6 SIMULATION MODELS OF WATER RESOURCE SYSTEMS

The advances in computer techniques have created the possibility to construct models of large-scale and complex systems. In most cases the optimization methods of operations research cannot be used for the solution of the issues involved in these systems, and therefore the use of simulation models employing digital computers is the basic technique for modelling these systems. The problems of water resource systems are typical of large-scale and complex systems, and simulation models have found many applications in this field.

6.1 THE TERM SIMULATION MODEL

Generally, the term *simulation* refers to the technique used for the evaluation of the consequences of some decision without its being implemented in the real system concerned. This definition (Habr and Vepřek, 1973) is somewhat too general for water resource systems and applies to a broader meaning of simulation. Such a concept includes managerial games which simulate a certain economic situation when the participants have to react according to their strategies, analogue models which may be either physical models of water supply and irrigation networks etc., or analogue simulation models which may provide a method of obtaining an approximative solution to the sets of complex integral and differential equations. The simulators used for training drivers, astronauts, etc., likewise refer to this broader meaning.

In water resource system design the term simulation is used in a narrower sense as a modelling technique in which the operation of the water resource system is represented by mathematical and logical relationships in a chosen time step based on specific inputs (inflows of water into the system, demands for the supply of water and for water-derived products and services), capital costs of hydroelectric power plants, capacities of diversion tunnels, etc., and on some predetermined operational policy.

This definition can be expressed in the following concise way: a *simulation model* of a water resource system is a mathematical technique expressing by arithmetical and logical procedures (algorithms) the dynamic behaviour of the water resource system in discrete time steps.

A simulation model describes the relationships among the elements of water resource systems that can be arranged in three classes, i.e. (1) *water engineering constructions*, with one or several characteristic parameters, (2) *natural water resources*, described by time series of flows and by the variables expressing the quality of water and (3) the *requirements for water in the water resource systems.* These requirements can be constant or variable, with some trend component; they may register cyclic variations, and/or they can have a stochastic component such as the requirements for water for irrigation (Kos, 1969a, 1970, 1982).

In principle, a simulation model of a water resource system is the simulation of its operation (with a defined operational policy) on the basis of a time series of flows and/or the variables describing water quality, with predetermined parameters of water engineering structures and other facilities, and demands for water resource systems. The correctness and variables of the parameters chosen are assessed by the *objective function*, consisting of technical quantities and their reliability in different forms and/or economic quantities.

The simulation model consists of *procedures* expressed by precise relationships and symbols describing a certain system, including its elements and their interrelations, and in this way simulates a real situation. The operations are usually expressed in flow-charts, and in a procedural language that is able to describe the *algorithm* of input-data processing and their transformation into output information. The prediction of the consequences of decisions (in the form of parameters of the system) is performed in procedural steps based on input data.

Since simulation models do not use an explicit mathematical, analytical procedure for the determination of the combination of the controlled variables, it is necessary to proceed by trial and error or by the *strategy of parameter sampling.* The structure of the simulated system is so complex that its analytical expression is not possible. Otherwise, a simulation model would not be used.

Simulation models are suitable for all issues of water resource systems with interrelations among variables that can be correctly described by arithmetical and logical expressions. A practically feasible simulation model needs a required amount of *input data* including time series of appropriate duration. These data should reflect the dynamic and often stochastic properties of the simulation process.

Simulation modelling is rather expensive in terms of both model preparation, and programming (however, this part of the costs may be significantly reduced by the use of procedures and simulation languages like SIM-WRS), input-data processing and the cost of the computer time necessary for the computation of alternatives during the search for the optimum solution. The advantage of the simulation model, however, lies in its relatively accurate description of the simulated reality; the method is suitable for communication between technicians as it uses the same principles as the traditional concept of water resource system design, and the output of the simulation models complies with familiar ideas. Simulation is reproducible and therefore it is easy to check. With respect to these properties, engineering estimation and intuition can be used in processing and in the choice of alternative simulation models, and thus the number of computer runs can be reduced.

6.2 PROPERTIES OF SIMULATION MODELS

Simulation models can be classified as *static* or *dynamic*. Dynamic models correspond to the development of human society. Such models take into account the changing parameters of water engineering structures and facilities and the variations in their operation. In view of the long economic lifetime of these facilities, and depending on the difficulties in the application of dynamic changes, it is often possible to use static models with good results. The simulation model of a water resource system is considered a dynamic one if the operational policy can be dynamically adjusted and if such adjustments correspond to the system demands and related changes in system parameters.

Deterministic and *stochastic* simulation models are distinguished by the relationship of the model to the concept of probability. Real situations have a stochastic character. Therefore, Vepřek (1970) defined simulation in a strick sense with reference to the Monte Carlo method and issues of random processes. However, under certain conditions deterministic simulation models may be used. If gauged monthly flows for a period of 40 years, for example, have been used as input variables, the simulation model is called deterministic. Series of gauged flows represent a sample of the stochastic process. If such a sample is used alone and if it can be considered a correct basis for characterizing the stochastic process, the output variables are defined by given input parameters and the operational policy of the system. However, such a modelled process is not deterministic, and the future operation of the simulated system will differ from the operation obtained by the deterministic model.

If phenomena of sufficient frequency in the observed series are simulated, it may be assumed that the differences between the real values and the values determined by the deterministic model will be small so that the deterministic model can be considered a reliable approximation of reality. For phenomena of relatively low frequency (e.g. if a 97–99% reliability is required) there is some danger of underestimation of the dimensions of water engineering structures if only the historical sequence of flows is considered (Kos, 1975).

