion unable to express the feedbacks, areal variabilities and other spatial integrational features needed to be included in a macroscale hydrologic land surface process model.

From the above and from our own experience it can be concluded that models based on continuum mechanics and/or on existing knowledge of transpiration control of vegetation canopy will hardly supply better results than the simplest models, such as the Budyko "bucket". The latter is oversimplified, while for the former, in the words of McNaughton and Jarvis "something simpler is indicated". Here the knowledge of hydrologists is to be put to use and their existing conceptual physically based modelling attempts could be a starting point for the "something".

Following this, the need for *physically based macroscale* hydrological land surface models again becomes evident. Klemes (1985) has pointed out that existing conceptual larger-scale hydrological models for land surface areas and river basins cannot be considered as sufficiently "physically based". Therefore, they can normally be applied only for the

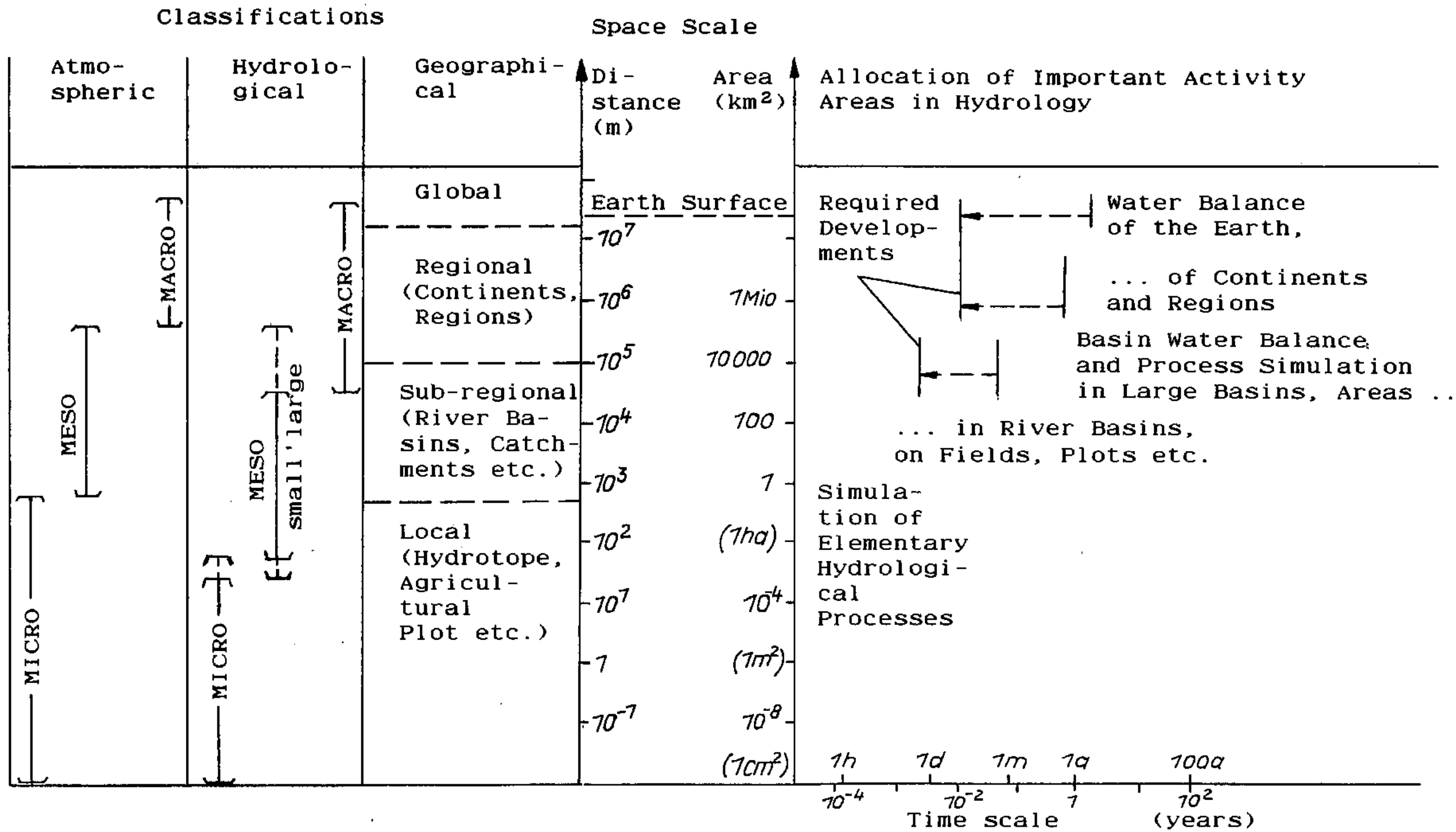


Figure 18 - Time and space scale in hydrological modelling

conditions for which they have been calibrated (by using available streamflow records, etc.). That is, for example, for

- Streamflow forecasting in real time;
- Interpolation and some extrapolation of time series of streamflow.

The limitations of the models become critical if they are applied for investigating the effects and influences of climate, land use and other changes of the environmental conditions on the hydrological regime and water resources. Models which can serve for such purposes must fulfil the following requirements of physically based models listed in section 4.1:

(*a*) They must be geographically transferable and this has to be validated in the real world;

(*b*) Their structure must have a sound physical foundation and each of the structural components must permit separate validation;

(*c*) The accounting of evapotranspiration must stand on its own and should not be a by-product of the runoff accounting. Precipitation and controlling factors for evapotranspiration should form independent input variables.

These requirements are inherent to physically based hydrological models, as they represent the system's components as they appear in nature.

One of the urgent tasks in the field of hydrological modelling, therefore, is to develop better physically based macroscale land surface models or to further improve suitable existing models. Important attempts in this direction have been mentioned in section 4.3 in connection with the so-called "two-level modelling approach".

6.5 Water-quality modelling

Although remarkable progress has been achieved in water-quality and ecological modelling during the last few years, it is generally agreed that developments in this field are still in an initial phase. What has been said in the previous chapter with regard to water balance components is even more important for the different water-quality parameters and their related processes. Research and hence modelling in this field have evolved from limnological studies to problem-oriented pollution research, environmental and water quality management.

The following main classes of model may be distinguished (Abriola, 1987):

- Transport models describing transport processes in surface waters, fractured porous media, dispersion and immiscible phase flow;
- Geochemical models, sorption models and biological transformation models.

These and other specific models are increasingly required for investigating such important processes and effects as pollutant transport; nutrient enrichment; acidification; eutrophication; and the influence of pesticides, heavy metals and toxic substances on water resources in the unsaturated zone and surface and in groundwater systems.

A separate report would be necessary to cover the full spectrum of water-quality problems and related modelling techniques. What can with certainty be said here is that water-quality modelling will play an increasing role in the field of hydrological modelling in general.

6.6 Other aspects

One of the most critical and complex problems in hydrology and in water-resource project planning is our lack of knowledge of the consequences and effects of different human activities in connection with solar, atmospheric and other influences on the hydrological regime and on water resources. Climate models, in particular atmospheric global circulation models, are required for predicting these consequences and effects. Necessary for these are land surface hydrological models which allow estimates to be made of the heat and moisture exchange between the ground (soil and vegetation surface) and the atmosphere.

