Internationale Kommission für die Hydrologie des Rheingebietes

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Comparison and selection of existing hydrological models for the simulation of the dynamic water balance processes in basins of different sizes and on different scales

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Report no. II-7 under the auspices of the CHR

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Vergleich und Auswahl bestehender hydrologischer Modelle für die Simulation von dynamischen Wasserbilanzprozessen in Einzugsgebieten verschiedener Größen und mit verschiedenen Maßstäben

Deutschsprachige Abschnitte:
Zusammenfassung: S. 47
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Comparaison et sélection des modèles hydrologiques existants, simulant les processus dynamiques du bilan hydrique, dans des bassins de différentes tailles et à différentes échelles.

Textes français:
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Vergelijking en keuze van bestaande hydrologische modellen voor de simulatie van dynamische waterbalans processen in stroomgebieden van diverse afmetingen en op verschillende schalen.

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Preface

The evaluation of possible climate change impact on the global and regional water cycle and on water resources is at present one of the major scientific challenges to hydrology. As a first step it is necessary to evaluate the tools available to meet this challenge. The knowledge of the physical processes involved in the functioning of the system is no doubt most important for the evaluation of the impact. Hydrological models of the above processes, simulating the water balance in a basin, are a suitable tool to accept as an input climate variables produced by a climate model or chosen from a climate change scenario, to produce corresponding hydrological variables impacting the water balance and eventually producing the "water scenario" that will in turn impact water resources management. These models may also be used to provide regional and global input of hydrological variables in the models of the climate system in which the hydrological cycle plays an important role and influences by feedback many climatic processes.

It is in these complex issues that large river basins, such as that of the river Rhine, acquire particular interest, since their scale starts to be compatible with that of the scale at which are operated the Global Circulation Models (GCM).

To meet the above challenge the International Commission for the Hydrology of the River Rhine (CHR) considered it important to start in 1989 a project on "Influence of climatic variations on the river-flow of the Rhine". In the context of this project the CHR organized a workshop in Coblence (21-22.January 1991), to provide an overview of the state-of-the art methods available to solve the core problems and discuss future actions.

Prof. J. Nemec at this workshop presented, as one of the speakers, his views on existing hydrological models and on the criteria to be used in selecting appropriate models for various scales. He based his review on a recent WMO inventory of hydrological models and on his experience in the field of intercomparison of models conducted in cooperation with a number of hydrologists by the WMO Department of Hydrology and Water Resources of which he was for many years the director.

This study was prepared by Prof. Nemec within the framework of his cooperation with the Hydrology Section of the Department of Geography of ETH Zurich, and was also supported by the Swiss Federal Hydrological and Geological Survey, Bern.

It is the intention, on basis of the recommendations contained in this study, to test in different Swiss basins some of the identified models and, if appropriate, improve them to be used for the evaluation of the impact of climate on water resources. It is also expected that these efforts, as coordinated by CHR, may lead to a selection of models most promising in this direction.

Zurich, 9.December 1991
Prof. H. Lang

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1. INTRODUCTION

The comparison of hydrological models of the rainfall-runoff process should not be considered as a theoretical exercise of general validity, since, if devoid of practical purpose, this exercise is also devoid of the main criterium needed for the comparison, namely, the intended use of the model. This statement is today recognized by all authors and institutions which conducted comparisons and evaluations of models and was first stated in an explicit way and documented in the report on the project conducted by the World Meteorological Organisation (WMO, 1975) from 1969 to 1974 to intercompare conceptual models used for operational hydrological forecasting. The recognition of this principle leads to further important methodological conclusions, which are less readily and universally accepted although they are directly originating in the first one. Among these is another conclusion reached by the WMO first intercomparison project, namely, that there is no such thing as "the best" model (or models). Even for the same purpose or use there is always a choice of models, so that the selection of a model depends on criteria which are often only partly and sometimes entirely independent of the scientific evaluation of the model. Such secondary criteria are for example availability of input data and computing facilities (hardware and/or software).

In the last resort the final selection of a model for a particular purpose is, in the experience of this author, the "proof of the pudding". In other words the perspective user has to operate a limited number of models simultaneously to ascertain their performance for the purpose and for different hydrological events in the technological and natural environment in which the model is operated. This conclusion is not readily and universally accepted, mainly because very often the user is at the same time the author ("developer") of one or more model(s) and it is only natural that he has a biased view, indeed one's "baby" is always the best in something, be it only in the fact that it is made for the particular purpose. Often the intellectual ownership, in itself not reprehensible, quite to the contrary, as it moves the progress ahead, can degenerate to the extent that proofs are artificially produced to justify the superior performance of the "baby". It took some effort to introduce an old experimental principle into hydrological modeling: the "split sample" test. For quite some time, for example, many authors of empirical "flood formula" used the same data on which such formula were developed mostly by regression, to provide evidence that the results of their application is good. Even today some authors of models, present results of their models only with two sets of data: "computed" and "observed" and do not specify whether the "observed" set was used also for the development (calibration) of the model or some or all of it kept aside for the testing. For these reasons it is strongly recommended by this writer, that in any selection of models, (and "comparison" means in most cases "selection"), authors of models compared are either all given the same treatment (all participate in the comparison) or they all are kept away and the comparison and selection is performed by institutions or persons, which have no own model to provide for the specified purpose. This principle was maintained in all WMO intercomparisons (WMO 1975, 1985, 1987) and has proven its value to the extent that several hydrologists have called these projects a "milestone in the hydrological science" (Chapman, 1982).

The boundary conditions of the present study have been set as follows:

a) It is to be based on desktop review and evaluation of existing models, thus no testing will be performed, at least not in the first phase.

b) The models should be used in the Switzerland's basin of the Rhine (its alpine reaches, prealpine sub-basins and low-lands contributing areas).

c) The evaluation criteria should encompass:
   - structure of the model
   - time step
   - representation of physical processes
   - requirements on input data
   - requirements on hardware/software

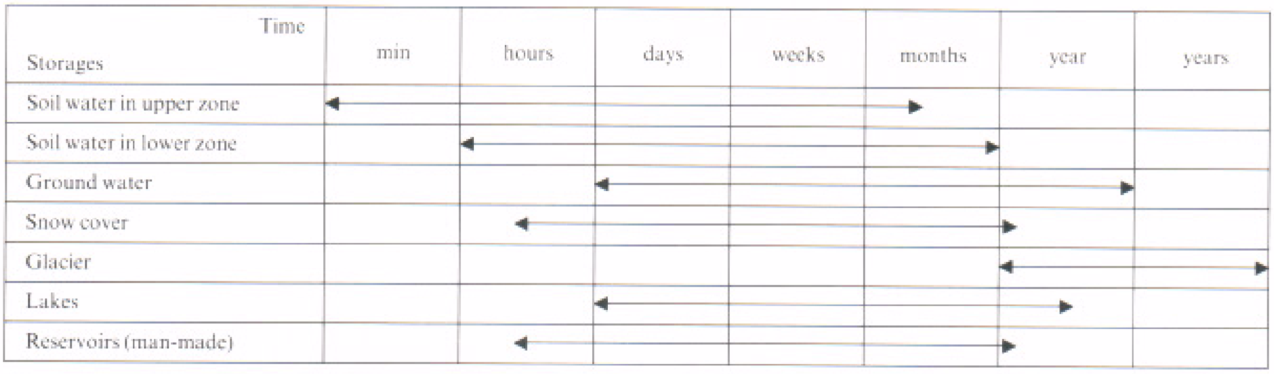
Furthermore the focus of the study is on water balance models that could be used for evaluation of impact of climate input variation (change) on water balance in basins of different scales.

The evaluation should consider also the ease of transfer of the model, its calibration and of computing procedure for simulation purposes.

2. VALIDITY OF THE CONCLUSIONS OF THE STUDY

The above boundaries of the study are not a real limitation in the spatial and morphological sense, since the Rhine basin in Switzerland comprises small, medium and large sub-basins of varied climatology, morphology, geology and vegetation cover. Thus without any study, it is obvious that no single physically based model will be able to accommodate the diversity of these catchments with respect to physical processes and climate inputs. Indeed any physically based model is consisting, among others, of conceptual representation and simulation of the process of storage in the basin. This storage may be only natural but in the Swiss basin of the Rhine a considerable role is also played by man-made storage. The storage processes are having each a different time scale which have been summarized in Table 1 (Schädler, 1990). Obviously, only complex models or several separate models may work on the different time steps corresponding to the storage times. This question receives a special consideration later in this study but is very well illustrated by Klemes (1982):

"The contemporary practice of conceptual model building can probably be best compared to a jump from an upper level using the model as a life saving rope and the flow record as the only peg to which the rope is tied. In principle, it may be feasible to start a mapping expedition in this manner if, after landing, one starts his way back by climbing the mountain, anchoring additional pegs in safe points along the mountain and fastening the rope to them. Where the modellers go wrong is that they climb back by pulling themselves by the rope through the foggy air. While this may be a good way of transport between the landing site and the top, it has obviously shortcomings as a method for the mapping of the mountain side."



Tab. 1 Time of storage in different Swiss basins (after Schädler, 1990)

The following example is an attempt to illustrate a possible way of how such mapping starting from the top can be approached.

The example evolves around the classical hydrologic topic - the rainfall-runoff relation (RRR) on a monthly time scale - (although) such time scale is, from the hydrological point of view, arbitrary but it is accepted here as a constraint beyond the analyst's control. Given the time scale the choice of spatial scale determines the kind of relationships that one can hope to identify. While the relationship between the two scales is not well understood, one thing seems to be obvious: if the time lags between rainfall and runoff on a given spatial scale are much shorter than the time interval selected (for example a month), the dynamic effects of the spatial unit will be "swallowed" by integration over a single time interval and cannot be revealed by monthly data. Hence a space unit with a "memory" longer than the selected time interval is necessary if the aim of the analysis extends beyond an interval -by -interval water balance. And of course the corollary requires that a time step shorter than the "memory" of the space unit should be chosen for such an analysis.

To be able to consider several models, of the same or of different types, an inventory and a classification of models is obviously necessary. The first is relatively easy, all it is necessary is to consult a few proceedings of symposia and conferences on modeling and note all models that are considered suitable for the specific purpose. This method is easy, nevertheless it is not always reliable, as some authors of models, in particular if these are developed within institutions, do not always consider desirable for various reasons the presentations at scientific symposia yet their models may be very suitable for practical purposes. On the other hand and bearing in mind the same purposes usually many of the models presented in scientific gatherings may represent a brilliant intellectual exercise, without any consideration for its application and subsequently without any proven procedures for their use. Obviously some middle ground should be sought. It is felt that such middle ground of inventories are international organisations involved in hydrology and water resources. Their inventory may not represent the newest state of the art of the research, yet provide some warranty (usually by national governmental hydrological or water management agencies) of the quality of the model and its application. One of the first inventories of models has been prepared by FAO; the latest and considered by this writer as reasonably reliable is that of WMO, originated in the Working Group for Hydrology of the WMO Regional Association for Europe (RA VI) in a report by Dr. Serban. This report was recently updated and extended to the whole world, and co-authored by Dr. Serban and Dr. A. Becker. The revised report (WMO, 1991) provides a classification of purposes of modeling, a classification of models and an inventory of these.