Two principal methods are used to account for stochastic properties in the simulation model:

– the synthetic flows generated by methods of stochastic hydrology are applied as input values,

– the simulation model is combined with other models that permit a stochastic solution (e.g. the chance-constrained model, Kos, 1975, etc.).

The aim of *stochastic hydrology* is to generate an unlimited number of realizations of the stochastic process on the basis of the gauged time series, which is a realization of the same process. The series generated should not be distinguishable from the series of gauged flows obtained by the methods of mathematical statistics.

Furthermore, a *degree of aggregation* can be used for the classification of simulation models. The simulation model with a detailed discriminative level (i.e. with a low degree of aggregation or high level of detail) is suitable for the investigation of the operation of existing water resource systems, particularly for systems in which gross errors in operational policy have been corrected after a sufficiently long transition period. The objective of such a model is the improvement of the system operation. Beard, 1975, published the results of a case study investigating a system consisting of 20 reservoirs, 12 hydropower plants and a system of thermal power plants. In this case a model with a rough discriminative level would not be able to improve the operation. It would tend to impair it, even if the computed values for the "optimal" solution seem to offer better results. A rough, highly aggregated model would not be able to reflect the specific heuristic policy successfully applied in the operation. A very detailed and precise algorithm had to be chosen for the description of power generation to serve power–system loads with the allocation of hydropower to "peaking" operation, taking into account the second main objective of the described system, i.e. flood control. The desired change in operation was to increase flood-control storage at times when floods are most severe and to increase active storage at other periods.

On the contrary (Jacoby and Loucks, 1972), simulation models with much more aggregated data are appropriate for the design of water resource systems as used, for example, in the investigation of the Delaware River Estuary in combination with analytical optimization models.

In Czechoslovakia, simulation models were used in case-studies of the General Water Plan (1976) and in many projects (Kos, 1970). In the General Water Plan the models encompassed entire basins and the main aim of the investigation was to plan water resource system development; therefore a medium level of aggregation was used. Demands for water supply were investigated in detail, and the optimization of operational policy was performed to the degree that was necessary for proof of design feasibility.

Aggregation of parameters and data is acceptable if it does not create significant deviations from reality. Aggregation simplifies reality. Further simplification can be achieved by *neglecting variables* that do not exercise a decisive effect on the system behaviour (this should be proved by analysis) and by a *change in the form of the variables* (variables which have only an insignificant effect on the output are considered constants). The modelling of a continuous process by a discrete model requires the assumption that the continuous changes during a defined period take place instantaneously at the end or at the beginning of the period.

Simulation models of water resource systems are *discrete* models. The modelled process however is continuous. The decision-making process is discrete. Therefore, the *model time step* is an important dimension of the model and great care must be devoted to its choice. This choice depends either on the degree of aggregation or on the time variability of the input information.

A simulation model reflects the processes in water resource systems by a series of "snapshots" in specified time steps. For water supply purposes monthly periods are generally used. These periods make it possible to reflect the seasonal variability of demand and hydrological data. On the other hand, low flows, which determine the output, change only slightly during the monthly period. The differences between the continuous reality and the monthly values in the simulation model are usually lower than the accuracy of the demand data (Kos, 1976).

In Central European conditions monthly periods are too long for flood control. Hourly gauging records are therefore applied. The reduction of the length of time steps requires an increase in their number in the simulation model. Therefore, in many projects of water resource systems, flood control simulation is investigated separately from the simulation of other objectives of the system. The flood control storage of the reservoir is determined on the basis of recorded or generated synthetic floods in one model and a second model serves for water supply and other objectives. This model takes flood control storage capacities into account. Such an approach ignores the flood control effect of active storage; the actual effect is greater than the value given by the simulation model.

6.3 DEVELOPING A SIMULATION MODEL

In developing a simulation model the following steps are necessary:

- definition of the problem,
- determination of model input and output, data requirement, availability and processing,
- description of the water resource system and its hydrological relationships, design of the model,
- definition of the parameters of existing structures, estimation of the design simulation parameters for the first model run,
- design of the operational policy of the system,
- assembly of the computer program,
- debugging of the program, model tests.

6.3.1 Defining the Problem

Defining the problem for a simulation model is a matter of prior systems analysis. This definition is not an isolated act but a continuous process of clarifying objectives and achieving precision, leading from verbal expression to a technical and quantitative specification. Many simulation models have been designed to meet the *satisfaction principle*, i.e. to satisfy some present or future demands on water resources in systems. The objective is to achieve the required results at minimum cost. With such a definition of the objective, the term optimum is reduced to a selection from a given number of alternatives (approx. 40 – 60). In view of the theoretically possible effects, this approach leads to a sub-optimum and represents a certain compromise between the requirements and possibilities created by our present state of knowledge (mainly in the economic field).

Simulation models are concerned with the quantitative aspects of the design and operation of water resource systems. An important characteristic is the ill-defined structure of a system involving difficult quantification of some objectives, such as environmental conservation, which are often expressed only verbally. Nevertheless, they influence the definition of the problem for simulation models. A heuristic approach is useful in this phase of model formulation (Kos, 1970).

A basic requirement in defining the problem, and in the formulation and running of the simulation model, is to *comply with limits*. In processes that cannot be simulated due to lack of input data or an insufficient knowledge of the process investigated (e.g. the determination of the relationship between the value of biological oxygen demand and the discharge) a minimum acceptable discharge is specified. This discharge should maintain, under certain conditions, the required water quality in the watercourse.