Hitherto, the very simple Budyko "bucket model" was used for this purpose (Dickinson, 1985). It represents a large-scale lumped soil reservoir with one single layer, that can be filled to some maximum theoretical "field water capacity" (e.g. 150 mm) and from which soil water evaporates at a rate proportional to the remaining water content. This macroscale "hydrology" conserves the mass (water) and net energy balance at the land-atmosphere interface, but it is oversimplified in areal integration to the extent that the results of the exercise become questionable and are in many respects not in accord with reality. Efforts are therefore being directed toward using models with better physical and biological bases.

One of the essential purposes of macroscale hydrological models, the need for which is emphasized in section 6.4, is to replace this oversimplified and unrealistic bucket model.

There are three additional aspects to be briefly mentioned here. The first concerns the sensitivity of the vegetation cover, in particular the dependence of its transpiration capability on the chemical composition of the air and of sub-surface waters. Taking account of these dependencies is likely to increase enormously the complexity of the models.

The second aspect concerns the problem of non-stationarity. If the predicted changes in climate really do occur, then a new theory of stochastic processes, and hence new models, simulation techniques and planning approaches will have to be developed and applied.

A third aspect relates to the rapid developments in the field of remote sensing and its interface with hydrology (Farnsworth *et al.*, 1984; Kuittinen, 1990). Remote-sensing systems (e.g. satellite and radar, but also ground-based automatic monitoring systems) generally supply a vast amount of hydrological and related data to be processed, very often in real time and without delay. For this purpose specific procedures and techniques, including problem-related mathematical models, analysis, interpretation, forecasting and other techniques are required. These have to be run on suitable computers, and in most cases they require powerful machines and make use of well-established program packages. It is clear and has already been proved that quite different models and techniques need to be developed and applied in order to ensure an effective and comprehensive use of remotely sensed data. It should be mentioned that remote sensing can help to overcome many of the problems concerning the availability of input data for models which are discussed in this report, particularily those referred to near the end of the Introduction. Therefore, the availability of remotely sensed data and development of models to use such data are matters of considerable importance.

This list of problems and demands in hydrological modelling could easily be continued, especially in light of the barriers explained in section 6.3 (Kundzewicz *et al.*, 1987).

7. CONCLUSIONS

This report has given a general overview of the availability of hydrological models for the solution of practical and research problems in the field of hydrology and water resources.

A number of well-developed models and related computer programs are available and in operational use for different real-time forecasting and control purposes as well as for planning and design, including long-term water-resource management.

Nevertheless, some serious gaps exist in the spectrum of required models. These concern, in particular,

- Larger-scale hydrological land surface models;
- Models of the soil-plant-atmosphere continuum for estimating areal evapotranspiration dependent on the controlling meteorological, vegetation, soil and other parameters;
- Water-quality and all kinds of ecological models;
- Models capable of directly processing remotely sensed data and information, in particular radar and satellite data for real-time forecasting and other purposes.

An entire set of technical reports would be required to cover the whole field of hydrological modelling, describing the various types of model in existence and the demands and directions in recent and future modelling. This report has only been able to give an overview and to outline some important aspects and future demands in hydrological modelling. Hydrological modelling will clearly be a strong growth area in the decades to come.

8. SELECTED REFERENCES

Abbott, M. B. *et al.*, 1986: An introduction to the European Hydrological Model "SHE". Journal of Hydrology 87, 1986, H. 1/2, pp. 45-134.

Abriola, L. M., 1987: Modeling contaminant transport in the subsurface: An interdisciplinary challenge. Reviews of Geophysics, Vol. 25, No. 2, pp. 125-134. AGU, US National Report 1983-1986.

Anderson, M.E. and Burt, T.P., 1985: Hydrological Forecasting. John Wiley and Sons, Chichester and New York.

Bathurst, J. C., 1988: Flow processes and data provision for channel flow models. *In*: Modelling geomorphological systems. M. G. Anderson (Ed.), John Wiley and Sons Ltd.

Becker, A. and Pfützner, B., 1986: Identification and modelling of river flow reductions caused by evapotranspiration losses from shallow groundwater areas. 2nd Scientific Assembly of the IAHS (Symposium S2, Budapest, July 1986). IAHS Publication No. 156.

Becker, A., 1987: Project on the intercomparison of methods and models for estimating areal evapotranspiration-Project description. WMO, Geneva.

Becker, A. and Kundzewicz, Z., 1987: Nonlinear flood routing with multilinear models. Water Resources Research, Vol. 23, No. 6, pp. 1043-1048.

Becker, A. and Nemec, J., 1987: Macroscale hydrologic models in support to climate research. *In*: The influence of climate change and climatic variability on the hydrologic regime and water resources. Proceedings of the Vancouver Symposium, August 1987. IAHS Publication No. 168.

Becker, A., 1988: Deterministic modelling in hydrology. Lecture notes. Nineteenth International Postgraduate Unesco Course on Hydrology. VITUKI, Budapest.

Beven, K. J. and Clarke, R. T., 1986: On the variation of infiltration into a homogeneous soil matrix containing a population of macropores. Water Resources Research, Vol. 22, No. 3, pp. 383-386.

Bergström, S., 1976: Development and application of a conceptual runoff model for Scandinavian catchments. SMHI, RHC7.

Black, T. A. *et al.*, 1987: Estimation of areal evapotranspiration. Proceedings of the Vancouver Symposium, August 1987. IAHS Publication No. 177.

Bredehoeft, J. D. *et al.*, 1982: Groundwater models. Studies and reports in hydrology No. 34. Unesco, Paris.

Brutsaert, W., 1982: Evaporation into the atmosphere. D. Reidel Publishing Company, Dordrecht, Boston, London.

Bultot, F. and Dupriez, G. L., 1976: Conceptual hydrological model for an average-sized catchment area. Journal of Hydrology, 29, pp. 251-292.

Burnash, R. J. C. and Ferral, R. L., 1980: Conceptualiztion of the Sacramento Model. RA II-RA V Roving Seminar on Mathematical Models Used for Hydrological Forecasting. WMO H/S-46/DOC. 7, WMO, Geneva.

Cebeci, T. and Bradshaw, P., 1977: Momentum transfer in boundary layers. McGraw-Hill, New York, 391 pp.

Crawford, N. H. and Linsley, R. K., 1966: Digital simulation in hydrology: Stanford watershed model IV. Technical report No. 39. Dept. of Civil Eng., Stanford University.

Cunge, J. A., 1969: On the subject of a flood propagation computation method (Muskingum method). Journal Hydrology Research 7, No. 2.

Cunge, J. A., Holly, I. M. and Verwey, A., 1980: Practical aspects of computational river hydraulics. Pitman, London.

Dickinson, R., 1985: Status of the formulation of the land-surface hydrological processes in GCMS. *In*: Report of the First Session of the JSC Scientific Steering Group on Land Surface Processes and Climate, Geneva, 21-25 January 1985). WCP Report No. 96, WMO/TD-No. 43, WMO, Geneva.

Dooge, J. C. I., 1985: Hydrological modelling and the parametric formulation of hydrological processes on a large scale. *In*: Report of the First Session of the JSC Scientific Steering Group on Land Surface Processes and Climate, Geneva, 21-25 January 1985). WCP Report No. 96, WMO/TD-No. 43, WMO, Geneva.

Dooge, J. C. I., 1986: Theory of flood routing. *In*: Kraijenhoff, D. A. and Moll, J. R. (Eds.), River flow modelling and forecasting. D. Reidel Publishing Company, Dortrecht.