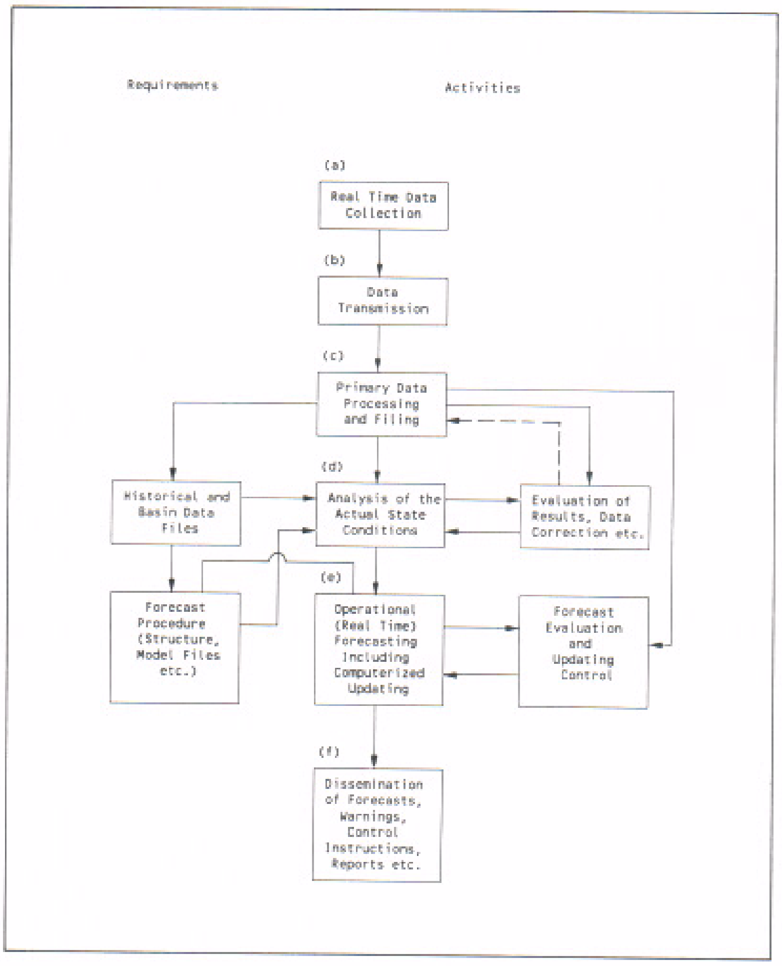


Fig. 1 General structure and components of operational hydrological real-time forecasting systems

The purposes of models to be identified in the framework of this study are classified by the WMO report as Prediction, Planning, and Design. As the name of the category indicates, these models are obviously connected with a multitude of human activities either needing or impacting water resources.

It should be noted, that the models used for these activities might be of the same structure as those used in real-time operation of water resources systems through forecasting represented in Figure 1. (Nemec, 1986). It is true that normally the input data for real time operation of a model differ from those used for balance computations, which may require an adaptation of the input procedure with the model structure remaining basically the same. This depends mainly on the character of the basin and purpose of the real time operation of the model.

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 which in the past used to be restricted to a 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. At the same time, 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), expansion of agricultural cultivation over previously bare or forested lands, 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. In these circumstances, significant modifications of the hydrological cycle components are liable to occur.

In consideration of these interactions two phases of the planning process may be considered:

i. First phase:

Long-term prediction of hydrological parameters required in the planning process (in the form of continuous time series, characteristics of extreme events, such as floods or droughts, with a given 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, (WMO, 1991);

(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.

ii. 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:

(a) Water supply for different users, or categories of users, in particular for industrial, energy and agricultural production, including irrigation;

(b) Waste water treatment and release;

(c) Low flow control;

(d) Storm-water management;

(e) Flood control and protection;

(f) Environmental control and protection;

(g) Transportation and communication.

Phase 1, represents well the hydrological aspects of the problems to be solved by the models required in the purposes of this study.

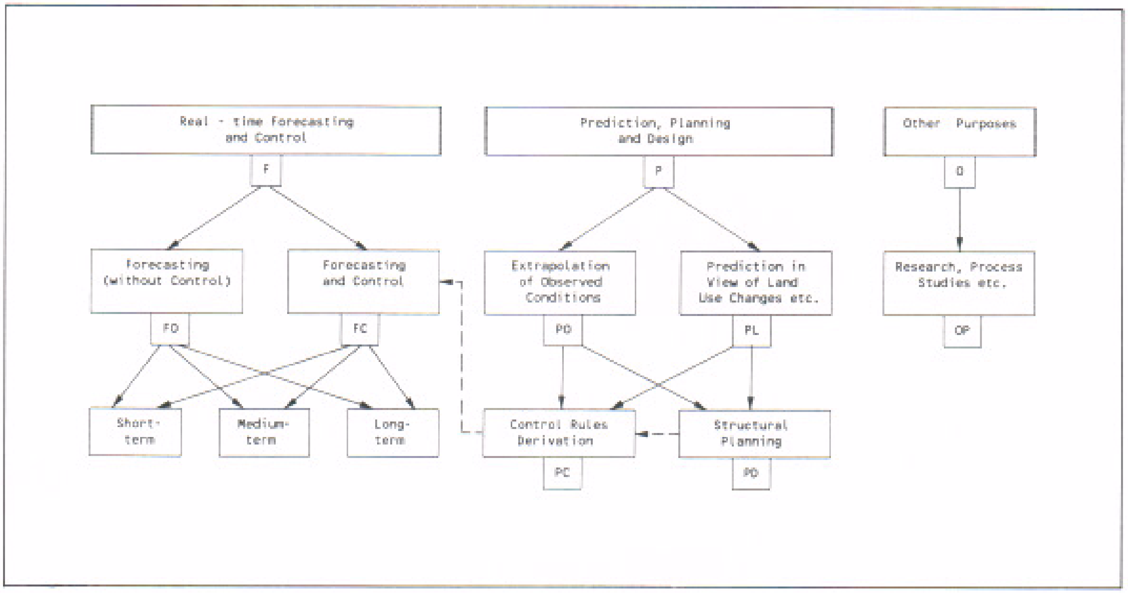


Fig. 2 Main purposes of using hydrological models

3. CLASSIFICATION AND INVENTORY OF MODELS

Since the years sixties, when digital (and at that time analog) computers started to be used for hydrological modeling the number of models marked an exponential growth. Very soon it became apparent that several authors used different names to describe some type of modeling approach (procedure). Some used the name of the mathematical operation (for ex., "convolution integral"), others borrowed names from the system analysis, a rapidly growing branch of science that found use in hydrology (black box), yet others remained with older hydrological terminology adapted for new developments (for ex. "instantaneous unit hydrograph") or combined mathematics with hydrology (for ex. kernel hydrograph). For the student of the science it often appeared that these models are four distinct ones, for the specialists it was evident that in essence it was one single procedure of a similar if not the same model. Thus a need for classifications became obvious for academic (teaching) purposes. On the other hand the identification of types of models required their grouping. The writer of this study has come across many classifications. He created also one of his own - but only for purposes of real time hydrological forecasting (Table 2, Nemec, 1987).

A. Purely deterministic forecasting procedures (models)
  A.1 Hydrometric data-based (involving only streamflow processes)
    A.1.a Correlations of stages and/or volumes (discharges)
    A.1.b System approach to streamflow (hydrologic routing)
    A.1.c Hydraulic routing using
      (i) Dynamic wave
      (ii) Diffusion analogy
      (iii) Kinematic wave
  A.2 Hydrometeorological and hydrometric data based models (involving rainfall/runoff and streamflow processes)
    A.2.a Correlations using physical variables and parameters or indexes (such as API)
    A.2.b System approach to the basic basin response to rainfall
    A.2.c Distributed parameter approaches (hydrological and hydraulic)
    A.2.d Conceptual moisture accounting using
      (i) soil moisture indexes
      (ii) implicit moisture accounting
      (iii) explicit moisture accounting
B. Hybrid stochastic-deterministic forecasting procedures (models)
  B.1 Using only time-series stochastic parameterization
  B.2 Using a system approach to the basic basin response and time-series stochastic parameterization

It should be noted that often some models of the categories A.1 and A.2 are combined in one single forecasting procedure and that lately categories A and B are being combined in the so-called »self-tuning algorithms«, namely models of category A are updated in operational mode by procedures of category B.

Tab. 2 Classification of models used for hydrological forecasting (Nemec, 1987)

The above mentioned WMO report (WMO, 1991) produces also a classification based, as any classification, on "a priori" established principles. These are, from the point of the model user, attempting to provide "problem oriented" and "user - friendly" criteria as follows:

(a) purpose of model application;

(b) type of system to be modeled;

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

(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). The suggested categories under these three criteria are explained in Tables 3 and 4 and Figures 2 and 3.

Number	*Type of system to be modelled*	*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*

Tab. 3 Scheme for classifying hydrological models in terms of the purpose of their application

Number	*Purpose of application*	*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

Tab. 4 Types of hydrological systems, as used in this report in the classification of hydrological models

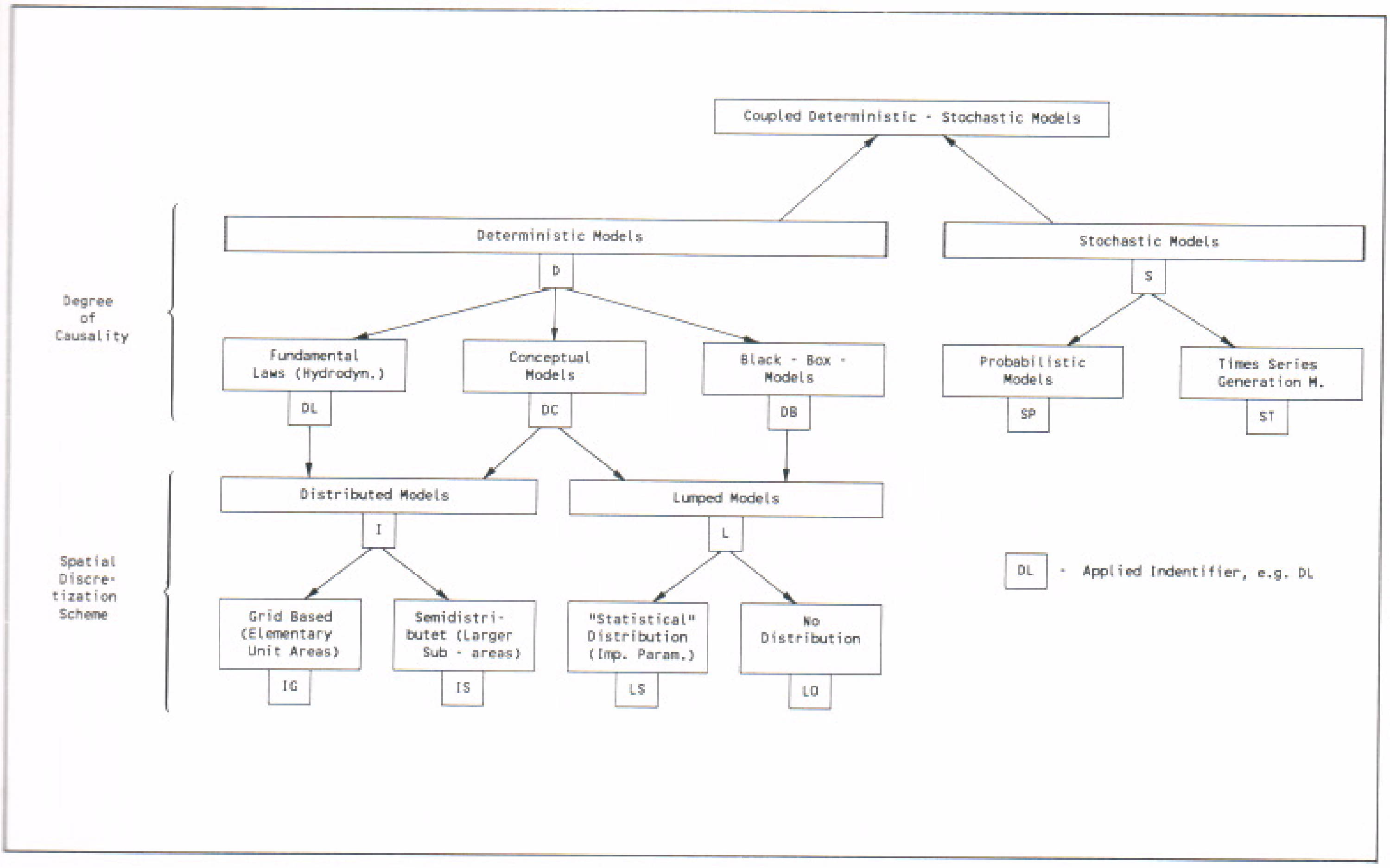


Fig. 3 Classification of hydrological models in terms of purposes of application, degree of causality and applied spatial discretization

3.1 Models and Procedures

In connection with this classification, it is important to explain the difference between a model and a procedure as introduced by the authors of the WMO publication:

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, such as a Kalman filter);
- 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 study, procedures also have to be taken into consideration.

Although the author of this study does not share the views of the above principles of classification entirely (as he has its own classification), he finds extremely useful the inventory of the models available and thus it is necessary to explain the identifiers of different model categories. The classification and identifiers are contained in a number of figures and tables and explained in the following text.

3.2 Classification According to Model Application and Purpose.

The classification identifiers included in Table 1 and Figure 2 denote basically models and procedures which should be directly usable 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.)