During the phase of model creation and definition of the problem, the question of the complexity of the model and its ability to reflect reality should be dealt with. The degree of mathematical complexity of the model aiming at a realistic representation should be considered as part of the decision-making process.

6.3.2 Input and Output Determination

There are two main types of *input data* for the simulation model: (1) the variables given by the natural conditions, e.g. the monthly flows in a system of gauging stations, and (2) parameters of water engineering structures and demands on the system, either existing or in the design stage. The acquisition of good hydrological data is not easy even with a relatively dense hydrological network and sufficiently long time series. The periods of observation often do not coincide for all the stations of the water resource system and the stations may not be located at points required by the simulation model. These discrepancies require *homogenization of the data.* If the records are interrupted and the observation periods are shorter in some stations, the records should be completed with reference to the homogenized period by methods of *hydrological analogy.* Cross-correlations between hydrological stations and meteorological and climatic elements are often applied.

In the course of the processing of observed data anomalies may occur. Sometimes peculiar physical phenomena are found (e.g. a negative contribution of a sub-basin without substantial withdrawals). Therefore, the *compatibility of data* in the system of stations is investigated and the necessary corrections are made. The final step is *space interpolation,* i.e. the transformation of the gauged values into values applying to the sites of reservoirs, diversion points, water quality observation points, etc.

In stochastic simulation models, this transformation of observed data is followed by a second phase aimed at the generation of synthetic flow series or stochastic irrigation water requirements. The methods of *synthetic flow generation* have been developed to such a degree that they are commonly used in simulation modelling (Beard, 1973; Kos *et al.*, 1974).

The generation of synthetic flows for shorter periods (daily or hourly flows) is far less reliable. Some successful approaches have been found in a combination of methods of stochastic and deterministic hydrology for a rainfall-runoff relationship, but the problem of coordinated generation in a system of stations with correct timespace relationships has not yet been solved. The stochastic simulation models of flood control and pumping systems are therefore less reliable than stochastic simulation models of water supply.

The *parameters of the system* include not only the storage capacities of reservoirs but also the acceptable minimum releases from reservoirs, the transfer of regulated flows, or of unregulated flows upstream of reservoirs for the enlargement of basins (transbasin diversion), the requirements for water quality, etc.

The input data include the demands in the demand centres and diversion points where these demands on water resource systems are summarized and covered (together with the minimum discharges) by operation of the systems. The designed capacities of reservoir transfers and diversions are variable, the demands in a static simulation model are constant. Sometimes the demands are variable due to the possibility of allocating some withdrawals to different points of the system or of changing the sites of the structures under design (e.g. thermal power plants).

Water resource balance is often the basis of the determination of demand input data. The demand data are sorted and allocated to demand centres of the water resource system, and their coverage is tested in advance. This test requires the values of the *available firm water supply* consistent with the hydrological constraints at the given point. When these data are not available, they have to be estimated by some of the common methods of water resource analysis (e.g. by Ripple's mass diagram). The accuracy of this estimation is not important, it is simply used for a reduction in the number of simulation runs; underestimation or overestimation becomes apparent from the output of the simulation model.

Sometimes some of the required input data are not available because their acquisition is either not possible or too expensive or there is a shortage of time. Then the model has to be adjusted and redesigned. Even in relatively simple models this may be an unfavourable complication. Therefore, it is necessary to compare the requirements on input data of the water resource system with the possibility of obtaining them in the first step of the system analysis, i.e. in the definition of the abstract system. In this way, the additional adjustments of the simulation model are reduced to a minimum.

The *outputs* of the simulation model are either *technical* or economic. The technical variables comprise the minimum values of reservoir storage, the deficits in the required reservoir releases at demand centres and diversion points, especially deficits in firm water supply. Some deficits cannot be allocated to a particular reservoir as they are covered by several reservoirs in the water resource system. Reliability indices are evaluated on the basis of volume deficits, e.g. their duration in time or their relative frequency (number of years without deficits divided by the number of years in simulation run).

For water power production the following inputs and outputs are used: the maximum and minimum operational storage of the reservoirs, the rated generating capacity, turbine water capacity, the number of hours at full generating capacity, the monthly firm and dump energy, the buffer storage, and in pumped-storage plants, energy storage capability, cycle efficiency, etc.

The recreational benefits are evaluated from the visitors-per-day attendance at recreational facilities and periods with reservoir pools at favourable levels (suitable for swimming, boating, fishing, camping, wind-surfing, etc.). For some purposes dynamic characteristics are important (e.g. the rate of the water pool fluctuation, the average duration of minimum water pool, etc).

The *economic* input parameters include costs of storage, irrigation diversion, power and recreation facilities, etc. The economic output values include the costs of operation, maintenance and replacement of facilities, benefits associated with various levels of firm water supply (for municipal, industrial and irrigational use), hydropower, recreation, reduction of flood flows and low-flow augmentation.

Water resource systems at certain periods fail to meet the targer outputs. Therefore, the simulation model outputs include the water supply deficits for various targets, energy deficits, reservoir level fluctuations, the duration, relative magnitude and total volume of the deficits, and the number of users concerned. The economic consequences of these deficits are evaluated by an economic loss function. With deficits these loss functions are the most important components as they determine the geatest differences between the alternatives. Construction of the loss functions, however, is complicated and practical application is hindered by lack of economic data. In view of this fact, the economic optimization in simulation models in Czechoslovakia has often been reduced to the method of relative efficiency. The costs have been minimized with respect to the claim to meet the demands on the system with a reliability given by certain standards. Now this method is being replaced by a differenciated approach; in the design of some water resource systems (e.g. with the primary goal of municipal water supply) this method is still used and will probably continue to be used in the near future. In other water resource systems (e.g. multipurpose systems with irrigation water demands and environmental objective) methods of decision analysis and total efficiency are implemented.