Dunne, T., Moore, T. R. and Taylor, C. N., 1975: Recognition and prediction of runoff producing zones in humid regions. Hydrological Science Bulletin, Vol. 20, pp. 305-327.

Dyck, S., 1983: Overview on the present status of the concepts of water balance models. *In*: New approaches in water balance computations (Proceedings of the Hamburg Workshop, August 1983). IAHS Publication No. 148.

Engelen, G. B. and Jones, G. B., 1986: Developments in the analysis of groundwater flow systems. IAHS Publication No. 163.

Farnsworth, R. K., Barrett, E. C. and Dhanju, M. S., 1984: Application of remote sensing to hydrology including groundwater. Technical Documents in Hydrology. Unesco, Paris.

Fiering, M., 1982: Overview and recommendations. *In*: Scientific basis of water management. National Academy Press. Washington, D.C.

Fleming, G., 1975: Computer simulation techniques in hydrology. Elsevier, Environmental Science Series.

Fread, D. L., 1985: Channel routing. *In*: Anderson, M. G. and Burt, T. P. (Eds.), Hydrological forecasting. John Wiley, Chichester and New York, pp. 437-503.

Gelb, A., 1974: Applied optimal estimation. The MIT Press, Massachusetts, USA.

Girard, G., Ledoux, E. and Villeneuve, J.-P., 1981: Le modèle couplé–simulation conjointe des écoulements de surface et des écoulements souterrains sur un système hydrologique. Cah. O.R.S.T.O.M., Paris, Sér. Hydrol., Vol. XVIII, Nº 4, pp. 195-278

Haimes, Y. Y. *et al.*, 1987: The process of water resources project planning: a system approach. Studies and reports in hydrology No. 44, Unesco, Paris.

Kalinin, G. P. and Miljukov, P. I., 1958: Проблемный расчет неустановившегося движения водных масс (Computation of unsteady flow). Trudy Centr. Inst. Prognozov, Leningrad, Vol. 66.

Kirkby, M. J. *et al.*, 1978: Hillslope hydrology. Wiley-Interscience, New York.

Klemes, V., 1985: Sensitivity of water-resource systems to climate variations, WCP Report No. 98, WMO, Geneva.

Knudsen, J., Thomsen, A. and Refsgaard, J. C., 1986: WATBAL - a semi-distributed, physically based hydrological modelling system. Nordic Hydrology, Vol. 17, No. 415.

Kraijenhof, D.A. and Moll, J.R. (Eds), 1986: River flow modelling and forecasting. D. Reidel Publishing Company. Dortrecht.

Kuittinen. R., 1990: Application of remote sensing to hydrology. Operational Hydrology Report (in preparation) WMO, Geneva.

Kundzewicz, Z. W., Afouda, A. and Szolgay, J., 1987: Mathematical modelling. *In*: Hydrology 2000 report. IAHS publication (in press).

Kutchment, L. S., Demidov, V. N. and Motovilov, J. G., 1983: Формирование речного стока, физико-математические модели (Formation of surface flow, physical-mathematical models) Izdatelstvo "Nauka", Moscow.

Loucks, D. P. and Fedra, K., 1987: Impact of changing computer technology in hydrologic and water resource modelling. Reviews of Geophysics, Vol. 25, No. 2, pp. 107-112. AGU, US National Report 1983-1986.

Lowing, M. J. *et al.*, 1987: Casebook of methods for computing hydrological parameters for water projects. Studies and reports in hydrology No. 48, Unesco, Paris.

McNaughton, K. and Jarvis, P., 1983: Predicting effects of vegetation changes on transpiration and evaporation. *In*: Water deficits and plant growth, Vol. VII, pp. 1-47, Academic Press, New York.

Nemec, J., 1986: Design and operation of forecasting operational real-time hydrological systems (FORTH). *In*: Kraijenhoff, D. A. and Moll, J. R. (Eds.), River flow modelling and forecasting. D. Reidel Publishing Company, Dortrecht.

NERC, 1975: Flood studies report. Natural Environment Research Council, 27 Charing Cross Road, London.

Nielsen, D. R., van Gnuchten, M. T. and Biggas, J. W., 1986: Water flow and solute processes in the unsaturated zone. Water Resources Research, 22 (9), pp. 895-1085.

Rutter A. J., Morton, A. J. and Robins, P. C., 1975: A predictive model of rainfall interception in forests II. Generalization of the model and comparison with observations in some coniferous and hardwood stands. Jour Appl. Ecol. 12, pp. 367-389.

Serban, P., 1986: Operational hydrological models used in Region VI (Europe). Technical report for IX-RA VI, WMO, Geneva.

Serban, P., 1988: Updating procedures. WMO, Geneva.

SSARR, 1972: Streamflow synthesis and reservoir regulation. US Army Engineers Division, North Pacific, Portland, Oregon.

Sugawara, M. *et al.*, 1984: TANK model with snow component. Research notes of the national research center for disaster prevention, No. 65, Japan.

United Nations, 1986: Application of computer technology for water resources development and management in developing countries. Technical Report. United Nations, New York.

US OTA, 1982: Use of models for water resources management, planning and policy. US Congress, Office of Technology Assessment. US Government Printing Office, Washington, D.C.

Van Gnuchten, M. T. and Jury, W. A., 1987: Progress in unsaturated flow and transport modelling. Reviews of Geophysics, Vol. 25, No. 2, pp. 135-140. AGU, US National Report 1983-1986.

Wallis, R. Jr. , 1987: Hydrology—The computer revolution continues. Reviews of Geophysics, Vol. 25, No. 2, pp. 101-105. AGU, US National Report 1983-1986.

WMO, 1975: Intercomparison of conceptual models used in operational hydrological forecasting, Operational Hydrology Report No. 7, WMO-No. 429, WMO, Geneva.

WMO, 1985: Intercomparison of models of snowmelt runoff. Operational Hydrology Report No. 23, WMO-No. 646, WMO, Geneva.

WMO, 1987: Real-time intercomparison of hydrological models. Report of the Vancouver workshop (1987), Technical report to CHy No. 23, WMO/TD No. 255, WMO, Geneva.

WMO, 1988a: Technical Regulations, WMo-No. 49, WMO, Geneva.

WMO , 1988b: Hydrological Operational Multipurpose Subprogramme (HOMS) Reference Manual, 2nd Edition. WMO, Geneva. (First edition: 1981).

Yeh, T.-C. J., Gelhar, L. W. and Goutjals, A. I., 1985: Stochastic analysis of unsaturated flow in heterogeneous soils. Water Resources Research, 21(4), pp. 377-472.

Zhidikov, A. P. and Mukhin, V. M., 1989: Methods of long-range forecasting of low flows and droughts. Technical report to CHy No. 27, WMO/TD-No. 320, WMO, Geneva.

Zuidema, F. C. *et al.*, 1987: Manual on drainage in urbanized areas. Vol. I—Planning and design of drainage systems. Studies and reports in hydrology No. 43. Unesco, Paris.