3.3 Classification in Terms of the Type of the System.

Classification in terms of this criterion is proposed in Table 4 which defines those water-resource systems and their important elementary sub-systems which are of primary interest in operational hydrology. A distinction is made between (1) elementary systems and (2) complex or coupled systems.

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

3.4 Classification in Terms of Hydrological Processes or Related Variables.

This classification is presented in Table 5. 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) was considered appropriate by the authors of the WMO 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 4 and 5, any required alternative or sub-classification can be introduced.

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 (≤ 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

Tab. 5 Hydrological processes or related variables to be considered in the classification of hydrological models

3.5 Classification in Terms of Causality.

3.5.1 Deterministic Models

Degree of causality is expressed in the form of cause-effect relations. These are best reflected in deterministic models 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):

$$y = f(x, a) \qquad (1)$$

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 modeled system and of the process to be modeled. Aspects of dimensionality, space and time discretization will be considered later in this study. Three main categories of deterministic models are introduced by the authors of the WMO study in Figure 3:

(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) 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 (black-box models).

3.5.2 Stochastic Models

The second main group classified according to causality comprises models which do not consider the principle of causality are the stochastic models (S in Figure 3). A sub-category of these models - the so-called probabilistic models (SP) - are generally represented by probability distribution functions of the hydrological characteristics such as, for example,extremes (flood peak flows, low flows, etc.) or storage volumes. They are described in terms of parameters such as averages, standard deviations and coefficients of skewness.

An other 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.

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 a system.Therefore, the type-of-system classification criterion cannot always be applied in connection with stochastic models. Conversely, deterministic models are clearly related to specified systems, as listed in Table 4, and thus to their inputs, state conditions and outputs.

3.6 Relationship of Deterministic and Stochastic Models

The author of this study considers that a rigid line cannot be drawn between the above two groups of models since the hydrological processes always include deterministic and stochastic elements. The WMO report considers coupled deterministic-stochastic models as in indicated in Figure 3. This is true particularly for prediction, planning and design models where at least the "prediction part" often needs a stochastic model component as a economic decision premise.

In addition any deterministic model of a complex hydrological system cannot take into account all input variables and process factors which influence the output. Therefore an inherent part of the model output will be a certain error y (n). This error, which can be described by a stochastic model, includes usually two types of error: the error of the deterministic model (or the error in the representation of the system) and the error of the measurement of the input variables.

If the understanding of the process and the measuring technique is improved then this error can be reduced.

In summary, it can be said that stochastic models form a substantial part of each prediction, planning and design study.

4. TIME AND SPACE DISCRETIZATION IN HYDROLOGICAL MODELLING.

4.1 Time Discretization

The problem of the time step of the model has been already discussed in para 3 above and illustrated in the quotation from Klemes (1982). The selection of the time step is subject of at least three considerations.

(a) The first concerns the storages in the system and is basically part of a general consideration both of the dimension (scale) and internal structure of the basin or aquifer.

(b) The second consideration is the purpose of the model. If the non-linearity of the processes (such as this of rainfall - runoff) is to be considered, then the correct time step is crucial for its assessment. In this case hourly or daily time step is normally needed. If only seasonal or annual characteristics such as flow volumes are considered a monthly or even annual time step is acceptable.

(c) The third consideration is the availability of input data. While daily data are acceptable in most cases and can be, if absolutely necessary, disaggregated in x-hourly values, monthly data are easier to handle and for water balance purposes are normally sufficient.

Often a trade-off between availability of data and accuracy of modeling may be necessary. Some models are designed to accept variable time step. The time step aspect is essential in the selection of an appropriate model for a specific application.

4.2 Space Discretization

Similarly essential but more difficult in modeling is the space discretization, sometimes characterized as "topological modeling".

There are two basic categories of space discretization (Figure 3 and Table 6): distributed models (I) and lumped models (L). These categories may have several sub-categories, the most salient are river basins or runoff surface areas (CB and SA in Table 4).

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.

Tab. 6 Categories of space discretization in hydrological modelling of large areas, river basins, etc.

4.3 Distributed Models

According to Table 6 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). This is achieved for instance by sub-dividing a runoff surface area into elementary unit areas determined either by a detailed regular grid (as in Figure 4, part c). In many cases, especially in microscale considerations, the grid areas are chosen small enough to ensure the validity of the governing fundamental physical laws. This means, in terms of the scale definition that they should not be greater than about 1 km^2.

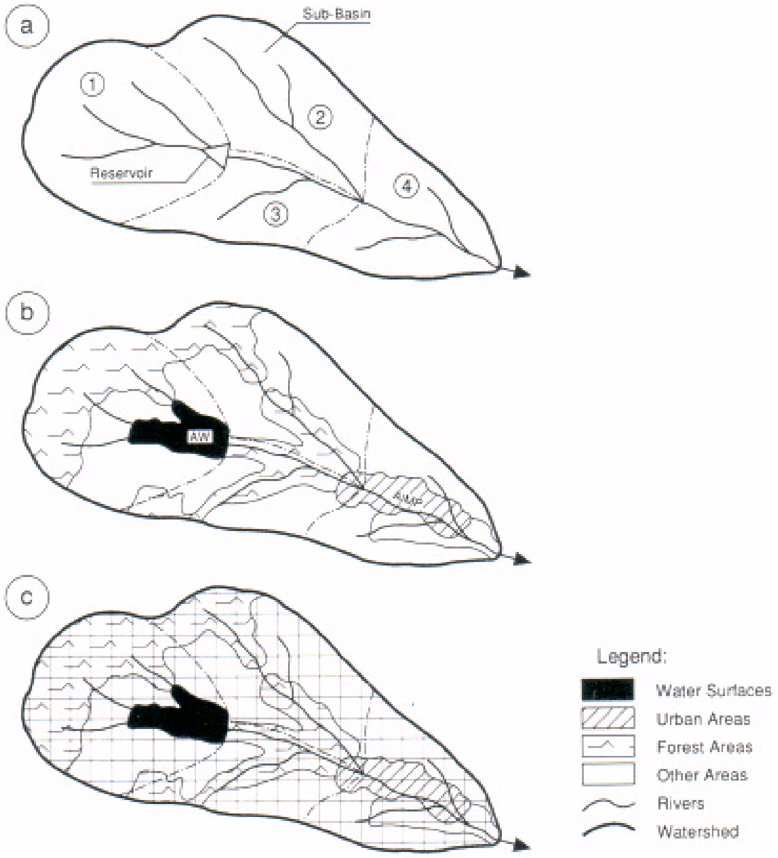


Fig. 4 Representation of different space discretization schemes in a rivers basin modelling:
(a) lumped (4 sub-systems)
(b) semi-distributed
(c) distributed (grid-based)

The application of distributed models for river basins or other surface areas is advantageous if the modeling intends to take into consideration:

- 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.);
- 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.

4.4 Lumped Models

Lumped models (L), as the other extreme, take into account the areal distribution of the above-mentioned characteristics to the extent that is given by limits of approximation of homogeneity (or averaging) of the characteristics of the geophysical variables needed as input in the model.They are therefore much simpler and are easier to handle. 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.

4.5 Semi-distributed Models

Mainly due to the increase in use of remote sensing and computerised digitizing techniques, an increased number of compromise solutions have emerged. They 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). An early attempt in this direction was the introduction of "statistical distribution functions" for essential parameters (sub-category LS in Table 6). One example is 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)). A second example is a linear distribution of the soil storage capacity for capillary water in the rooted soil layer as introduced by Becker in 1975 (Becker and Nemec, 1987).

Further developments consist in sub-dividing the land surface or river basin area into larger sub-areas (zones) of approximately equal inputs and hydrological behaviour (Figure 4, part b). This sub-category (IS) of distributed models is indicated in Table 6 as semi-distributed, after Refsgaard (Knudsen et al., 1986). This type of models, while achieving a better representation should not require spatially detailed input data to the extent of grided distributed models.

4.6 Sub-areas of a Semi-distributed Model

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 evapo-transpiration (taking into account the available data collection network).

(b) The areal distribution of basin characteristics which significantly influence general hydrological conditions and regime such as:

- topography;
- soil and land use;
- hydrogeology;

In this connection it should be noted that a sub-division of a river basin into sub-basins according to Figure 4, part a, must not be interpreted as a semi-distributed model. It is merely a mosaic of lumped models fitted to sub-basins.

4.7 Dimensions of Surface Water Models

The spatial discretization scheme in the case of surface water systems (RR, RL and CS in Table 4) is principally related to the dimensionality of the model which may be one- two- or three-dimensional.

For simple flow routing through river reaches without extended flood plains, reservoirs, lakes, etc. a one-dimensional description is generally sufficient. 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. 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 "computational reaches". For extended flood plains it is more appropriate to apply a two-dimensional distributed or semi-distributed model. A very fine grid is necessary only in detailed and specific investigations, e.g. in planning and design of hydraulic structures. In many cases it is also here possible to apply the much simpler and 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 routing 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.

4.8 Criteria for Selection of Space Discretization

The different deterministic model types and the above mentioned space discretization schemes are related. These relations are represented in Table 7 and should be taken into account in any model selection.

The criteria for selecting the space discretization in river basins and surface water systems can be summarized as follows (see also Table 8 and 9.):

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

(b) the amount and quality of available input data;

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

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

In connection with the consideration of data availability it is necessary to select certain procedures influencing model selection.

These procedures may not be part of the model but must be compatible with it. The two most important ones are procedures for data input and results output. In the early stage of mathematical modeling in hydrology, this procedure was almost invariably an inherent part of the model. Each model had and even today some do have a special subroutine to store the input data and an other one to supply them to the model algorithms. This had some advantages among which was a privileged use of the model by its author on the hardware he worked with. With the increased use of models in operational activities this state of the art, together with the rapidly decreasing cost of hardware and appearance of PCs, led to the cost-effective practice to transfer models to different users together with the hardware on which the model was developped.

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

Tab. 7 Relation between model types and spatial discretizations schemes

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 particularly on direct runoff, erosion, matter transport and related processes	As 1. above	Distributed (e.g. unit grid areas) or semi-distributed

Tab. 8 Appropriate time and space discretization in river basin modelling in relation to purposes and objectives of model applications (Becker, 1988)

With the appearance of the off-the-shelf software data-bases, of which several have been either adapted or specially written for geophysical data in general or hydrology in particular,it appeared that these data bases could be used in data input procedures,and thus allow for use of one data base for more than one model. The WMO report on modeling (WMO, 1991) does not present an inventory of such data bases but the WMO HOMS Reference Manual (second edition;WMO,1988) contains a good number of them.

Model category	*Main fields of application*	*Advantages*	*Special requirements and problem*
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 of 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) Possibly beyond the limits defined by the calibration

Tab. 9 General characteristics and fields of application of hydrological models for river basins and other land surface areas

4.9 Geographic Information Systems (GIS)

Simultaneously with the off-the-shelf data bases, started to be developed digital mapping (e.g.digital terrain modeling) and data referencing to geographical coordinates, first as a help to cartography: the Geographic Information System (GIS). Hydrology was, however, as user of geographical data, in the foreground of such developments, which were particularly useful in large basins and in models with distributed parameters. As a merger of the geographical referencing of data and the distributed models was developed Square Grid Technique (Solomon et al, 1968; Girard et al, 1970).

These developments were further accelerated by the availability of remote sensed data, in particular from satellites, some of which soon appeared usable in distributed but also lumped hydrological models, although mainly in research (Schultz ,1990). Much work is underway in this direction as several difficulties still exist. Among them is unavailability of the remote sensed data for several important parameters of hydrological models (e.g. soil moisture) and the problem of scale, as will be discussed below.

The above developments in data input to hydrological models, namely the gridding of spatially distributed data in a Geographic Information System or a similar data grid and the remote sensing of some data have however seen, for the time being, even on a semi-operational level, their application in relatively small basins. Yet their importance is capital in large basins, for which they offer perhaps the only possibility of a large quantitative step forward in the improvement of the accuracy in modeling, in particular with respect to the spatial distribution of the output. On the other hand the importance of large basins is increasing in the past ten years, as hydrology aspires to become an equal partner to its geophysical sister sciences, meteorology and oceanography, and leave its position of semi-empirical application in the service of engineering. The environmental changes on planetary scale, the concept of "Global Change" and in particular the "greenhouse effect" menacing the planet with a man-produced climate change climate are challenging hydrology to take up its role as a geophysical science and participate in several global experiments, among which the Global Energy and Water Experiment (GEWEX) is probably the most important. This experiment is unthinkable without modeling of most large basins of the world, which in its turn is unthinkable without use of a GIS and remote sensed data. In this regard it is important that the Swiss hydrologists together with those of other countries in the center of Europe, relatively small on global scale, take up this challenge, since the size of a scientist's country or of its basins does not preclude a large methodological contribution to the shared effort to solve problems of a shared future. This perspective is in the background also of this study and will be further developed in the conclusion.