The greatest progress in economic data acquisition and processing was achieved in water power where costs and benefits from generating capacity and energy are available (Schmidt, 1976).

The methods of Cicchetti *et al.*, 1972, for recreational benefit determination were used in "Model of Comprehensive Water Resource Management, 1968 – 1976", and in the evaluation of the utilization of the South Moravian water resource system for recreation.

At best, the output of the simulation model is a value of a *scalar objective function*, where all the effects on the system have been expressed in financial terms. Such an objective function would be the best criterion for comparing the alternative simulation models. The existence of such a function may be supposed theoretically. In practical applications its construction is obstructed by a lack of data. The output of the simulation model should therefore include several parameters for a multicriterial evaluation by the method of decision analysis.

6.3.3 Description of Water Resource Systems, Simulation and Model Design

In the first place, the description of a water resource system includes a *specification of its elements*. In the design of the simulation model, the list of these elements is reduced to quantifiable elements. This step is not a closed one; during the process of model specification the list of elements is often extended by additional elements

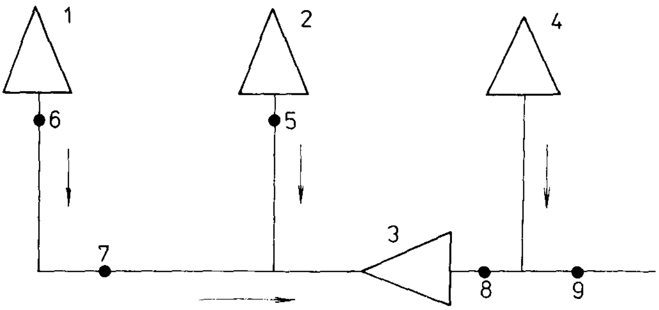

Fig. 6.1 Schematic diagram of the water resource system

(e.g. transfer of water from a neighbouring basin when the hydrological capacity of a particular basin has been exhausted etc.) or is reduced (e.g. some reservoirs are omitted as superfluous for the system).

The *hydrological relationships* between the elements of the system are the other components of the description of the water resource system (Kos, 1967). The schematic diagram of the system (Fig. 6.1) serves as a decription of the basic hydrological relationships especially the movement of water in the system. It contains the basic elements of the system and the directions of the inflow and outflow water. The analysis of water flow helps to identify the connections and cause-and-effect relationships that are used for the description and design of the model. The starting point is usually the demand for water and the water resources are allocated accordingly. In fairly simple systems this process can be carried out by engineering intuition, and, if more resources are available, they may be included in alternative simulation models. In complex systems like the water resource system of the River Delaware (Jacoby and Loucks, 1972) and in the basin of the River Sava (Study of the River Sava, Yugoslavia, 1972), etc., a screening model preceded the simulation modelling. For this purpose, *optimization* by linear programming can be used for water resource allocation to reduce the variety of possible alternatives. However, the linear allocation model is often oversimplified and it has to be complemented and verified by the simulation model.

The description of water resource systems contains the specifications of what is called its *essential environment*. This includes the catchment area or the region where the water resource system is defined, the nature and intensity of agricultural production, soil types (including the texture and structure of soils if water supply for irrigation is a goal of the water resource system) and a brief climatological description of the area.

Towns and cities, especially industrial centres with a *high population density and concentration of activities*, are also demand centres of water resource systems. Therefore, they are included in the essential environment of the systems. Topographical and geological conditions are important for the choice of reservoir sites. They influence the design of a water resource system, so they also form components of its essential environment. The description of the environment of the system includes technical, economic, environmental and social relationships (e.g. economic relationships with different water consumers, consequences of protective measures in the basins of reservoirs for municipal water supply, influence of water resource systems on ecosystems and natural beauty, aesthetic quality of the environment, etc.).

Depending on the definition of the system, the essential environment may include other elements that are not significant for the objectives of the simulation model. For instance, a system of water power plants may be omitted from the water resource system, if it is not important for combination with the thermal and nuclear power plant system and if it does not substantially modify the releases.

Water quality may be included in the environment of some systems. The question is not the importance of water quality in streams but the difficulties of combining quantitative and qualitative aspects in a single model. In such a case, the qualitative model serves for the determination of constraints that have to be considered in the releases in the quantitative simulation model.

The effects of the water resource systems on the environment, e.g. wildlife conservation, fishing, boating and other water-based recreational activities, navigation, river training, etc. are often expressed (for the purpose of simulation modelling) in the environment of the system.

The relationship of the system with its environment is translated into constraints of the model. This process is interactive. If the model runs show that these constraints cannot be compiled with or that they induce high costs, such constraints are often reduced.

In simulation models in Czechoslovakia, the *water supply* for different purposes and low-flow augmentation under certain constraints were the main objectives of the water resource systems. In some systems, water power generation was the objective, in others it formed the constraints. Flood control was investigated in separate simulation models with shorter time steps.