[illegible]

ANNEXES

Standardized format of a HOMS component description

WORLD METEOROLOGICAL ORGANIZATION

HOMS COMPONENT
....
(Indicator)
(................)
(Date of issue)

....
(Name of the component)

1. Purpose and objectives
2. Description
3. Input
4. Output
5. Operational requirements and restrictions
6. Form of presentation
7. Operational experience
8. Originator and technical support
9. Availability
10. Conditions on use

(First entered: (date) Last update:

(Total length: maximum 2 pages)

Annex 2

W O R L D   M E T E O R O L O G I C A L   O R G A N I Z A T I O N

REGIONAL ASSOCIATION VI (EUROPE)

Date ____________________

QUESTIONNAIRE
on the characteristics of operational hydrological models

1. Country ____________________

2. Name of model, author, institution where he/she works

____

____

____

3. Model objective ____________________

____

____

4. Model algorithm

4.1 Modelled processes

____

4.2 Components of Man's inflence

____

____

Annex 2. p. 2

5. Required data

5.1 Model calibration

5.2 Model application

6. Data acquisition

7. Data transmission

8. Data processing

9. Place of model application and its outcomes

10. Do you intend to test the model on account of the data provided by one or several RA VI members within the working group activities?

11. References

Models available as HOMS - components

Supplier (Country)	Name of the model	Model index	Model classification criteria(+) Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Australia	Water supply streamflow and storage forecasts	AU1	FO	-	QM	DB	-
	Operational flood forecasting program suite	AU2	FO	SA	QF	DB	-
Belgium	Storage capacity of a reservoir for low-flow regulation	BE1	PD	RL	QM	DC	LO
	Storage capacity of a flood-control reservoir	BE2	PD	RL	QM	DC	LO
Canada	Culvert hydraulic model	CA1	OP	RR	QF		
	Hydrologic and hydraulic procedure for flood plain delineation	CA2	PD	CS	QF		
	One-dimensional hydro-dynamic modelling	CA3	PD	CS	QF	DL	IG
	Simple reservoir routing	CA4	PD	RL	QF	DC	LO
	Hydro configuration modelling system (HCMS)	CA5	PD	CS	QM	DC	LO
	Digital aquifer model	CA6	PO	AQ	SG	DL	IG
	Noncompliance analysis program	CA7	OP		WQ		
	Water quality simulation model	CA8	PO	RR	WQ	DL	IG

(+) Defined in Tables 1 to 4 and Figures 2 and 5.

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
China	A conceptual watershed model for flood forecasting	CN1	FO	CB	QF	DC	IG
	Methods for computing design floods	CN2	PO	SA	QF	DC	LO
	Design flood estimation using historical flood data in frequency analysis	CN3	PO	-	QF	SP	-
	Mathematical model for two dimensional salinity distribution in estuaries	CN4	PO	RR	WQ	DL	IG
Colombia	MODRIE model for operation	CO1	FO	SA	ES	DC	LO
	CAHYDRO model	CO2	OP	SA			
Czechoslovakia	DC2 Hydrodynamical river model	CS1	FO	RR	QF	DL	IG
	NONLIN nonlinear cascade hydrological model	CS2	FO	RR	QF	DC	LO
	MUFSYS 3 multipurpose unsteady flow simulation system	CS3	FC	CB	QF	DC	IS
	KS2 reservoir operation model	CS4	PD	RL	QF	DC	LO
Denmark	NAMS11/FF General purpose flood forecasting modelling system	DK1	FC	CB	QF	DC	IS
	NAM General purpose rainfall/runoff model	DK2	PO	SA	QF	DC	LO

Supplier (Country) 1	Name of the model 2	Model index 3	Model classification criteria: Purpose 4	Type of system 5	Variable 6	Degree of Causality 7	Space discretization 8
Denmark (continued)	SYSTEM general purpose river and estuary hydrodynamic model	DK3	PD	RR	QF	DL	IG
France	Deterministic rainfall-runoff model for basins of 100 to 1000 sq. km.	FR1	FO	SA	QF	DC	LO
	Rainfall-runoff model for medium-sized urban basins	FR2	PO	SA	QF	DC	LO
	Short method for cost/benefit analysis of protective measures against flooding	FR3	OP				
GDR	BASTER long-term mean value of basin water balance	DD1	PO	SA	ET	DC	LO
	EGMO hydrological land surface and river basin model system	DD2	PL	CB	QF	DC	IS
	CAMOS/EGMO for operating hydrological land surface and river models	DD3	OP	CB	Q	DC	IS
Hungary	Flooding forecasting by graphical correlation	HU1	FO	SA	QF	DB	LO
	Flood peak forecasting by a grapho-analytic technique	HU2	FO	RR	QF	DB	LO
	Flood peak forecasting by a multiple linear regression model	HU3	FO	RR	QF	DB	LO

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Hungary (continued)	Flood routing using a discrete linear model	HU4	FO	RR	QF	DC	LO
	Recursive river flow forecasting using a Kalman filter	HU5	FO	RR	QF	DC	LO
	Real-time adaptive hydrological prediction	HU6	FO	RR	QF	DC	LO
	River station selection for forecasting	HU7	OP				
	Input detection as the inverse task of forecasting	HU8	OP	RR	QF	DC	LO
	Determining surface water resources for semi-arid and arid basins without data	HU9	PO	SA	QM	DB	LO
	Design of storage reservoir by stochastic simulation	HU10	PD	RL	QM	ST	–
	Design of reservoirs by an extension of Moran's theory	HU11	PD	RL	QM	ST	–
	Design of co-operating reservoirs in series	HU12	PD	RL	QM	ST	–
	Analysis of reservoir operation in the case of random drafts	HU13	PD	RL	QM	ST	–
	Determination of hydraulic conductivity by test pumping with observation wells	HU14	OP	AQ		DL	IG

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Hungary (continued)	Computation of drawdown of vertical and horizontal partially penetrating wells	HU15	OP	AQ	SG	DL	IG
Ireland	The linear perturbation model	IE1	FO	SA	QF	DB	LO
Israel	Seasonal forecast of inflow to a lake	IL1	FO	SA	QM	DB	LO
	Forecasting inflows to a lake	IL2	FO	SA	QM	DB	LO
	Groundwater levels forecast	IL3	FO	AQ	SQ	DL	IG
	Peak discharge frequency in an arid region	IL4	PO	-	QF	SP	-
	Runoff model for cultivated soils	IL5	PO	SA	QF	DC	LO
	Aquifer simulation system	IL6	PO	AQ	SG	DL	IG
	Multi-aquifer simulation system	IL7	PD	AQ	SG	DL	IG
	Computation of sea water-fresh water interface	IL8	PO	AQ	WQ	DL	IG
	Groundwater interface model	IL9	PO	AQ	WQ	DL	IG
	Groundwater salinity model	IL10	PO	AQ	WQ	DL	IG
	Evaluation of water resources in a country	IL11	PD	CB	SG;QM	DC	LO

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Italy	CLSX constrained linear system extended model	IT1	FO	CB	QF	DB	LO
	MISP real-time streamflow forecasting model	IT2	FO	CB	QF	DB	LO
	Semi-conceptual watershed model	IT3	PO	SA	QF	DC	LO
	Channel network computation	IT4	PD	CS	QF	DL	IG
	Multivariate streamflow generator for short and long-term cyclicity	IT5	PO	–	QM	ST	–
	IDROSIM simulation model for flow in a costal aquifer	IT6	PO	AQ	SG	DL	IG
	WQM water quality model	IT7	PO	RR	WQ	DL	IG
	Salt wedge intrusion	IT8	PO	AQ	WQ	DL	IG
Japan	Tank model	JP1	FO	CB	QF	DC	IS
	Runoff calculation by the storage function	JP2	PO	SA	QF	DC	LO
Norway	A system for calibration and use of hydrological model	NO1	FO	CB	QF	DC	LO
Philippines	Mini-computer based flood forecasting system	PH1(JP1)	FO	CB	QF	DC	IS