5. ESTIMATION OF GRID VALUES FROM SPATIALIY DISTRIBUTED DATA

This problem has been in the foreground of several recent studies concerned with use of GIS in hydrology. It has been proposed (Solomon,1989) that different techniques are used for climate parameters needed as inputs to hydrological models and hydrological data proper. This, in the view of this writer is not caused by the fact that the climate data are related to a particular point - the observation station - while the hydrological variables are resulting from a process on an area - a river basin. Indeed both variables represent fluxes over a space, it is only because until recently it was impossible to measure these fluxes in the atmosphere in a tridimensional continuity, while due to the basin effect on surface and subsurface runoff the result of the integration in time and space of the fluxes, river and ground water flow was relatively successfully measured in one point. This integration, which the nature graciously offers to the science of hydrology was not sufficiently exploited by the hydrologists and willingly or unwillingly ignored by some meteorologists. It is however a fact that this differentiation can be avoided in very small basins and providing that sufficiently large grids are used, the same procedure to estimate grid point and grid area value can be used for climatological and hydrological parameters.

5.1 Gridding of Climatic Variables and Parameters

As indicated in the paper referenced above, currently several techniques can be considered for practical application in estimating grid values of climatic parameters. Two of these, isoline interpolation and weighted averaging require a rather dense station network, unless the climatic field is fairly homogenous in time and space. Other techniques include multiple regression, kriging and square grid estimation. Of these kriging assumes no knowledge of process dynamics and multiple regression technique requires correct selection of the independent variables and small or no errors in their measured values, which is seldom the case. Hydrologists used for many years as independent variables topographic and geographic parameters and lately also land-cover characteristics. The quantification of these in larger basins is however almost impossible without the help of a GIS.

5.2 Gridding of Hydrological Variables and Parameters

The situation with hydrological parameter's estimation in grid points and areas is even more difficult than that of the climatic ones. The above reference considers only three techniques as practical and of acceptable accuracy:

- multiple regression analysis with conventionally determined basin characteristics;
- multiple regression with basin parameters established with the help of a hydrology oriented GIS (GHEIS) or Square Grid Technique;
- various hydrological balance models using a GIS.

The use of the hydrological balance models however does present a conceptual problem of observed versus surrogate data. Several researchers rightly object to the use of models to produce grided data, since these in their turn are to serve as input data in the models.

5.3 Global Runoff Data Center

The Global Runoff Data Center (GRDC) sponsored by WMO and established at the Bundesanstalt für Gewässerkunde (Federal Institute of Hydrology) of Germany in Coblence, has proposed in the framework of preparation of a Global Runoff Data Set a method for grid point and area estimation of runoff, as described in the IIASA cooperative paper CP-90-09, 1990. The proposal is under scrutiny and no decision was taken on it.

The purpose of the eventual use of the GRDC gridded data is multiple, but one of them is the use for developing and testing macroscale hydrological models in the Central European region defined by the basins of rivers:

Rhine
Danube (until its outflow point from Hungary),
Weser
Elbe - Labe
Vistula
Oder

plus the contiguous area draining directly to seas. A preliminary plan of work is being considered for the necessary data collection, testing and the preparation of the gridded data.

While the work connected with the data procedures may be not the substantive scientific activity in the modeling exercise, in the view of this author the model may be only a smaller part of the whole software package and certainly not the most laborious one.

5.4 Physically Based Models

Before examining the main processes that have to be included in the model, it is necessary to state the a priori preference to be given to such models, which have parameters that can be adapted to conditions which not only exist on the prototype today but may exist in the future. Such models have been called, as indicated earlier in this study, "physically based".

If the model is "physically based", then its 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 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).

6. PROCESSES AND SUB-PROCESSES INCLUDED IN MODELS

Having the above requirements in mind it is important to recall the processes and sub-processes which the model has to take into consideration in their space and time variability,as represented in Figure 5 (after WMO, 1991):

(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;

(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.

6.1 Vertical and Horizontal Structure of the Processes and Two Level Modeling

This sequence clearly reflects the vertical and horizontal structure of the natural system and any model of it. Accordingly, and with concern for the main differences in the character of the above-mentioned processes, the elements can be sub-grouped as follows (as shown in Figure 5):

- Vertical elements:

(a), (b)	Atmospheric (meteorological) system inputs;
(c), (d), (e)	Losses (moisture recharge and evapo-transpiration), infiltration and runoff formation at any place (elementary unit area) within the catchment or reference area;

- Horizontal elements:

(f), (g), (h)	Flows (surface and sub-surface flows), areal flow concentration and outflows from the catchment.

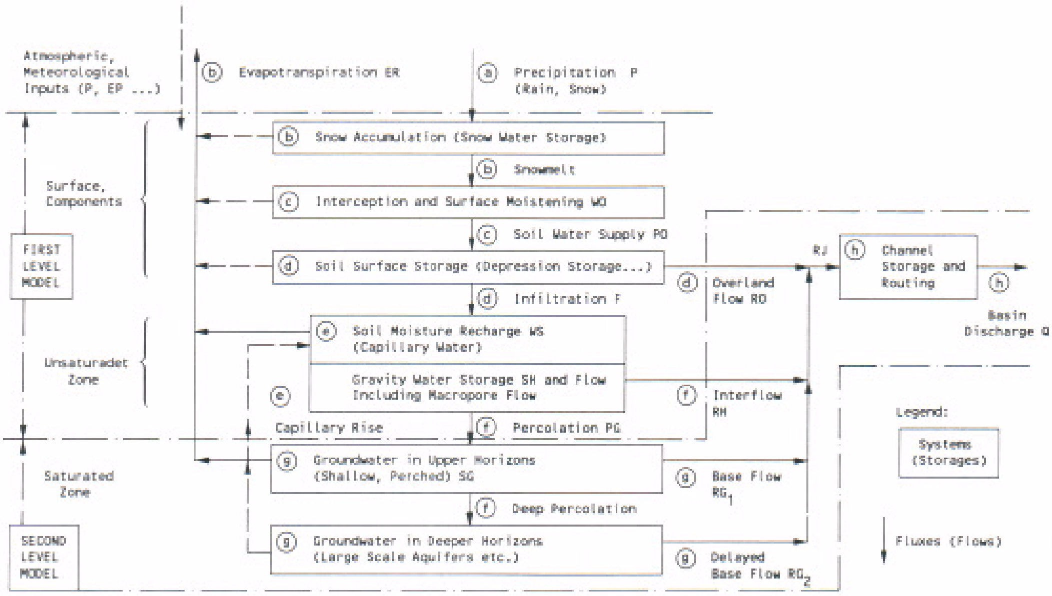


Fig. 5 Components and sub-processes of the land phase of the hydrological cycle

6.2 Two Level Modeling

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).

According to Figure 5, 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 could 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.

6.3 Flow Modeling

As regards the flow models (second-level sub-models), it can be said that in the past, river basin modeling very often considered only two flow components: direct flow and base flow. As the 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 5):

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

ROI = flow from impervious sub-areas (AIMP);

ROS = flow from saturated sub-areas (AS);

ROE = 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

RG1 = short-term base flow from upper ground-water systems (near to the surface), highly permeable aquifers, perched groundwater, etc;

RG2 = 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.

In the runoff process, conceptually the first consideration is given to canopy interception. In water balance that exceeds in time one day the water in the canopy can be represented as a storage that gets filled initially to its maximum capacity and then depleted by evaporation. As the models that are relevant to this study will not have a time step inferior to one day, a variable storage in time and space would be not necessary.

More critical, and also more difficult, is the modelling of excess infiltration, overland flow formation and unsaturated flow and water transport in the ground ((d) and (e) in Figure 5). 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:

(i) 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.);

(ii) 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 concepts and approaches are required if it is necessary to model on a physical basis larger-scale unsaturated flow and infiltration or excess rainfall. These concepts have to take into account the 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). They 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):

$$ROs = PO.AS \quad (2)$$

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.

6.4 Evapotranspiration

The other important sub-process to be considered is evapotranspiration. The estimation of areal evapo-transpiration 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, Priestley-Taylor equation);
  - Combination equations with resistance 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 boundary 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.

6.5 Composition of Processes in a Model

Composition of processes and sub-processes is the most common way to create integrated hydrological models for river basins (WMO,1991).

In the case of lumped modelling, the required sub-process models can be arranged simply in a cascading manner in the sequence represented in Figure 5. Areal variabilities are neglected or approximately taken into account by statistical distribution principles (LS in Table 6). 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 computational procedure for estimating "effective rainfall" (direct runoff) as input to the unit-hydrograph application.

6.6 Typical Composition in Conceptual Models

Later, simple conceptual models were introduced as sub-processes models, in particular those based on a series of storage reservoirs or tanks with a certain storage capacity and outflow characteristics (e.g. 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, 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. These models can be further subclassified as indicated in Table 2 (Nemec, 1987).

The most important performance characteristics of these models and the limitations on their use are briefly outlined in Table 9 (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).

6.7 Physically Based Models Lead to Distributed Parameters

This clearly underlines the 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 above. As also mentioned above, 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). 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 fulfills 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 9. A quite similar model was developed by Kutchment et al. (1983). The CEQUEAU model (Girard et al., 1981), its version for smaller mountain basins HYTEL (Kite, 1989) and the Square Grid model (Solomon et al., 1974) belong partly to this group and partly to the next: the semi-distributed models.

6.8 Rationale for Semi-distributed Models

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 became an attractive proposition.

The composition of a river-basin model which takes this sub-zoning into account is the substance of the semi-distributed models as briefly described below. When considering the sub-zoning, it is necessary to define first the different types of sub-area to be separately modelled. First this consists in identifying important areal differences in evapotranspiration and direct runoff formation. 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 4.

6.9 Examples of Semi-distributed Models

Existing examples of semi-distributed river-basin models are: specific version of the TANK model (Sugawara et al., 1984), however this model cannot be considered as explicitly physically based, the EGMO model (Becker, Pfuzner, 1986), WBCM-2 (Kovar, 1981) and the WATBAL model (Knudsen et al., 1986).

Fortunately, for a number of modeling purposes, some of the sub-processes listed in Figure 5 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.

6.10 Problems of Scales

Thus, as stated above and according to Table 8, the structure and composition of a river-basin model is strongly dependent on the purpose and objective of its application. 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 4) with river-basin models for the inflowing rivers and their catchments (SA or CB). The definition of what is meant by larger or smaller is of course very relative.This will be considered in more detail below.

It will be recalled that this study is concerned with the evaluation of models that could be used in Switzerland's basins of the Rhine, in alpine, prealpine and low-lands contributing areas. The focus of the study is on water balance models that could be used for evaluation of impact of climate input variation (change) on water balance in basins of different scales. In the two requirements is an inherent difficulty. The climate impact is basically on a large geographical scale while the hydrological modeling of small alpine basins and large lowland basins will be governed in many models by different principles. A fully distributed model will be difficult to apply in a large basin for lack of input data, yet an integration of small areas cannot constitute by averaging a model of the large basin. The problem of the scale is thus important for the evaluation.