In the design of simulation models it is often advantageous, to subdivide large problems into *subsystems*. Sometimes, however, processing and output and results specification in a single system is easier. Modern computers have a sufficient inner and outer memory for the simulation models of relatively extensive water resource systems. However, systems analysis is very often concentrated on part of the system, and it is not efficient to use the simulation model of the whole system for this purpose. Ways of dividing the system into subsystems are therefore being investigated. Subsystems of large problems can be defined by the following methods:

(1) The first method uses an approach based on the *flow of water particles*. The subsystems are defined on the basis of flow modification. If some groups of elements show few and slight relationships to other elements (they are relatively independent) but the interactions inside these groups are relatively strong and numerous, then a subsystem and a corresponding simulation model can be defined for this group of elements.

(2) The second method of identifying the subsystems is the *functional approach*. This method is recommended if the flow approach fails due to strong interactions among all the system elements. The sequence of functions to be performed for different goals of water resource systems is investigated. The design of a simulation model with a functional approach is scarcely advantageous, since the interactions among the functional groups expressed in flow control complicate the problem, and a simulation model for the whole system seems to be more convenient. An exception is the simulation model for flood control in water resource systems that can be treated as subsystem isolated by the functional approach. A short-term operation has so

many characteristics that the functional approach dominates other views. Although the flood control objective is simulated separately in many water resource systems, methods are being sought to integrate this objective into a single simulation model with variable time advances (steps). In such a model, flood control would not be analysed in detail since the results of a separate functional system would be used, and more attention is paid to the interactions between the flood control and water supply objectives.

(3) The third method, based on the *rhythm of the changes* in the state of the system (state-change approach), is connected with the segmentation into subsystems. In water supply subsystems long-term characteristics are important, whereas in flood control subsystems, short-term characteristics predominate. The rhythm and time advances in the simulation model correspond to this fact. In some water resource systems, some elements (e.g. reservoirs with a long-term operating cycle) show such remarkable long-term effects that the annual flows are more important than their distribution within a year.

In modelling subsystems that are less complex than the systems themselves, some relationships can be expressed mathematically, i.e., analytically. An example is the subsystem consisting of two reservoirs on a river arranged in a close cascade. These reservoirs may be considered as a single reservoir with a storage capacity equal to the sum of the two individual storage capacities. The statistical methods developed for one reservoir (e.g. storage–probability curves), or some special approach, like the chance-constrained model for one reservoir, can be used.

If the system cannot be split into subsystems (where some problems may be investigated in advance), the process of design and application of the simulation model of the whole system is more complex. Even more difficult is the testing of the assumptions and premises of the simulation model and of the effect of parameter changes on the behaviour of the system.

In complex water resources systems, whose effective design and/or operation would be endangered by neglecting important relationships in the subdivision of the problem into subsystems, a simulation model has to be designed for the whole system.

During the design of the simulation model the managers and decision-makers should be informed about the assumptions and premises of the model. They can express certain demands, and the model can be adjusted to meet them. The model provides a new insight into the interrelations between the components of the system. The results of the simulation model can be better interpreted and possible objections forestalled.

6.3.4 Input Parameters of Simulation Models

The *input parameters* are defined as the values that can be changed by the planner, e.g. the design parameters of the reservoirs, capacities of water transfer facilities, values of minimum pools, some water requirements.

The simulation model does not implicitly include the optimization of the system. The optimum is therefore obtained by repeated runs of the model with altered parameters. The parameters are modified to improve the values of the objective function.

The number of possible alternatives is enormous and has to be reduced. Different procedures may be applied. One possibility is to use the results of isolated solutions, i.e. each water management facility is modelled separately to get an idea of its effects on the system. *Operation research* methods, mainly dynamic and linear programming are another possibility. With some simplifying assumptions, the screening of alternatives is carried out to reduce the range of values of the system parameters and the number of their combinations.

During this phase of preliminary investigation the proper definition of the abstract system uses a *rough discriminate level*, so that only substantial features of the problem will be reflected in the model. At the same time, the influence of unquantifiable (environmental, social, aesthetic, etc.) aims on the system parameters is investigated. The purpose of this analysis is to determine input parameters and their range.

The better the combinations of input parameters are estimated, the lower the number of interactive runs of the simulation model. The same number of runs allows either a better approximation of the optimum or the investigation of more alternatives in the case of multi-purpose optimization (the objective function is a vector).

The choice of parameters is complicated by the *stochastic relationship* between the input parameters and the corresponding response of the system. The stochastic nature of the problem is taken into account in the simulation model by the use of the synthetic flows (generated by the methods of stochastic hydrology) and in some WRS by the use of stochastic irrigation water requirements (Kos, 1982) for the input of the model or by combining the simulation model with a method allowing probabilistic evaluation, e.g. with the chance-constrained model. From this aspect, it is useful to start the simulation with the maximum values of the reservoir parameters (or values within the upper third of their range), as the yield of the system is often reduced in the stochastic model (as compared with the deterministic simulation model). This phenomenon may be observed in the combination of relatively high demands on the water resource system with high indices of reliability (e.g. 97 – 99%).

Further allowance should be made for the *dynamic character* of water resource systems. The dynamics of the development is modelled in the dynamic simulation models. In these models, not only the input parameters are considered but also the process of stepwise storage and transfer capacity expansion in relation to growing demands (Kos, 1968).

If relatively low values of some parameters of water resource systems are determined by a preceding investigation, the next step is often a design involving zero values of these parameters, i.e. omitting of the elements concerned. The choice of the correct input configuration of elements is difficult in water resource systems where the capacity considerably exceeds the demand; a large number of elements can be eliminated from the system.