Supplier (Country) 1	Name of the model 2	Model index 3	Model classification criteria: Purpose 4	Type of system 5	Variable 6	Degree of Causality 7	Space discretization 8
Sweden	HBV conceptual watershed model	SE1	FO	SA	QF	DC	LO
	A method to forecast the spring flood volume	SE2	FO	SA	QM	DB	LO
	Two dimensional many layer hydrodynamic model	SE3	PD	RL	QF	DL	IG
	Two dimensional hydrodynamic estuary model	SE4	PO	RR	QF;WQ	DL	IG
USSR	Model to forecast rainfall floods	SU1	FO	SA	QF	DC	LO
	Model for the calculation of snow-melt and rainfall runoff	SU2	FO	SA	QF	DC	LO
	Method for short-term forecasts of discharges in mountain rivers	SU3	FO	SA	QF	DC	IS
	Short-term forecasts of spring inflow to reservoirs on plainland rivers	SU4	FO	SA	QF	DC	LO
	Method of unsteady flow calculation in braided river beds	SU5	FC	RR	QF	DL	IG
	Operational calculation of the water storage in rivers from water level data	SU6	PO	RR	QF	DC	LO
	Computation of reservoir sedimentation	SU7	PD	RL	QF	DC	LO

Country (HNRC)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
UK	Inflow-storage-outflow (ISO) function models	GB1	FO	CB	QF	DC	LO
United States	SRM snowmelt-runoff model	US1	FO	SA	QF	DC	IS
	NWSFRS-SAC-SMA Sacramento soil moisture accounting model	US2	FO	CB	QF;ES	DC	LS
	NWSRFS-SNOW-17 snow accumulation and ablation model	US3	FO	SA		DC	LO
	SSARR streamflow synthesis and reservoir regulation	US4	FC	CB	QF	DC	LO
	NWSRFS-MCP3 manual calibration program	US5	OP	CB	QF;ES	DC	LS
	NWSRFS-STAT-QME statistical summary - mean daily discharges	US6	OP		QF		
	Resource information and analysis using grid cell data bank	US7	OP				
	Techniques for estimation of probable maximum precipitation	US8	OP				
	EAD expected annual flood damage computation	US9	OP				
	DAMCAL damage reach stage-damage calculation	US10	OP				

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
United States (continued)	DAMBRK dam-break flood model	US11	PD	CS	QF	DL	IG
	Chart method for determining peak discharge	US12	PL	SA	QF	DC	IS
	Tabular method for determining peak discharge	US13	PL	CB	QF	DC	IS
	DAMS2 computer program for project formulation structure site analysis	US14	PD	RL	QF	DC	LO
	Engineering field manual for soil and water conservation practices	US15	PL	SA	QF;QM	DC	IS
	Graphical method for determining peak discharge	US16	PL	SA	QF	DC	IS
	HEC-1 flood hydrograph package	US17	PD	CB	QF	DC	LO
	HYDPAR hydrologic parameters	US18	PO	CB	QF	DC	IS
	SWMM urban rainfall-runoff model	US19	PD	CB	QF;WQ	DC	TS
	TR-20 computer program for project formulation-hydrology	US20	PD	CB	QF	DC	IS
	CSP cross-section properties program	US21	OP	RR	QF	DL	IG
	HEC-4 monthly streamflow simulation	US22	PO	–	QM	ST	–

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
United States (continued)	NWSRFS-LAG/K lag and K routing	US23	PO	RR	QF	DC	LO
	DWOPER dynamic wave operational model	US24	PD	RR	QF	DL	IG
	STEP backwater and floodway analyses	US25	PD	RR	QF	DL	IS
	HGP hydraulics graphics package	US26	OP	RR	QF	DL	IS
	INTDRA interior drainage flood routing	US27	PD	RL	QF	DC	LO
	DYNMOD dynamic rating curve model	US28	OP		QF		
	SHP stream hydraulics package	US29	PD	RR	QF	DL	IG
	HEC-2 water surface profiles	US30	PD	RR	QF	DL	IG
	WSP2 computer program	US31	PD	RR	QF	DL	IG
	SWCULRAT stage-discharge relation at culverts	US32	PO				
	Water-surface profile computation model	US33	PD	RR	QF	DL	IG
	Reservoir temperature stratification	US34	PD	RL	TW	DC	IS
	Storm storage, treatment, overflow, runoff model	US35	PL	CB	QF;WQ	DC	IS

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
United States (continued)	WQRRS water quality for river-reservoir systems	US36	PD	CS	QF;WQ	DL	IG
	HEC-6 scour and deposition in rivers and reservoirs	US37	PD	CS	QS	DL	IG
	HYDUR hydropower analysis using streamflow duration procedures	US38	OP	RL			
	HEC-3 reservoir system analysis for conservation	US39	PD	CS	QM	DC	IS
	HEC-5 simulation of flood control and conservation systems	US40	PD	CS	QM	DC	IS
Yugoslavia	Estimation of the unit hydrograph and correction of net rainfall time distribution	YU1	OP	SA	QF	DB	LO
Mekong HOMS focal point	One-dimensional mathematical model of deltaic river system (Mekong delta model)	MH1(FR)	PD	RR	QF	DL	IG
	Program for preliminary economic evaluation of a hydropower project (HLHEAD)	MH2	PD	CS	QM	DC	LO
	Application of hydrologic models for river forecasting	MH3(US)	FC	CB	QF	DC	LO
Upper Nile HOMS focal point	Model result analysis by the methods of the WMO model intercomparison	UN1	OP				

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Upper Nile HOMS focal point (continued)	Sacramento model modified for use in the Upper Nile Basin project	UN2(US2)	FO	CB	QF;ES	DC	LS
	Channel routing Muskingum-Cunge method	UN3(GB)	PO	RR	QF	DC	LO
	Channel routing - implicit solution of full equations	UN4	PO	RR	QF	DL	IG
	Lake routing using a monthly time interval	UN5	PD	RL	QM	DC	LO
WMO Secretariat	Computer program for evaluation of regional flood risk	WMO1	PO	-	QF	SP	-
	MITSIM multipurpose river basin simulation model	WMO2	PD	CB	QM	DC	LO

List of models - RA VI (Europe)

Supplier (Country)	Name of the model	Model index	Model classification criteria(+) Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Austria	River level forecasting model on the Danube at Linz	AT1	FO	RR	QF	DB	LO
	River level forecasting model on the Danube at Vienna	AT1	FO	RR	QF	DC	LO
	EKW-EG forecasting model for flood waves	AT3	FO	SA	QF	DB	LO
	ODK-AG forecasting model	AT4	FO	RR	QF	DC	LO
Belgium	Conceptual hydrological model for an averaged-sized catchment area	BE1	PL	SA	QF;QS	DC	LO
Bulgaria	FSBGIM1 forecasting model for the maximum monthly levels	BG1	FO	-	Q	DL	LO
	Forecasting model for the average monthly, seasonal and annual discharge	BG2	FO	-	Q	ST	-
Czechoslovakia	Two-stage adaptive estimator and predictor of the runoff of medium and large scale watersheds	CS1	FC	CB	QF	DC	LO
	Real-time estimation and short-term forecasting of tributaries of the cascade of reservoirs	CS2	FC	CB	QF	DC	LO

(+) Defined in Tables 1 to 4 and Figures 2 and 5.