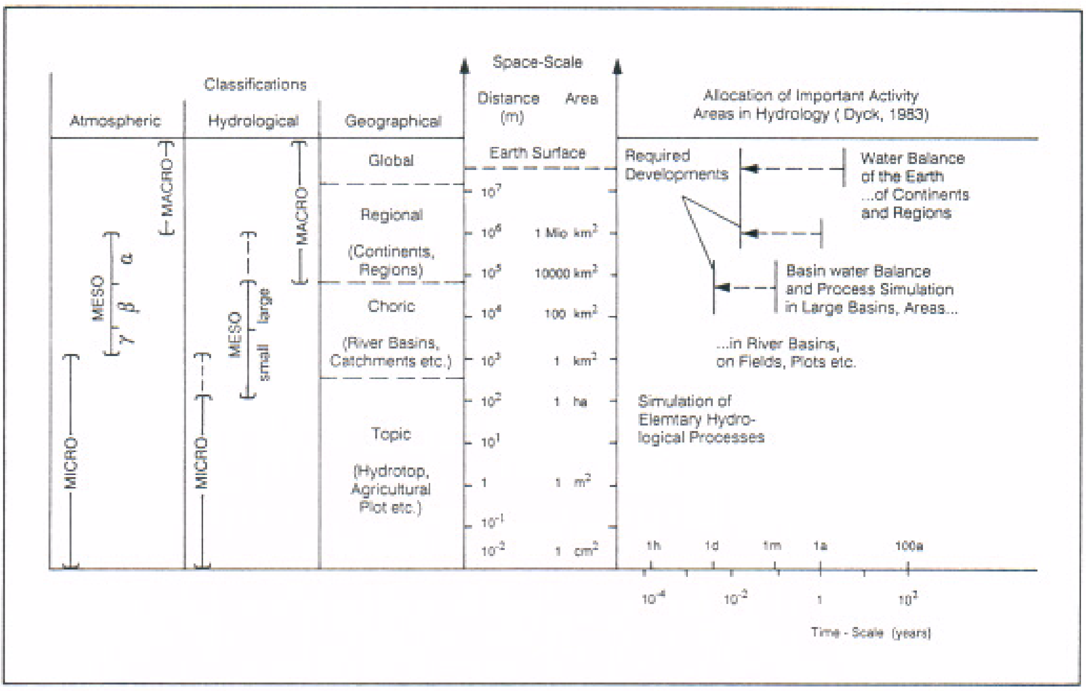


Fig. 6 Classification of scales and allocation of important activities areas in hydrology

Indeed the distributed physically based models, in particular these which apply differential equations of the physical continuum to the hydrological processes are lacking on one side sufficient input data and on the other hand reliable feedback processes in space and in time. The reasons of this scale problem have been the subject of consideration on different occasions and in different recent papers. Thus at the occasion of a Symposium on Remote Sensing in 1990 in the Netherlands it was stated that "the requirement of the ideal model to be suitable for short-term and long-term processes as well as for micro-scale and macro-scale is at present still an illusion" (Schultz, 1990). "Models for short term processes in micro scale systems exist ...while models for the other extreme, long term models for macroscale systems do not yet exist." And the author continues: "Between existing micro-scale and not existing macro-scale model also models on the meso-scale (order of magnitude 100x100 km) are under development". The problem is illustrated by Figures 6 (Becker,Nemec, 1987, after Dyck,1986) and 7 (Schultz,1990).

6.11 Use of Remote Sensed Data

The remote sensed data aspect illustrated in Fig. 7 is documented (Schultz, 1990) in the statement: "Experience shows that it is not possible to extend microscale models based on e.g. Landsat pixels just to larger areas." This and also the creation of the so called macro pixels was tried in the author's institute and was proven ineffective. Such macro- pixels do not show an "average" behaviour, neither in soil type nor in land use, vegetation, slope exposition, drainage system etc. The author finally suggests that in addition to macro-scale models the concept of "hydrological units", explained above in connection with semi-distributed models, becomes attractive for meso-scale modeling.

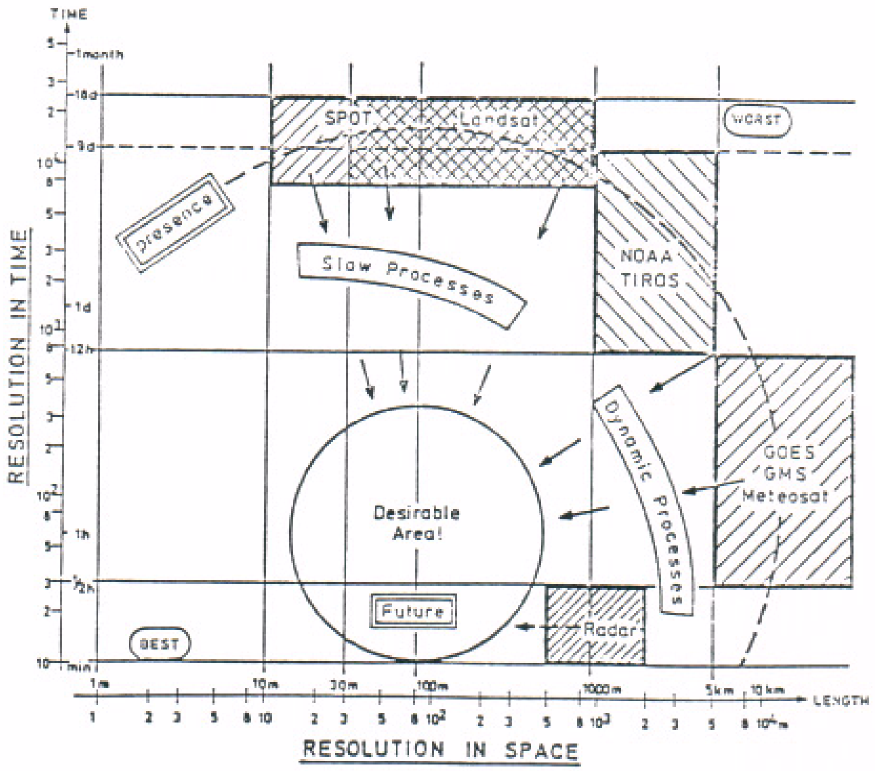


Fig. 7 Space-time grid of resolution of remote sensed data from satellites (Schultz 1990)

7. SELECTION OF THE TYPE OF THE MODEL

In order to proceed with a typological selection it is also noted that the models should allow the evaluation of possible future hydrological changes caused by climate and land use variations and changes in surface water systems and large river basins.The transfer of the model input in time requires that it be physically based.Thus it is obvious that there will be necessary to use a physically based model for a large basin and the results of simulation should be controlled and if needed amended or supplemented on the basis of modelling of smaller basins by physically-based distributed or semi-distributed models of small basins. The compatibility between the scales may be enhanced by using in the large scale modeling also semi-distributed models.

7.1 Meso-scale Model

As will be seen, the choice of large scale physically based models is relatively very small and of these the majority are lumped conceptual models. The disadvantage in this latter type of models is that they do not permit any conclusion on the impacts of such changes in small sub-basins and small areas. Thus a meso-scale model might be the best solution.

7.2 Availability of Models Corresponding to the Selected Type

In the above paragraph a certain selection was already performed on basis of establishing characteristics of the models that should have been identified and discussed by the terms of reference of this study for the Rhine basin in Switzerland. What remains to be demonstrated is that the selection corresponds to the availability of models (to their actual existence). This demonstration is possible by scrutinizing the inventory of all models produced by the inquiry by WMO. In the Appendix 1 to this study is included the inventory in question containing technical information about 200 models of all types, collected trough the HOMS (Hydrological Operational Multipurpose Subprogramme) of WMO, and an inquiry in all countries of the WMO Regions.

7.3 Description of the WMO Inventory of Models

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 3 and Figure 2;
5. Type of system modelled (identifiers of Table 4);
6. Process or variable considered (identifiers of Table 5);
7. Degree of causality according to Figure 3;
8. Applied space discretization scheme according to Table 6 and Figure 3.

A summary of equal identifiers in different columns provides a general overview of the availability of hydrological models with regard to the classification criteria defined. This overview is presented in Table 10 which contains all available information on surface water resources systems and processes models (RR, RL and CS, column 1 of Table 10), and on the models of source areas (SA) and basin areas (CB) of these systems.

(Note: The information presented in columns 15 to 17 of Table 10 on models for variables other than discharges and water levels and is not representative from a general point of view. It is 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.)

Variables		*Surface water levels or discharges Q*												*Others*		
		Purpose of application														
		Forecasting		*Prediction (P)*				*Model type*			*Space discretization*					
Type of system	*Evaluation source*	*Without control* FO	*With control* FC	*Observed conditions* PO OP	*With land-use changes* OL	*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 SA	HOMS	13		6	3	1	1	2	18	8		5	21		1	
	RA	23		11	7		1		30	11	3	1	39		(PL)	
River reaches RR	HOMS	7	1	8		8		15	9	2	13	2	11			3
	RA	16	1	3		6		8	13	3	8		16			PO
Reservoirs, lakes RL	HOMS		1			5	6	3	9		3	2	7	1	1	1
	RA		2			2	1	1	7		1		7	(PD)	(PD)	(FC)
Surface water systems CS	HOMS		1			4	5	5	4		5	2	2		1	
	RA		6			2	1	2	6		3		5		PD	
Large river basins CB	HOMS	8	4	2	3	6	1		20	2		10	12	1		2
	RA	8	16	2	1	4			31			3	28	(FO)		(PD)

Tab. 10 Availability of hydrological models for surface water bodies and systems, surface areas and river basins

8. RECOMMENDATIONS CONCERNING APPLICATION OF IDENTIFIED MODELS

The analysis of Table 10 indicates that the number of concrete models typologically selected in the above considerations is relatively very small. Among the meso- scale models most are conceptual lumped parameters models. The distributed physically based models are usable only in smaller basins.

It is recommended on basis of all the above considerations that the following models listed in the inventory be selected for further development in the basin of the Rhine in Switzerland:

(a) For modeling of small alpine basins the HYDROTEL, a version of the CEQUEAU model for microcomputers. This is a semi-distributed model, permitting use of remote sensed data in a square grid GIS, which is being tested in the Canadian Rocky Mountains. The Appendix 2.1 contains a description of the model (Kite, 1989).

(b) EGMO, another semi-distributed model, developed in Germany, for testing in the sub alpine and valley catchments. Appendix 2.2. contains a description of the model (Becker, Nemec, 1987).

(c) WATBAL, a water balance model of the Danish Hydraulic Institute, to be tested concurrently on the same catchments as EGMO. Appendix 2.3 contains a description of the model (Knudsen et al., 1986).

(d) To model all catchments with the VHB conceptual lumped parameter model (as adapted at ETH Zurich) for output data control and comparison.

(e) It is finally proposed to establish a mesoscale hydrology oriented geographical information system (GIS or data base), which would assist all above modeling efforts as well as those proposed below.

9. DEVELOPMENT OF A MACROSCALE PHYSICALLY BASED MODEL

It is probable that the whole of the basin of the Rhine in Switzerland, and no doubt also downstream, will be incorporated eventually in a macroscale model for the interfacing with a climate model. This would require to develop a macroscale hydrological model. This model cannot be only an extension or integration of the above models, or even much more detailed micro-scale models based on physical continuum. These considerations are only summarizing the views expressed by the co-authors of (Becker, 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.

In the framework of the GEWEX programme of the IAHS and the CLIMATE-WATER programme of WMO, the European efforts of modeling of some large European basins should lead not only to application of existing physically based models, on a coordinated basis, but also to the development of the first European large scale hydrological model to be used as the surface processes validation part of the GCMs and help in the regional assessment of the climate variation and change impact on water resources. It is proposed that Switzerland is in good position to contribute to this effort by developing one version of such model, possibly in cooperation with other European institutions, for example along the lines of Figure 5 and Figure 8, or any other documented proposal.

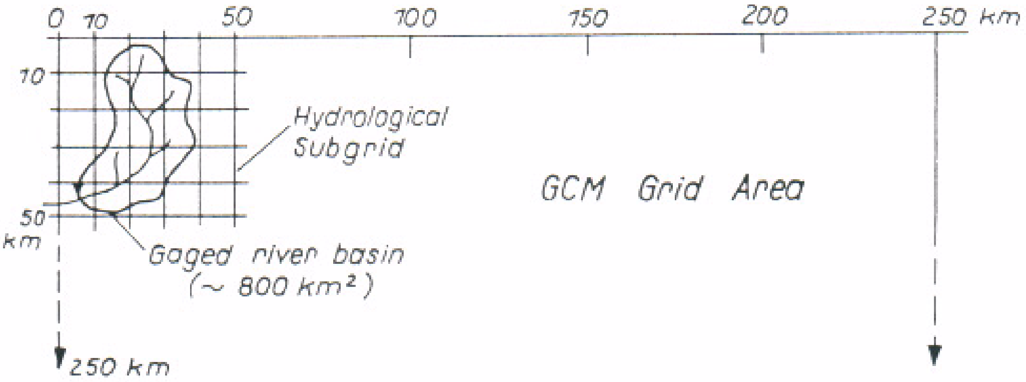


Fig. 8 Schematical representation of a river basin and of a hydrologic subgrid within a GCM grid area

10. ACKNOWLEDGMENTS

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11. SUMMARY

This study is reviewing the models which can be used to simulate the water balance of the basin of the river Rhine in Switzerland. It is examining the models according to criteria of their structure, time step, representation of physical processes, requirements on input data and on hardware and software with a focus on models that can be used for evaluation of impact of climate input variation on water balance in basins of different scale.