The proposed Danube–Oder–Labe water resource and transport system may influence many water resource systems in Czechoslovakia. The parameters of water resource systems should therefore be designed in alternatives which take this possibility into account. The development of these water resource systems should be reviewed from the standpoint of their future function as subsystems of the general water resource system in Czechoslovakia with the Danube–Oder–Labe canal as the central element.

In hydroelectric simulation models the parameters of reservoirs (dead storage, active storage, flood control storage, reliable minimum release) are followed by parameters characterizing the water power plant. These are: the rated generating capacity, the turbine water capacity, and the maximum and minimum operational pool of the reservoir. Other parameters of the power plant, such as average annual energy production (firm energy and dump energy), number of hours at full generating capacity, service and out-of-service states for all generating units, are output parameters, and they are determined by the simulation runs.

6.3.5 Operation of Water Resource Systems

The operation of water resource system (WRS) requires continual adaptation of its function to variable conditions determined by the environment of these systems. The course of action to meet the objectives of WRS is also influenced by these conditions. This process has to be anticipated in the design of WRS. It is a complex prognostic problem; the more detailed the design is to be, the farther from reality it may turn out. However, an overall estimate of the operation of WRS (e.g. constant minimum releases from reservoirs in drought periods) may be a very rough reflection of the *real operational policy* of a future WRS.

Experience gained from the operation of existing WRS (e.g. WRS in the basins of the Rivers Odra nad Ohře) show that, in simulation models used for design, the operation of WRS can be modelled by a *simplified scheme* using two kinds of time steps: a simulation model with a main water supply objective (long-term operation) in monthly time steps and a simulation model with a flood control objective (short-term operation) in hourly time steps.

The long-term operational policy should contain an allocation of reservoirs in accordance with the objectives of WRS, e.g. which reservoir should release water for river flow regulation in demand centres. Often, there are several reservoirs that can meet the same objective (e.g. river flow regulation). In that case, the *order* (or an algorithm determining this order) in which the reservoirs can be used for this objective must be specified. The operational rule determining priority can be a fixed one, or it can be a function of the storage of reservoirs (absolute or relative), of the month, or of the demand centre concerned.

Water supply, as well as other objectives influence the operational rules, especially the *minimum pool* constraint in relation to month or season. For instance, for the months of July and August (and sometimes June and September) some minimum pool must be maintained for recreational purposes in WRS reservoirs. In the winter months, in order to secure an effective head for hydroelectric power production, some minimum pool must be maintained in certain reservoirs.

In simulation models the operation of WRS with a *reduction of functions*, e.g. the critical storage in reservoirs, is not usually considered. An exception may be the combined utilization of reservoirs in meeting the demands of users with different requirements concerning reliability, e.g. water supply for industry and irrigation. In this case, two steps of operational policy are often used: the first step without any reduction of irrigation withdrawals, and the second with these reductions in case the storage in the reservoir drops below the critical level. This level is a design parametr that is corrected by trial and error in simulation.

Other courses of action for operation during critical situations are difficult to determine in the design stage of WRS. For instance, in some situations it is advantageous to prolong the duration of reduction in order to lessen the relative magnitude of deficits (e.g. instead of a total failure, i.e. 100% deficit, in one month, three months with 33% deficits). This operation policy rests on an assumption of *non-linear response* of the loss function to the deficits when the economic losses grow more rapidly than the deficits.

Often the optimization of operational policy is carried out by simulation of existing WRS when the design parameters are given and a better operation policy is sought. In view of the uncertainty in some parameters, especially with regard to future requirements on WRS, e.g. till the year 2000, such opearational policy optimization in the design stage could be misleading.

In WRS with water power plants as elements of the system, the operation of power plants influences the overall operational policy in simulation models. Big water power plants are important elements not only of WRS but also of *power systems*. It is, therefore, advisable to consider their function in the power load in combination with thermal and nuclear power plants, which influences the operation of WRS.

Operational policy includes not only the rules determining the quantity and timing of releases, the priority of reservoirs in meeting the demands, etc., but also the rules for *transbasin transport of water*, related to the conditions limiting this transfer.

Depending on the mutual interrelations among the WRS elements in time and space, feed-back is considered in the design of operational policy of WRS, which results in an iterative process.

6.3.6 Assembling a Computer Program

The amount of computation involved in simulation models makes it impossible to perform without a computer. Only a limited part of such computation can be done with a simple calculator.This serves for debugging programs for a few periods. (However, programmable calculators like TI-59 and SHARP PC-1500 are used for simple WRS). Simulation models are therefore discussed in connection with computers and their programming.

A comparison of programs for computers for simulation models with scientific and technology tasks, on the one hand, and data for business information processing, on the other, reveals certain common properties. Simulation models are of a complexity similar to that encountered in scientific and technological problems, and the number of operations performed is similar for the two cases. However, simulation models have more input and output data than these problems. This property of an abundance of input and output data, is a common characteristic of business data processing. It is apparent that simulation models combine the disadvantages and difficulties of both types of computer tasks. *Fast computers* with a sufficient capacity of internal and external memory are therefore necessary for running simulation models.

Programming computers for WRS is a problem that is highly dependent on the model chosen. Therefore, the development of modelling WRS is connected with advances in languages like FORTRAN, ALGOL, etc. Nevertheless, the programming of computers, especially debugging using these languages, is difficult and time-consuming. Therefore, ways were investigated of subdividing the whole program into relatively independent parts that can be debugged separately. The program can be created by linking up these parts, coded as subroutines in FORTRAN or procedures in ALGOL. However, *subroutines*, as stated by Mass *et al.*, 1962, are still dependent on the structure of the model system. For a new WRS, new subroutines must be prepared even if the methodology of their assembly is common to all these tasks.