Country (HNRC)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Denmark	NAM SS 11-FF floodwave forecasting model	DK1	FC	CB	QF	DC	SD
	NAM rainfall - runoff model	DK2	PO	SA	QF	DC	LO
	WATBAL hydrological rainfall - runoff model	DK3	PO	CB	QF	DC	SD
	SHE model - European hydrological system	DK4 (4 countries)	PD	SA	QF	DL	DE
Finland	Spring flood forecasting model	FI1	FO	SA	QF	DC	LO
GDR	Snow accumulation and melting model	DD1	FO	SA	QF	DC	LO
	RIMO/RIDO - nonlinear threshold model, multilinear model for river reaches	DD2	FO	RR	QF	DC	LO
	EGMO - system approach and subroutiness for river basin modelling	DD3	FO	CB	QF	DC	SD
Germany, Federal Republic of	LWM analysis and simulation model for floodways	DE1	FO	SA	QF	DC	LO
	Hydraulic streamflow routing model	DE2	PD	RR	QF	DL	DE
	OFCORS model for the optimum flood control of reservoir systems	DE3	FC	RL	QF	DC	LO

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Germany, Federal Republic of (continued)	NIDDA model for flood wave simulation in large watersheds	DE4	PL	CB	QF	DC	LO
	FGMOD model for runoff computation (floods and low flow)	DE5	FC	CB	QF	DC	LO
	Water quality model	DE6	FC	RL	WQ	DL	DE
	SIM-MOD IV model for simulating water quality characteristics	DE7	PO	-	WQ	D	-
	Computation model for groundwater flow	DE8	PO	AQ	SG	DL	DE
	Water management model for groundwater	DE9	PO	AQ	SG	DL	DE
France	Runoff extrapolation model starting from precipitation	FR1	PL	SA	QF	DC	LO
	UREP 13 rainfall-runoff model for rural and urban areas	FR2	PL	SA	QF	DC	LO
	Distributed model for surface runoff and groundwater flow simulation	FR3	PL	SA	QF	DC	DE
	MODLAC simulation model for surface runoff in a watershed with reservoirs	FR4	PD	CS	QF	DC	DE
	SAPHARI hydrological forecasting model	FR5	FO	RR	QF	SI	LO

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
France (continued)	Models for flow forecasting and simulation	FR6	PO	-	QF	SP	-
	Model for hydrological and climatological data processing	FR7	PO	-	QF	SP	-
	Flood routing model	FR8	PD	RR	QF	DL	DE
	MUSIC model for flow routing	FR9	PD	RR	QF	DL	DE
	CRUE model for assessing the effects of hydraulic structures on flood routing	FR10	PD	RR	QF	DL	DE
	Reservoir management model	FR11	PD	RL	QF	DC	LO
	GARDENITA model for discharge and piesometric level simulation and forecasting	FR12	PO	SA	QF	DC	LO
	Simulation model for the groundwater table	FR13	PD	AQ	SG	DL	DE
	Automatic management model of low flows in a river	FR14	FC	CB	QF	DC	LO
Hungary	DLCM forecasting model for streamflow routing	HU1	FO	RR	QF	DC	LO
	FWSMOV model for the simulation of floodwaves in rivers with movable bed	HU2	PO	RR	QF	DL	DE

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Ireland	Hybrid model for flow forecasting on large catchments	IE1	FO	SA	QF	DB	LO
Israel	Regional model for the estimation of statistical runoff parameters	IL1	PO	-	QF	SP	-
	Bayesian calibration of models	IL2	OP	-	-	-	-
Netherlands	PREDIS model for runoff simulation	NL1	PL	SA	QF	DL	DE
	NETFLOW model for streamflow routing	NL2	PD	RR	QF	DL	DE
	GROVERPLA model for groundwater flow simulation in a vertical plane	NL3	PO	AQ	SG	DL	DE
	GROMULA model for groundwater movement simulation within a multi-layer aquifer	NL4	PO	AQ	SG	DL	DE
Poland	GCHJ forecasting model for floods in mountain regions	PL1	FO	CB	QF	DC	LO
	ISOP forecasting model for floods in mountain regions	PL2	FO	SA	QF	DL	LO
	MONICA and NONS forecasting models for the runoff and discharge hydrograph	PL3	FO	CB	QF	DC	LO
	DOWI model for level and discharge forecasting on the lower Vistula	PL4	FO	RR	QF	DL	DE

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Portugal	The OMEGA model for flow simulation and forecasting	PT1	FO	SA	QF	DC	LO
	XSLNEC rainfall - runoff model	PT2	PL	SA	QF	DC	LO
	NWSIST runoff simulation model	PT3	PL	CB	QF	DC	LO
Romania	IMH1 model for floodwave forecasting	RO1	FO	SA	QF	DC	LO
	IMH2 model for floodwave forecasting	RO2	FO	SA	QF	DC	LO
	VIDRA model for floodwave forecasting and operation of the reservoir	RO3	FC	CB	QF	DC	DS
Sweden	HBV forecasting model for discharge hydrograph	SE1	FO	SA	QF	DC	LO
Switzerland	The SRM forecasting model for snowmelt runoff	CH1	FO	SA	QF	DC	DS
USSR	Floodwave forecasting model using radar data	SU1	FO	CB	QF	DC	LO
Yugoslavia	Non-linear adaptive model for level and discharge forecasting	YU1	FO	RR	QF	DC	LO

List of models - RA I - Survey (Africa)

Supplier (Country)	Name of the model	Model index	Model classification criteria(+) Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Kenya	Sacramento model	US2*	FO	CB	QF;ES	DC	LS
Nigeria	CLS model	IT1*	FO	CB	QF	DB	LO
	Muskingum method	NG1	FO	RR	QF	DC	LO
	SAPHARI	FR5	FO	RR	QF	DC	LO
Upper Nile HOMS focal point	Reservoir and channel routing model	UN1	FC	CS	QF	DL	DE
	Sacramento model	US2*	FO	CB	QF;ES	DC	LS
	Markov model	UN2	PO	-	QM	ST	-

(+) Defined in Tables 1 to 4 and Figures 2 and 5
* Index of the original supplier

List of models - RA II - Survey (Asia)

Supplier (Country)	Name of the model	Model index	Model classification criteria(+) Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
India	Physically based Muskingum model	IN1	PO	RR	QF	DC	LO
	Non-linear cascade model	IN2	FO	CB	QF	DC	LO
	Real-time flood forecasting based on discrete linear reservoir cascade model	IN3	FO	CB	QF	DC	LO
	CWC flood hydrograph package	IN4	PD	CB	QF	DC	LO
	Forecasting of monsoon rainfall and runoff	IN5	FO	SA	QM	DB	LO
	CWC water yield model	IN6	PD	SA	QM	DC	LO
	GENSEA generation of synthetic data of seasonal hydrologic series	IN7	PO	-	QM	ST	-
	UMOSE1 procedure for estimating the parameters of the ARMA models	IN8	OP	-	-	-	-
	Model for predicting the aquifer response to various time variant excitations	IN9	PD	AQ	SG	DL	DE
	Unsteady flow to a large diameter well during pumping and recovery period	IN10	PD	AQ	SG	DL	DE
	River multiaquifer interaction	IN11	PO	AQ	SG	DL	DE

(+) Defined in Tables 1 to 4 and Figures 2 and 5.