To do so it adopts a model classification and inventory included in a recent report of the World Meteorological Organisation. It describes the processes to be modeled, examines the needs for discretization of data in time and space, and selects the type of models needed. On basis of the WMO inventory it recommends identified existing models. It finally proposes the development of a macroscale physically based model.

RÉSUMÉ

Cette étude passe en revue des modèles capables de simuler des bilans hydrologiques dans le bassin du Rhin en Suisse. L'interêt pricipal est leur utilisation pour évaluer l'influence des variations du climat sur le bilan hydrique de bassins de différentes dimensions. On examine ces modèles selon divers critères: leur structure, leur interval d'opération dans le temps, la représentation des processus physiques dans le bassin, leur besoin en données d'entrée, en ordinateurs et en logiciel.

L'étude utilise une classification et un inventaire des modèles qui font partie d'un rapport récemment publié par l'Organisation Météorologique Mondiale (OMM). On décrit les different processus à simuler, on examine les besoins de discrétisations des données dans le temps et dans l'espace et on sélectionne les types des modèles à utiliser pour les besoins susmentionnés. Sur la base de l'inventaire de l'OMM, on recommande des modèles identifiés comme disponibles. En conclusion on propose le développement d'un modèle, à l'echelle macroscopique, basé sur des pricipes de la physique des processus dans le bassin versant.

ZUSAMMENFASSUNG

Die vorliegende Studie gibt einen Überblick über Modelle, welche die Simulation des Wasserhaushaltes im schweizerischen Teil des Einzugsgebietes des Rheins erlauben würden. Sie untersucht die Modelle aufgrund verschiedener Kriterien wie: Aufbau, Zeitschritt, Widergabe der physikalischen Prozesse, Anforderungen an die Eingabedaten, an Hardware und an Software. Das Ziel ist, Modelle zu finden, welche den Einfluß einer Klimaänderung auf den Wasserhaushalt in Einzugsgebieten verschiedener Größe erfassen können.

Die Studie verwendet dazu ein kürzlich in einem Bericht der WMO (World Meteorological Organisation) publiziertes Inventar und eine dazugehörige Klassifikation. Ferner beschreibt sie die zu modellierenden Prozesse, untersucht die notwendige zeitliche und räumliche Auflösung. Darauf basierend wird ein den Anforderungen entsprechender Modelltyp ausgewählt. Ausgehend vom WMO-Inventar werden Empfehlungen für bestimmte bestehende Modelle formuliert. Schließlich wird die Entwicklung eines makroskaligen, physikalisch fundierten (physically based) Modells empfohlen.

SAMENVATTING

Deze studie geeft een overzicht van de modellen die kunnen worden gebruikt voor de simulatie van de waterbalans in het stroomgebied van de Rijn in Zwitserland. Deze modellen zijn onderzocht op hun opbouw, de gebruikte tijdstap, weergave van fysische processen, voorwaarden waaraan inputgegevens, hardware en software moeten voldoen. Daarbij werd vooral gekeken naar modellen die geschikt zijn voor het evalueren van het effect van klimaatveranderingen op de waterbalans in stroomgebieden van verschillende grootte.

Voor deze studie is gebruik gemaakt van een modelclassificatie en -inventarisatie uit een recent rapport van de Wereld Meteorologische Organisatie. De te modelleren processen worden beschreven en de behoefte aan ruimtelijke en temporele resolutie van gegevens wordt onderzocht. Voorts is het type model dat nodig is voor bovengenoemd doel geselecteerd. Op basis van de inventarisatie van de WMO worden bepaalde bestaande modellen aanbevolen. Tenslotte bevat het rapport een voorstel voor de ontwikkeling van een grootschalig, fysisch model.

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Appendix 1

MODELS AVAILABLE AS HOMS - COMPONENTS

			Model classification criteria(+)				
Supplier (Country)	Name of the model	Model index	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
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

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

Appendix 1

Model classification criteria

Supplier (Country)	Name of the model	Model index	Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
Colombia	**MODRIE** model for operation	CO1	FO	SA	ES	DC	LO
	CAHYDRO model	CO2	OP	SA			
Czecho-slovakia	DC2 **Hydrodynamical** river model	CS1	FO	RR	QF	DL	IG
	NONLIN nonlinear cascade hydrological model	CS2	FO	RR	OF	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	DCIS
	NAM General purpose rainfall/runoff model	DK2	PO	SA	QF	DC	LO
	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

Appendix 1

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	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
	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 for 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
	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

Appendix 1

			Model classification criteria				
Supplier (Country)	Name of the model	Model index	Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
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
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

Appendix 1

			Model classification criteria(+)				
Supplier (Country)	Name of the model	Model index	Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
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
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

Appendix 1

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
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
	NWRFRS-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	OF;ES	DC	LS
	NWSRFS-STAT-QME statistical summary – mean daily discharges	US6	OP		OF		
	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				
	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

Model classification criteria(+)

Supplier (Country)	Name of the model	Model index	Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
United States (continued)	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	–
	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 analysis	US25	PD	RR	OF	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

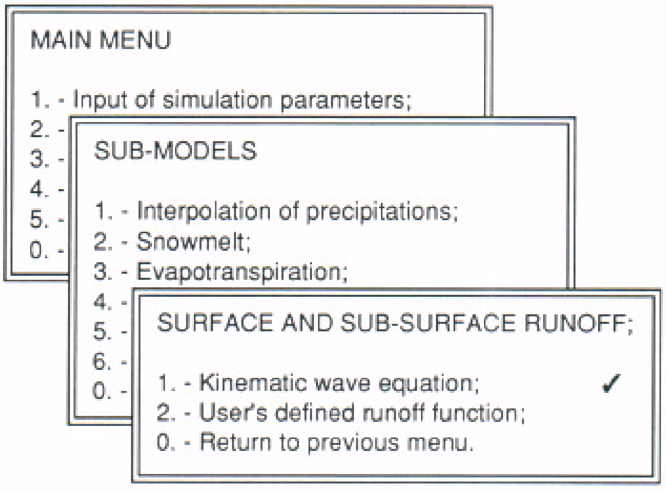
Appendix 1

			Model classification criteria				
Supplier (Country)	Name of the model	Model index	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				
	Sacramento model modifies 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

			Model classification criteria				
Supplier (Country)	Name of the model	Model index	Purpose	Type of system	Variable	Degree of Causality	Space discretization
1	2	3	4	5	6	7	8
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

HYDROTEL MODEL

The HYDROTEL model was developed by the Canadian INRS-EAU at the University of Quebec (Fortin et al., 1988). It is a simplified PC version of a distributed, square grid based model CEQUEAU developed by Girard and Fortin in the seventies. The CEQUEAU model participated in both WMO intercomparison projects. The HYDROTEL model was lately considered for modeling of several high mountains basins in Canada with the help of satellite data on snow cover and snow water equivalent (Kite, 1989).



MAIN MENU

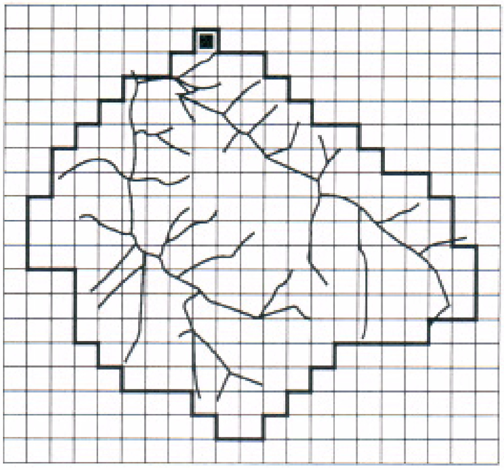
1. - Input of simulation parameters;
2. -
3. -
4. -
5. -
0. -

SUB-MODELS

1. - Interpolation of precipitations;
2. - Snowmelt;
3. - Evapotranspiration;
4. -
5. -
6. -
0. -

SURFACE AND SUB-SURFACE RUNOFF;

1. - Kinematic wave equation; ✓
2. - User's defined runoff function;
0. - Return to previous menu.



Easting: 303000
Northing: 5025000

Altitude: 3.8e+002
Slope: 2.e-002
Aspect: 6
Reach: -1

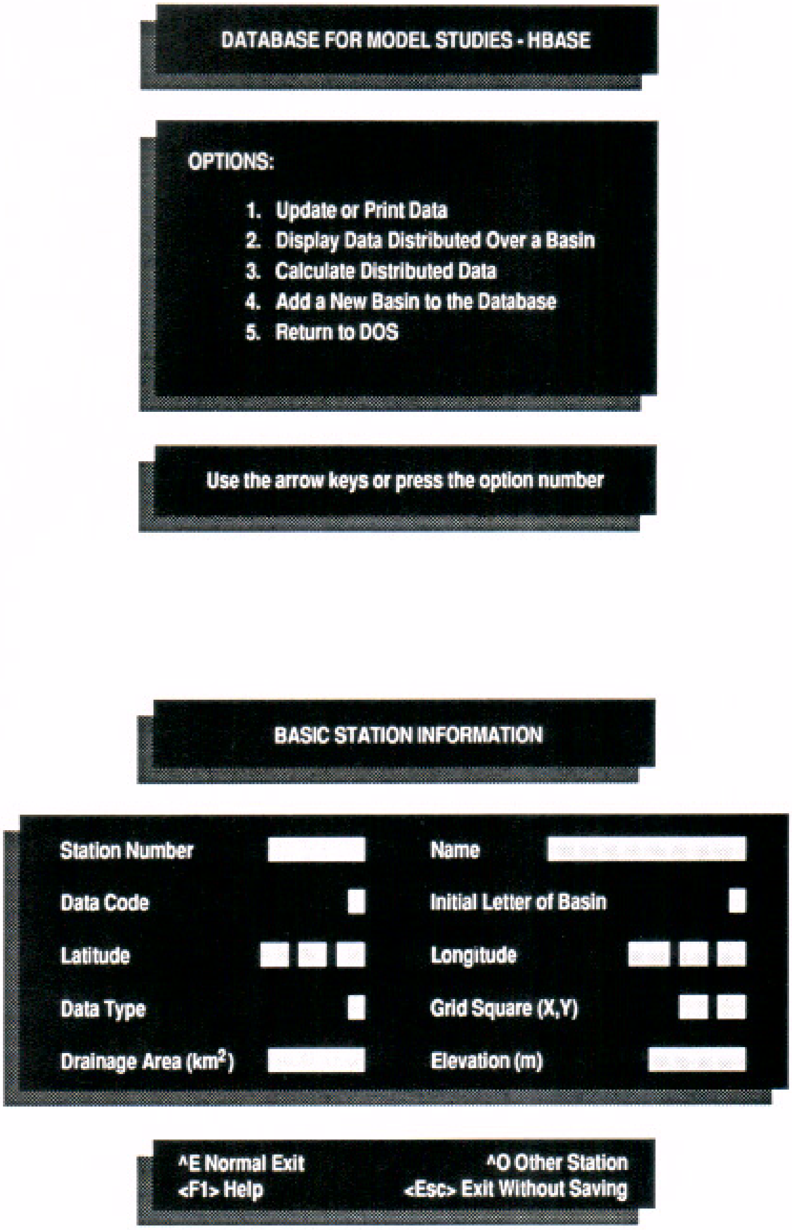
Year: 72
Day: 152

Temp: 0.
Rain & Melt: 0.
Etp: 0.
Outflow: 1.9e-003
Runoff: 7.71e-006

F1: Step F5:Go

Fig. 2.1.1 HYDROTEL model menue system

The HYDROTEL model operates on a menu system, the user selecting the required operations of the model and specifying the necessary parameters (Fig. 2.1.1). A basin "mask" defines the arrangement of grid squares over the basin and further computer files define the channel reaches and the channel nodes. During a simulation run, the user can display the status of the variables and parameters for any grid square, channel reach or channel node at successive time steps. The use of this model was enhanced by a development by Kite (1989) of a data base system for distributed data over the grid squares including precipitation, temperature, snow depth, elevation, slope, aspect and landuse types (Fig.2.1.2).



```
DATABASE FOR MODEL STUDIES - HBASE

OPTIONS:

        1.  Update or Print Data
        2.  Display Data Distributed Over a Basin
        3.  Calculate Distributed Data
        4.  Add a New Basin to the Database
        5.  Return to DOS

Use the arrow keys or press the option number
```

```
BASIC STATION INFORMATION

Station Number                      Name
Data Code                           Initial Letter of Basin
Latitude                            Longitude
Data Type                           Grid Square (X,Y)
Drainage Area (km²)                 Elevation (m)

^E Normal Exit                      ^O Other Station
<F1> Help                           <Esc> Exit Without Saving
```

Fig 2.1.2 HYDROTEL database

EGMO SYSTEM

The EGMO (from Einzugsgebietmodel) or CAMOS (from Catchment Model System) includes a semi-distributed hydrological model, originally designed for flow forecasting and later developed into a system with several submodels, which permit simulation of hydrological processes in basins of different types for different purposes. The system includes several procedures for data management, parameter optimization and validation and output formating. The time step of the operation of this system is selected by the user. Thus if daily values are to be simulated (for forecasting purposes mainly) the model version EGMOF is selected, if ten days or monthly periods are simulated (for long-term water balance purposes mainly) the EGMOD version is available. The system was developed for physiographic conditions of East Germany, but the flexibility of the system permits its adaptation, by insertion of different sub-models, to other climatic and physiographic conditions.