In the meantime, some *general-purpose simulation languages* (see Chapter 4) have been developed. These languages are more appropriate for simulation in a broader sense, and they are suitable for the representation of some types of production, communication and distribution systems (e.g. queueing problems). They have not found much application in simulation models of WRS.

Special simulation languages have been developed for WRS, e.g. HYDRO, HYCO, etc. In Czechoslovakia, SIM-WRS (Zeman, 1974) is the simulation language of this type. The basis of this language is a simulator package of ALGOL-60 procedures. These procedures have such interface that the properties of WRS and their changes can be modelled by choosing a correct sequence of these procedures and by the determination of their parameters. Details of the application and properties of this language are given in the following section 6.3.7.

Another method for programming the computer for simulation models of WRS used in Czechoslovakia is the development of a *universal simulation model program* that can be used for a wide range of systems (Study of the Sava River, 1972).

For implementation in case studies, some modification of the simulation program is often necessary, as it is not possible to anticipate the whole range of requirements. The symbolic simulation language SIM-WRS, used in many case studies in the General Water Plan, does away with most of the difficult routine programming activities and facilitated a better analysis of input data, better results of simulation models, and a better reflection of operational policy in simulation models.

6.3.7 Principles of the Symbolic Language SIM-WRS

The simulation language SIM-WRS (Zeman, 1974) is a procedure-oriented symbolic language based on a version of ALGOL-60, viz., Elliott-Algol. The procedures constituting the structure of this language can be classified into three groups. (Table 6.1).

Procedures concerning the *function of the reservoirs* or water power, if included in the system, are in the first group. These procedures can be used separately or can be joined into derived subgroups, which simplifies assembling the program. These procedures have the following functions:

MIREL (*P1*, *P2*). This procedure performs the minimum release operation, i.e. operation of the reservoir in such a way as to maintain a guranteed minimum release from reservoirs at points *P1* to *P2*. The corresponding changes in reservoir storage are computed within the limits 0 and WZA_i where WZA_i is the active storage; $i = P1$ to $P2$. (In computation, WZA_i is often the reduced value of active storage. This reduction takes into account losses due to seepage, evaporation and operation).

FLAD (*P3*, *P4*). This procedure performs the adjustment of flows on the basis of the difference DELTA and SPB at points $i = P3$ to *P4*. The DELTA value is equal to the change of storage in one time step. SPB equals zero if the preceding procedure was MIREL; it is equal to the sum of demands covered at points $i = P3$ to *P4* (demands satisfied by the function of WRS) if the preceding procedure was DESU.

Procedure FLAD often follows procedure MIREL. These two procedures can therefore be replaced by the joint procedure MF (*P1*, *P2*, *P3*, *P4*) that performs the function of MIREL (*P1*, *P2*) and FLAD (*P3*, *P4*).

Table 6.1 Basic procedures of the language SIM-WRS

No. of group	Goal of group	Procedure	Main goal of procedure
1	Modelling of functions of reservoirs	MIREL (*P1*, *P2*)	Minimum release operation
		FLAD (*P3*, *P4*)	Flow adjustment
		RES (*N*, *P1*, *P2*)	River flow regulation by water reservoir and minimum release operation
		DESU (*P1*, *P2*)	Demand-supply relationship
		ADDIT1 (*P1*, *P2*, *N1*, *N2*)	Additional release from reservoirs, option 1
		ADDIT2 (*P1*, *P2*, *N1*, *N2*)	Additional release from reservoirs, option 2
2	Input and output of data	DATA	Reading of basic data of WRS – File 1
		MGT	Reading of flows from the magnetic tape (disc) – File 2
		PT	Reading of flows from punched tape or punched cards – File 2
		PRINLP	Print of output on the line-printer
3	Service procedures	ZERO	Initialization of data
		YEAR	Computations at the end of the hydrological year
4	Derived procedures	RDF	Joined procedures RES, DESU, FLAD
		ADF	Joined procedures ADDIT1, DESU, FLAD
		MF	Joined procedures MIREL, FLAD

Procedure RES (N, $P1$, $P2$) performs the river flow regulation at points $i = P1$ to $P2$ by the release from reservoir N. The reservoir active storage is within the limits 0 and WZA_N and the change of storage DELTA is computed. If reservoir N is not able to cover the demand, the deficit CRP is computed.

DESU ($P1$, $P2$) – Demand-supply relationship, i.e. the comparison between the demands on the WRS and the possibilities of WRS to supply water for them is carried out in this procedure at points $i = P1$ to $P2$. In addition, the variables are computed for the determination of various forms of reliability of the WRS at these points, viz., occurrence-based reliability R_1, time-based reliability R_2 and quantity-based reliability R_3. They are defined as follows:

$$R_1 = \frac{m}{n+1} \quad \text{or} \quad R_1 = \frac{m - 0.3}{n + 0.4}$$

where m is the number of years without any deficit,
n – the number of years under study,

$$R_2 = \frac{d}{t}$$

where d is duration of all periods with no deficit,
t – duration of all periods under study,

$$R_3 = \frac{w - v}{w} = 1 - \frac{v}{w}$$

where v is the total volume of all deficits under study,
w – the total volume of water that needs be supplied.

In addition, the sum of demands covered (SPB) and the above-mentioned value DELTA at points $i = P1$ to $P2$ are computed. The output of this procedure contains the values of discharge FP influenced by the releases, withdrawals and consumption of water.