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
India (continued)	NAM-S11F model	DK1*	FC	CB	QF	DC	DS
	SSARR model	US4*	FC	CB	QF	DC	LO
	HEC-1F model	US	FC	CB	QF	DC	LO
Japan	Tatsugami unit hydrograph method	JP1	PO	SA	QF	DB	LO
	Nagayasu synthetic unit hydrograph method	JP2	PO	SA	QF	DB	LO
	Quasi-linear reservoir model	JP3	PL	SA	QF	DC	LO
	Storage function model	JP4	PO	SA	QF	DC	LO
	Kinematic wave model	JP5	FO	SA	QF	DC	LO
	Water level forecasting model	JP6	FO	SA	QF	DC	LO
	Tank model	JP7	PO	CB	QF	DC	DS
Korea	Storage function method	KR1	FO	SA	QF	DC	LO
Pakistan	Nonlinear cascade model	CS3*	FO	RR	QF	DC	LO
	APIC model	US41*	FO	SA	QF	DB	LO

* Index of the original supplier.

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Pakistan (continued)	CLS model	IT1*	FO	SA	QF	DB	LO
Qatar	HHWMD7 groundwater program	QA1	FO	AQ	SG	DL	DE
Vietnam	Streamflow forecasting model	VN1	FO	CB	QF	DC	LO
	Thomas-Fiering model	US*	PO	–	Q	–	–
	SSARR model	US4*	FC	CB	QF	DC	LO
	NAM model	DK2*	FO	SA	QF	DC	LO
	TANK model	JP7*	FO	CB	QF	DC	DS

* Index of the original supplier.

List of models - RA III - Survey (South America)

Supplier (Country)	Name of the model	Model index	Model classification criteria(+) Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
	Flood forecasting model	US*	FC	CB	QF	DC	LO
	DAMBRK	US11*	PD	CS	QF	DL	DE
	Snowmelt-runoff model	US1*	FO	SA	OF	DC	DS
	HEC-5 model	US40*	PD	CS	QM	DC	DS
	HEC-4 model	US22*	PO	-	QM	ST	-
	HEC-2 model	US30*	PD	RR	QF	DL	DE
Argentina	HEC-1 model	US16*	PD	CB	QF	DC	LO
	Sacramento model	US2*	FO	CB	QF;ES	DC	LS
	Soil moisture model	AR1	PO	AQ	SQ;ES	DL	DE
	HIDRO model hydrodynamic	BR*	FO	RR	QF	DL	DE
	Regression model	AR2	FO	RR	QF	DB	LO
	Kalman model	VE*	FO	SA	QF	DB	LO

(+) Defined in Tables 1 to 4 and Figures 2 and 5.
* Index of the original supplier.

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Argentina (continued)	OTTHYMO model	CA*	FC	CB	QF	DC	LO
	HYMO10 model	CA*	PO	SA	QF	DC	LO
	OTTSWMM model	CA*	FC	CB	QF	DC	LO
Brazil	CASTOR model	BR1	FC	CB	QF	DC	LO
	IARA model	BR2	FC	CB	QF	DC	LO
	BILIK model	FR*	PO	SA	QF	DC	LO
	Multiple regression model	BR3	FO	SA	QF	DB	LO
	Ven te Chow model	US*	FO	SA	QF	DB	LO
	NLYVNA model	BR4	PD	RL	QF	DC	LO
	PREV model	BR5	FO	RR	QF	DC	LO
	MSRCE model	BR6	FC	RL	QF	DC	LO
	SACM model	BR2	FO	RR	QF	DC	LO
	DIANA model	BR8	PO	-	ST	QT	-
	SIMULADIN model	BR9	PD	RL	QM	DC	LO

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Brazil (continued)	RAFA-1	BR10	FO	SA	QF	DB	LO
	Time series generation model	BR11	PO		QM	ST	
	Sistema TARTARUS	BR12	FO	CB	QF	DC	LO
	RVD model	BR13	PD	CS	QF	DC	LO
	Sistema preva 2	BR14	PO		QF	SP	–
	VOLESP model	BR15	FO	RR	QF	DC	LO
	CMEIA model	BR16	PD	CB	QF	DC	LO
	SMAP model	BR17	PO	SA	QF	DC	LO
	MOSH model	BR18	FO	CB	QF	DC	LO
	SARR model	US4*	FC	CB	QF	DC	LO
	STANFORD model	US*	FO	CB	QF	DC	DL
	Decision model	BR19	FC	CS	QF	DC	LO
	OPERA model	BR20	FC	RL	QF	DC	LO

* Index of the original supplier.

Supplier (Country)	Name of the model	Model index	Model classification criteria: Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Brazil (continued)	RIBA model	BR21	FC	CB	QF	DC	LO
	SIMMQE model	FR*	PO	CB	QF	DC	LO
	PROHD model	BR2	PO	SA	QF	DC	LO
Chile	Prevision discharge model	CL1	PO	SA	QF	DC	LO
	Simulation discharge model	CL2	FO	CB	QF	DC	LO
	SIMUL model	CL3	PO	AQ	SG	DL	DE
	SIMAC-4 model	CL4	PO	AQ	SG	DL	DE
	Flood forecasting model	CL5	FC	CB	QF	DC	LO
	TRANZIT model	CL6	PO	AQ	SQ	DL	DE
Colombia	Soil model	CO1	PO	SA	QF	DC	LO
	CONVOL model	NL*	FO	SA	QF	DC	LO
	COSSARR model	US*	FC	CB	QF	DC	LO
	CRECIDA model	CO2	PO	SA	QF	DC	LO

* Index of the original supplier.

Supplier (Country)	Name of the model	Model index	Model classification criteria				
			Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Colombia (continued)	DOBLE model	NL*	PD	CB	QF;QM	DC	LO
	UNIMORF	US*	PO	SA	QF	DC	LO
	REMANSO	NL*	PO	RR	QF	DC	LO
Ecuador	Flood forecasting model	EC1	FC	RR	QF	DC	LO
	PRES model	EC2	FO	SA	QF	DC	LO
Paraguay	OPEDIA model	PY1	FC	CS	QF	DC	LO
	DM1 model	PY2	FO	RR	QF	DB	LO
	HYMO-10	CA*	FO	SA	QF	DC	LO
	Hydrodynamic model	PY4	FC	CS	QF	DL	DE
	Cuenca model	PY5	FC	CS	QF	DC	LO
	Terra-baygorria model	PY6	FC	CS	FQ	DC	LO
Venezuela	Sacramento model	US2*	FO	CB	QF;CS	DC	LS

* Index of the original supplier.