The EGMOF is the basic model which was later adapted into EGMOD version. Both version acknowledge the importance of the horizontal water flow in the catchment but in EGMOD, serving mainly for long-term water balances simulation, this flow is given less computational space.

The vertical movement of moisture is in both versions represented by (see Fig. 2.2.1):

- an interception submodel;
- a soil moisture transport submodel,based on capillary movement, which is spatialy distributed, using the field capacity as a distribution parameter, creating thus different zones (source zones, sub-areas);
- soil moisture and ground water storage submodels for each zone (thus distributed as well);
- submodels for direct surface runoff formation from different zones in periods of intensive or long lasting rainfall and snowmelt;

The above vertical movement submodels are supplemented by routing submodels for surface and groundwater (recession) flows.

The concept of zones (subareas) makes of this system a semi-distributed one and some of the parameters are taken from data in situ, thus they are physically based. The characteristics of the zones are in the following table:

Zone characteristic	Symbol	ETP	Direct runoff formation
Free water surfaces	AW	potential	100% of precipitation
Impervious	AIMP	low	near 100% of precipitation
near ground water	AN	near potential	from saturated soil
far from ground water	AG	depending on soil moisture	near zero
slope surfaces	AH	depending on soil moistuire	interflow

The sum of the zones (subareas)is the area of the basin (A = 1).

Each zone can have one or two components of outflow. In case of mountaineous basins this number may be increased. It should be however noted that with the existence of four types of zones with runoff, there are already four different types of outflow.

The input variables are precipitation and potential ETP. The model applies a seasonal correction to both (the ETP being calculated according to TURC formula).

The EGMOD version, using 10-30 days time step omits all submodels based on short term processes, such as interception and surface retention, infiltration from intensive rainfall.

Appendix 2.2

On the other hand the EGMOD version has a submodel of long-term recession flow, which divides the simulation in periods of precipitaton and runoff formation and of basin depletion expressed in a season dependent exponentially decreasing curve.

Most of the parameters are however the same for both versions and there is a possibility to use the two versions, if necessary, in an interchanging way.

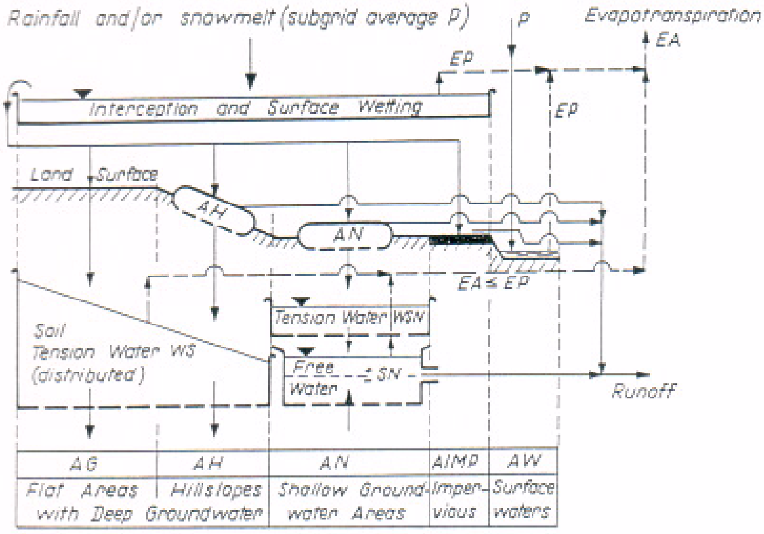


Fig. 2.2.1 Schematical representation of water storage and fluxes in a subgrid area (hydrologic first-level model) according to the EGMO-system conception

WATBAL SYSTEM

A semi-distributed, physically based hydrological system.

This system was proposed and used by the Danish Hydraulic Institute (Knudsen et al., 1986) as a compromise between lumped conceptual approach (such as is the Stanford model) and a physically based, fully distributed representation of the catchment hydrology such as in the SHE model. The main attention in WATBAL is given to the root zone - or to the vertical moisture movement - through a distributed, physically based approach. The ground water - or the horizontal moisture movement - is treated as a lumped process. This allows to introduce a rather detailed spatial variability of meteorological conditions, of vegetation and soil properties, which allows for the introduction of satellite data and/or GIS based information in general.

The general structure of fluxes and storages is represented on Fig. 2.3.1. The distributed character of the model appears on Fig. 2.3.2. The simulation of the land phase of the hydrological cycle by WATBAL is represented in the flowchart on Fig. 2.3.3. The model uses five connected storages: interception, surface detention, soil moisture, subsurface and groundwater storages. Each hydrological unit (source zone) has a separated interception and soil moisture storage, each topographical zone (as defined by the user) has only one surface and subsurface storage, the groundwater storage is only one for the whole basin, replenished from several subsurface storages.

The following processes are mathematically represented by sub-models :

- interception, by a variable leaf-area index;
- infiltration, by Green-Ampt formulation using pre-ponding and postponding stages. This model was validated by experiments in the field and can be adapted to heterogenous soil profiles and variable intensity of rainfall;
- overland flow, by hydraulic formulation of turbulent flow similar to this used in the Stanford model. It is different for each topographical zone;
- soil moisture; a two bucket (layers) model is used. Both buckets are filled by water balance computing from infiltration, actual evapotranspiration and percolation to ground water.
- actual evapotranspiration, calculated from the potential one by the Kristensen and Jensen model. Potential evaporation is considered as an input (on a monthly step at least) and is applied directly to the interception and surface storages.
- subsurface and groundwater storages, represented as linear reservoirs,the first with two outlets,the second with one only.

Table 2.3.1 includes a list of all parameters of the Watbal system in its complete version. The authors stress the flexibility of the system, which permits to use mean values for some data, if in situ measured data are not avaliable, or omit the simulation of some processes, if they are not essential for the desired purpose. Daily series of rainfall data are required. If detailed simulation of infiltration and surface runoff is selected (for flood prediction), intensities of rainfall for given durations are also necessary.

The authors have tested the system in Europe and Africa, in particular with respect to transferability to ungaged basins. Data from LANDSAT were also used in this testing.

Appendix 2.3

TOPOGRAPHY	Within each topographic zone:	length of flow plane slope Manning number depression storage
VEGETATION	For each type of vegetation:	leaf area index (time varying) root depth (time varying)
SOIL TYPES	For each texture class:	wilting point field capacity total porosity saturated conductivity average suction
SUB-SURFACE REGIME	For each topographic zone	threshold value two time constants (interflow/percolation outlets)
	Groundwater storage	groundwater area relative to catchment area time constant of base flow outlet

Tab. 2.3.1 Model parameters for the most advanced mode of operation of WATABAL

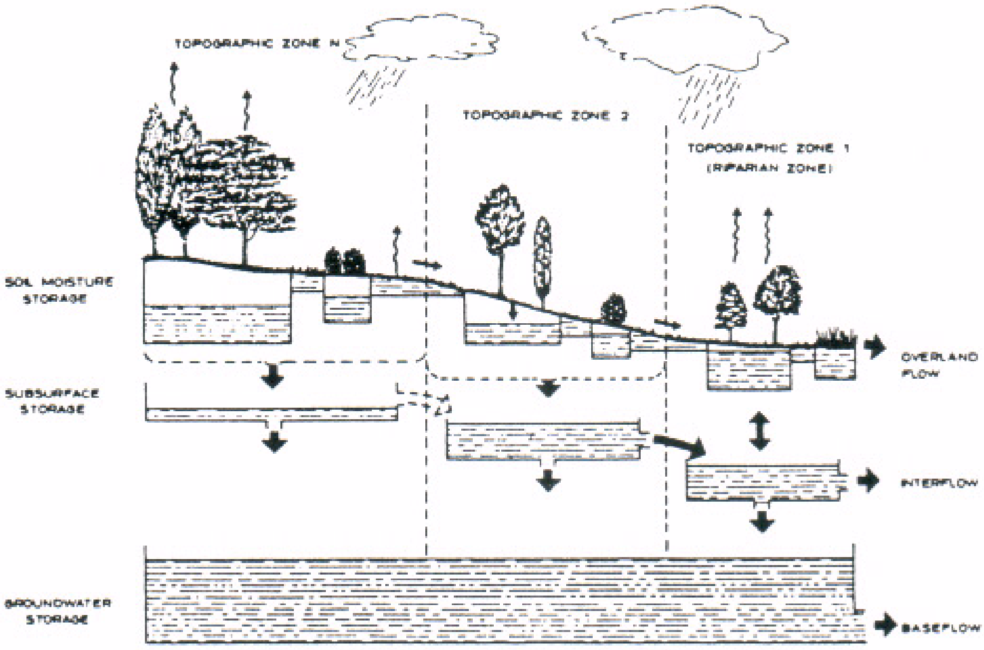


Fig. 2.3.1 Principal structure of WATBAL

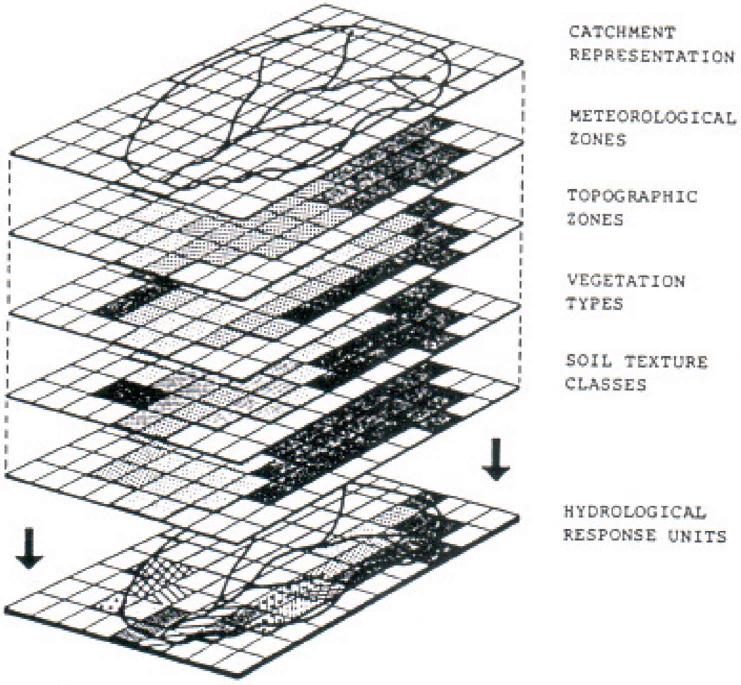


Fig. 2.3.2 Representation of catchment characteristics and definition of hydrological response units