Annex 8

Surface water flow and supply model evaluation

Issue	Information required for applications	Overall rating
Water availability:		
1. Flood forecasting and control	a. Flood peaks for channel and bridge design	B
	b. Flood hydrographs for reservoir design and operation	C
	c. Simultaneous flood hydrographs for flood control system design and operation	C
	d. Flood depth mapping for flood plain land-use planning	C
	e. Effects of land use on downstream flows for upstream land-use planning	C
	f. Flood peaks after dam failures for emergency preparedness planning	D
	g. Soil moisture conditions for land drainage design	C
2. Drought and low-flow river forecasting	a. Low river flows for offstream uses	C
	b. Timing of drought sequences for estimating cumulative economic impact	B
	c. Soil moisture conditions for precipitation-supplied uses	C
3. Streamflow regulation (including reservoirs)	a. Runoff volume for maximum obtainable yield	A
	b. Runoff time patterns (with and among years) for reservoir sizing	B
	c. Simultaneous runoff volumes in regional streams for regional water supply planning	C
4. Instream flow needs: Fish and Wildlife	a. Low river flows for estimating fish support potential	C
	b. Within-year timing of low flows for fish lifecycle matching	B
	c. Timing of drought sequences for estimating minimum reservoir or lake levels	B
	d. Flow velocities within streams for estimating effects on fish species	C
Recreation	a. Low river flows for sustaining recreation capacity and esthetic appeal	C
	b. Timing of flow sequences for matching with recreation periods	B
	c. Runoff time patterns (within and among years) for estimating the impact of fluctuations in lake levels	B
Navigation	a. Low river flows for determining waterway capacity	C
	b. High river flows for determining navigation interference	C
	c. Formation of surface ice for determining navigation interference	D
Hydroelectricity	a. Timing of flow sequences for estimating run-of-the-river-generating capacity	B
	b. Runoff time patterns (within and among years) for designing streamflow regulations	B
	c. Simultaneous runoff volumes in regional streams for regional generating system planning	C
Water uses:		
5. Domestic water supply	a. Timing of water use for delivery system design	D
	b. Water pressures throughout delivery system for delivery system design	C
	c. Volume of use for sizing supply facilities	B
	d. Return flow volumes for designing wastewater collection systems	C
6. Irrigated agriculture	a. Timing of water use for delivery system design	C
	b. Volume of use for sizing supply facilities	B
	c. Return flow volumes for drainage system design	B
7. Other offstream uses	a. Volume of industrial use for sizing supply facilities	B
8. Water use efficiency	a. Effect of increased use-efficiency on return flows for evaluating conservation measures	C

Rating Key:

- A Modelling of the physical process at the current state-of-the-art does a good job in supplying the needed information.
- B Information between adequate and good.
- C Modelling does an adequate job for most purposes.
- D Information between unsatisfactory and adequate.
- F The supplied information is generally unsatisfactory.

Source: Office of Technology Assessment, 1982

Annex 9

Surface water quality model evaluation

Issue	Generic type: I No computer, not complex	II Computer, not complex	III Computer, complex	IV Computer, complex operational	Overall level of modelling sophistication
Nonpoint source pollution and land use					
Urban runoff:					4
Source/generation	C	C	B	B	
Transport to receiving water	-	A	A	A	
Transport in receiving water	-	C	B	B	
Impacts on beneficial use	C	C	C	C	
Control options/costs	B	B	B	B	
Erosion and sedimentation:					4
Source/generation	A	C	C	C	
Transport to receiving water	C	-	C	-	
Transport in receiving water	B	-	C	-	
Impacts on beneficial use	B	-	-	-	
Control options/costs	A	-	-	-	
Salinity:					9
Source/generation	A	A	A	-	
Transport to receiving water	A	A	A	-	
Transport in receiving water	A	A	A	A	
Impacts on beneficial use	B	C	C	-	
Control options/costs	A	-	-	-	
Other agricultural runoff:					3
Source/generation	C	C	B	B	
Transport to receiving water	-	B	A	A	
Transport in receiving water	-	C	B	B	
Impacts on beneficial use	C	C	C	C	
Airborne pollutants:					6
Source/generation	A	A	A	A	
Transport to receiving water	A	A	B	B	
Transport in receiving water	C	C	C	-	
Impacts on beneficial use	C	C	C	-	
Control options/costs	A	A	A	A	
Water quality (other than nonpoint sources and land use)					
Wasteload allocation:					7
Source/generation	A	A	A	A	
Transport to receiving water	A	A	A	A	
Transport in receiving water	A	A	A	A	
Impacts on beneficial use	C	C	C	C	
Control options/costs	B	B	B	-	
Thermal pollution:					9
Source/generation	A	A	A	A	
Transport to receiving water	A	A	A	A	
Transport in receiving water	B	A	A	A	
Impacts on beneficial use	C	C	C	C	
Control options/costs	A	A	A	A	
Toxic materials:					1
Source/generation	C	C	C	C	
Transport to receiving water	-	-	C	C	
Transport in receiving water	-	-	C	C	
Impact on beneficial use	C	-	C	-	
Control options/costs	C	-	C	-	
Drinking water quality:					2
Source	A	-	C	-	
Treatment	A	-	C	-	
Impacts on beneficial use	C	-	-	-	
Water quality impacts on aquatic life	B	-	B	B	3

Key: A Reliable, credible modelling may be readily used for most problems of this subissue. Some models may be suitable for regulation and design.
B Same as C, but some models may be useful for planning and related purposes, and suitable for determing relative effects.
C Modelling is possible. Credibility and reliability of results is low due to weaknesses in the data base.
\- Modelling of this type is not usually performed.

Overall level of modelling sophistication:
0 No models available.
10 Routine use of models of all types.

Source: Office of Technology Assessment, 1982

Annex 10

Ground water model evaluation

Spatial considerations	Model types																			
	Site										Local						Regional			
Pollutant movement, if any	Flow only				Transport w/o reactions			Transport w/ reactions			Flow only		Transport w/o reactions		Transport w/ reactions		Flow only		Transport w/o reactions	
Flow conditions	sat P	sat F	unsat P	multi fluid	sat P	sat F	unsat P	sat P	sat F	unsat P	sat P	sat F	sat P	sat F	sat P	sat F	sat P	sat F	sat P	sat F
Issues																				
Quantity-available supplies...	B	C									A	B					B	B		
Quantity-conjunctive use.....	B	R									A	B					B	B		
Quality-accidental petroleum products..................				R	B	C	R						C	R						
Quality-accidental road salt..					B	C	C													
Quality-accidental industrial chemical..................					B	C	C	C	R	-			B	C	C	-				
Quality-agricultural pesticides and herbicides..............					B	C	C	C	R				B	C	C					
Quality-agriculture salt buildup					B	C	C						B	C						
Quality-waste disposal landfills					B	C	C	C	R	-			B	C	C	-				
Quality-seawater intrusion....				B	B	C	C						B	C					C	C

Key:

Rows – issue and subissue areas discussed in text.

Columns – model types and scale of applications, e.g., the sixth column applies to a site-scale problem in which pollutant movement is described by a transport model without chemical reactions under saturated flow condition in fractured media.

Application scale:

- Site – models dealing with areas less than a few square miles.
- Local – models dealing with areas greater than a few square miles but less than a few thousand square miles.
- Regional – models dealing with areas greater than a few thousand square miles.

Abbreviations:

- w/ – with.
- w/o – without.
- sat – saturated ground waterflow conditions.
- unsat – unsaturated flow conditions.
- P – porous media.
- F – fractured or solution cavity media.

Entries:

- A a usable predictive tool having a high degree of reliability and credibility given sufficient data.
- B a reliable conceptual tool capable of short-term (a few years) prediction with a moderate level of credibility given sufficient data.
- C a useful conceptual tool for helping the hydrologist synthesize complicated hydrologic and quality data.
- R a model that is still in the research stage.
- \- no model exists.
- Blank – model type not applicable to issue area.

Source: Office of Technology Assessment, 1982