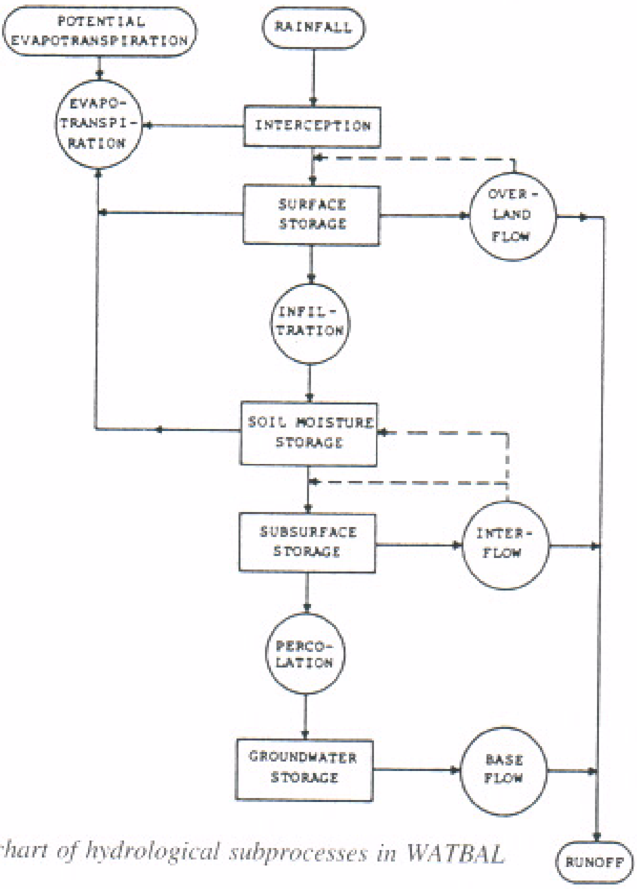


Fig. 2.3.3 Flowchart of hydrological subprocesses in WATBAL

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Le bassin du Rhin. Monographie Hydrologique. Staatsuitgeverij, La Haye. ISBN 90-1201-775-0

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I-2 GERHARD, H.; MADE, J.W. VAN DER; REIFF, J.; VREES, L.P.M. DE (1983): Die Trocken- und Niedrigwasserperiode 1976. (2. Auflage 1985)/
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ISBN 90-70980-17-7

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II-1 MADE, J.W. VAN DER (1982): Quantitative Analyse der Abflüsse (nicht mehr lieferbar)/
Analyse quantitative des débits (édition épuisée)

II-2 GRIFFIOEN, P.S. (1989): Alarmmodell für den Rhein/
Modèle d'alerte pour le Rhin. ISBN 90-70980-07-x

II-3 SCHRÖDER, U. (1990): Die Hochwasser an Rhein und Mosel im April und Mai 1983/
Les crues sur les bassins du Rhin et de la Moselle en avril et mai 1983. ISBN 90-70980-09-6

II-4 MAZIJK, A. VAN; VERWOERDT, P.; MIERLO, J. VAN; BREMICKER, M.; WIESNER, H. (1991): Rheinalarmmodell Version 2.0 - Kalibrierung und Verifikation/
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Analyse des coûts et des bénéfices pour le projet d'un réseau hydrométrique. ISBN 90-70980-14-2

II-6 CHR/KHR (1992): Contributions to the European workshop Ecological Rehabilitation of Floodplains, Arnhem, The Netherlands, 22-24 September 1992. ISBN 90-70980-15-0

II-7 NEMEC, J. (1993): Comparison and selection of existing hydrological models for the simulation of the dynamic water balance processes in basins of different sizes and on different scales. ISBN 90-70980-16-9

Einige Informationen über die:

INTERNATIONALE KOMMISSION FÜR DIE HYDROLOGIE DES RHEINGEBIETES (KHR)

Gründung

1970 Im Rahmen der Internationalen Hydrologischen Dekade (IHD) der UNESCO.

1975 Fortsetzung der Arbeiten im Rahmen des Internationalen Hydrologischen Programms (IHP) der UNESCO und des Operationellen Hydrologie-Programms (OHP) der WMO.

1978 Unterstützung der Arbeiten der Kommission durch Austausch einer Verbal-Note zwischen den mitarbeitenden Ländern.

Aufgaben

- Förderung der Zusammenarbeit hydrologischer Institutionen und Dienste im Einzugsgebiet des Rheins.

- Durchführung von Untersuchungen über die Hydrologie des Rheingebietes und Austausch der Ergebnisse diesbezüglicher Studien.

- Förderung des Austausches von hydrologischen Daten und Informationen im Rheingebiet (z.B. aktuelle Daten, Vorhersagen).

- Entwicklung von standardisierten Verfahren für die Sammlung und Bearbeitung hydrologischer Daten in den Rheinanliegerstaaten.

Mitarbeitende Länder

Schweiz, Österreich, Bundesrepublik Deutschland, Frankreich, Luxemburg, Niederlande

Arbeitssprachen

Deutsch und Französisch

Organisation

Ständige Vertreter (Sitzungen 2mal pro Jahr) unterstützt von einem ständigen Sekretariat.
Die Bearbeitung von Projekten wird von Rapporteuren und internationalen Arbeitsgruppen durchgeführt.

Quelques informations sur la:

COMMISSION INTERNATIONALE DE L'HYDROLOGIE DU BASSIN DU RHIN (CHR)

Institution

1970 Dans le cadre de la Décennie Hydrologique Internationale (DHI) de l'UNESCO.

1975 Poursuite des travaux dans le cadre du Programme Hydrologique International (PHI) de l'UNESCO et du Programme d'Hydrologie Opérationnelle (PHO) de l'OMM.

1978 Appui des travaux de la Commission par l'échange d'une note verbale entre les pays concernés.

Tâches

- Encourager la coopération entre les instituts et les services actifs dans le bassin du Rhin.

- Réalisation d'études hydrologiques dans le bassin du Rhin et échange de résultats des études concernées.

- Encourager l'échange de données et d'informations hydrologiques dans le bassin du Rhin (p.ex. données actuelles, prévisions)

- Elaboration de méthodes standardisées pour la collecte et le traitement des données hydrologiques dans les Etats riverains du Rhin.

Pays participants

la Suisse, l'Autriche, la République Fédérale d'Allemagne, la France, le Luxembourg, les Pays-Bas

Langues de travail

allemand et français

Organisation

Les représentants permanents (réunions deux fois par an) sont soutenus par le secrétariat permanent.
Les études sont réalisées par des rapporteurs et des groupes de travail internationaux.

Auswahl der laufenden Arbeiten

»Änderungen im Abflußregime«

- Beschreibung des Einflusses der menschlichen Aktivitäten auf die Rheinabflüsse.
- Bestimmung der Auswirkungen von Bodennutzungs- und Klimaänderungen auf das Abflußregime des Rheins.
- Untersuchungen über Auswirkungen des Waldes auf den Wasserhaushalt.

»Fließzeiten«

- Ermitteln von Fließzeiten und Stofftransport im Rhein zur Verbesserung des Rheinalarmmodells (in Zusammenarbeit mit der IKSR).

»Sediment«

- Verbesserung und Standardisierung der Verfahren zur Messung von Schwebstoffgehalten und Bodentransport des Sediments.
- Beschreibung des Sedimenthaushaltes im Fluß.

»Fortschreibung der Monographie«

- Übersicht hydrologischer Daten über die Perioden 1971-1980 und 1981-1990 als Fortsetzung der im Jahre 1978 veröffentlichten Monographie »Das Rheingebiet«.

Fertiggestellte Arbeiten

siehe Publikationsliste, Seite 70.

Principaux thèmes en cours

«Changements dans le régime des débits»

- Description de l'impact des activités humaines sur le débit du Rhin.
- Détermination des effets des changements du climat et de l'utilisation du sol sur le régime des débits du Rhin.
- Etude de l'influence du forêt sur l'hydrologie.

«Temps d'écoulement»

- Détermination des temps d'écoulement et de transport des substances dans le Rhin pour l'amélioration du modèle d'alerte du Rhin (en collaboration avec la CIPR).

«Sédiments»

- Amélioration et standardisation des méthodes pour la mesure des matières en suspension et du charriage de fond.
- Description de la situation de la sédimentation dans le fleuve.

«Actualisation de la Monographie»

- Données hydrologiques sur les périodes 1971-1980 et 1981-1990 complétant celles de la monographie hydrologique «le Bassin du Rhin» publiée en 1978.

Travaux effectués

voir la liste de publications, page 70.

Some information on the:

INTERNATIONAL COMMISSION FOR THE HYDROLOGY OF THE RHINE BASIN (CHR)

Foundation

1970 Within de framework of UNESCO's International Hydrological Decade (IHD).

1975 Continuation of activities within the framework of UNESCO's International Hydrological Programme (IHP) and the Operational Hydrology Programme (OHP) of WMO.

1978 Support of the Commission's activities by exchange of a verbal note between the participating countries.

Tasks

- Support of co-operation between hydrological institutes and services active in the catchment area of the Rhine.
- Executing hydrological studies in the Rhine basin and exchange of research results.
- Promoting the exchange of hydrological data and information in the Rhine basin (e.g. current data, forecasts).
- Development of standardized methods for collecting and processing hydrological data in the Rhine riparian states.

Participating countries

Switzerland, Austria, Federal Republic of Germany, France, Luxemburg, the Netherlands

Working languages

German and French

Organization

Permanent representatives (meetings twice a year) supported by a permanent secretariat. Studies are carried out by rapporteurs and international working groups.

Enige gegevens betreffende de:

INTERNATIONALE COMMISSIE VOOR DE HYDROLOGIE VAN HET RIJNGEBIED (CHR)

Oprichting

1970 In het kader van het Internationaal Hydrologisch Decennium (IHD) van de UNESCO.

1975 Voortzetting van de werkzaamheden in het kader van het Internationaal Hydrologisch Programma (IHP) van de UNESCO en het Operationeel Hydrologisch Programma (OHP) van de WMO.

1978 Ondersteuning van het werk van de Commissie door een nota-uitwisseling tussen de samenwerkende landen.

Taken

- Bevordering van samenwerking tussen hydrologische instituten en diensten in het stroomgebied van de Rijn.
- Uitvoeren van hydrologische studies in het Rijngebied en uitwisseling van de onderzoeksresultaten.
- Bevorderen van de uitwisseling van hydrologische gegevens en informatie in het Rijngebied (bijv. actuele gegevens, voorspellingen).
- Ontwikkeling van standaardmethoden voor het verzamelen en bewerken van hydrologische gegevens in de Rijnoeverstaten.

Deelnemende landen

Zwitserland, Oostenrijk, Bondsrepubliek Duitsland, Frankrijk, Luxemburg, Nederland

Voertalen

Duits en Frans

Organisatie

Vaste vertegenwoordigers (vergaderingen tweemaal per jaar) ondersteund door een permanent secretariaat. Onderzoeken worden door rapporteurs en internationale werkgroepen uitgevoerd.

Selection of current subjects

'Changes in the discharge regime'

- Description of the impact of human activities on the Rhine discharges.
- Determination of the effect of changes in land use and climate on the discharge regime of the Rhine.
- Research into the effects of forest on the hydrology of the basin.

'Travel times'

- Determination of the travel times and constituent transport in the Rhine for the improvement of the alarm model for the Rhine (in co-operation with CIPR/IKSR).

'Sediment'

- Improvement and standardization of methods to measure suspended load and bed-load transport.
- Description of sediment characteristics of the river.

'Continuation of the Monograph'

- Hydrological data for the periods 1971-1980 and 1981-1990 as a continuation of the hydrological monograph 'The Rhine basin' published in 1978.

Completed projects

see list of publications, p. 70.

Belangrijkste lopende onderzoeken

"Veranderingen in het afvoerregime"

- Beschrijving van de invloed van menselijke activiteiten op de Rijnafvoeren
- Bepaling van de invloed van veranderingen in bodemgebruik en klimaat op het afvoerregime van de Rijn.
- Onderzoek naar de invloed van bos op de waterhuishouding.

"Stroomtijden"

- Bepaling van de stroomtijden en stoftransport in de Rijn ter verbetering van het alarmmodel voor de Rijn (in samenwerking met de IRC).

"Sediment"

- Verbetering en standaardisering van meetmethoden voor gehalten aan zwevend materiaal en bodemtransport.
- Beschrijving van de sedimenthuishouding in de rivier.

"Voortzetting Monografie"

- Overzicht van hydrologische gegevens over de perioden 1971-1980 en 1981-1990 als voortzetting van de in 1978 uitgegeven hydrologische monografie "Het stroomgebied van de Rijn".

Afgesloten onderwerpen

zie lijst van publikaties, blz. 70.