Procedures RES, DESU and FLAD often follow in this sequence and the joint procedure RDF (N, $P1$, $P2$, $P3$, $P4$) can be used instead of these three procedures.

ADDIT1 ($P1$, $P2$, $N1$, $N2$) computes and allocates the additional releases from reservoirs $j = N1$ to $N2$ for demands at points $i = P1$ to $P2$. If procedure RES was used, then the total amount of release is computed. Otherwise it is known, and this value is only allocated among the reservoirs. In ADDIT1 option 1 is used, i.e. water is released from reservoirs in a predetermined order (if there is not enough water in the first reservoir, the second is used, etc.). Apart from the changes of reservoir storage the values DELTA and CRP are computed.

ADDIT2 ($P1$, $P2$, $N1$, $N2$). This procedure is similar to ADDIT1. Option 2, used in this procedure, involves a difference in the operational policy. The releases are determined so that the ratio of the actual reservoir storage to its maximum value (active storage) should be constant for all reservoirs $j = N1$ to $N2$.

ADDIT3 (*P1*, *P2*, *N1*, *N2*) uses option 3 for the same purpose. This operational policy is known as the space rule (Maass *et al.*, 1962).

The sequence of procedures ADDIT, DESU, FLAD occurs very often, and it can therefore be replaced by a joint procedure ADF (*P1*, *P2*, *N1*, *N2*, *P3*, *P4*).

If water power generation is the objective of WRS, then procedures SVEN and PVEN are used. SVEN is used for peaking operation of power plant and PVEN for pumping-storage power plant.

The second group of procedures is used for input and output of data. In ALGOL-60 there is no definition of input and output procedures. Therefore, the procedures in the second group are dependent on the applied modification of ALGOL for the computer, its installation and input/output devices. In the SIM-WRS language the modification was Elliott-Algol with the following procedures: DATA – reads the basic data of WRS. Procedure DATA calls further procedures for reading of data, i.e. PFR, PFNR, PFPNR, CRS. If hydroelectric power is included, then procedures SVE and PVE are called. These procedures have the following function:

PRF, PFNR, PFPNR, CRS are used for the reading of data determined by various forms of demands and minimum flows in demand centres of WRS.

SVE, PVE – reading of input parameters of power plants for peaking operation and pumping-storage power plants, respectively.

MGT – reading of flows from magnetic tape or disc,

PT – reading of flows from punched tape or punched cards (especially in debugging),

PRINLP – printing of output on lineprinter. This procedure is called after the last step of stimulation by the procedure YEAR (see below).

The main service procedures consist of ZERO and YEAR:

ZERO – initialization of variables and indices at the start of computation,

YEAR – computations at the end of the hydrological year, such as the determination of initial storage for the next year, or computation of variables for the evaluation of various forms of reliability.

The application and possibilities of SIM-WRS are apparent from their description. The program for simulation of WRS operation is formed by the appropriate sequence of these procedures with adequate parameters. In this process some rules must be be followed, depending on the organization of input data and the functions of procedures. The main parameters describing the organization of data for simulation are the following:

The dimensions of the task are characterized by parameters:

NA – number of reservoirs in WRS,

CPPF – the total number of demand centres and reservoirs (points),

T – the number of hydrological years under study (the hydrological data at all points of WRS should be available for these years),

PPC – the number of rank indices.

Firstly, the reservoirs are given serial numbers from the natural series, i.e. numbers

1′ 2, 3, ... NA, and the demand centres of WRS the serial numbers $NA + 1, NA + 2, \ldots$ .. $CPPF$. Numbering is performed downstream. In addition to the serial numbers, every point is given one or more rank indices.

In these procedures the reservoirs and demand centres must be assigned natural serial numbers (e.g. 15, 16, 17, 18 and not sequence 8, 12, 3, 7). Therefore, the rank indices in the array *P0* are used for this purpose. The parameters of reservoirs *N1* to *N2* and demand centres *P1* to *P2* and *P3* to *P4* are the elements of array *P0* (rank indices), not the serial number of points (with the one exception of parameter *N*). This explains the function of the array of rank indices *P0*. This array is read in input parameters. Further parameters are:

PHPF – the number of gauging stations in which data for computation of flows at points of the WRS are available,

PRIO – flag for function of procedure DESU.

Further input parameters are the pairs AN_i, KO_i that are read for all points of WRS. AN_i is the serial number of the gauging station and KO_i is a reduction coefficient for transformation of monthly flows from the gauging station AN_i to the point i of WRS.

Next, the parameters of reservoirs are read, i.e. for each reservoir, the active storage WZA_i (or reduced active storage taking losses into account) and the minimum guaranteed release MON_i. The demands in demand centres are read by procedures PFR, PFNR, PFPNR, CRS.

The demands are characterized in each demand centre by three parameters:

M_j – minimum flow that has to be maintained at this point j for environmental, water quality, aesthetic, ecological or other reasons apart from water supply,

$W_{m,j}$ – withdrawals of water in month m, at point j. The withdrawn discharge is returned into the river in the section between point j and the following point (often with altered quality or temperature),

$C_{m,j}$ – consumption in month m and at point j.

With the exception of the main parameters NA, $CPPF$, T, PPC, which are read at the beginning and facilitate the dynamic arrangement of arrays, all stated para-

Table 6.2 Scheme of operation policy

No. of reservoir	River flow regulation at points No.
1	6, 7
2	5
3	8
1, 2	8
4	9

meters are read by the procedure DATA. Having called this procedure, the program performs the initialization of variables by the procedure ZERO. Then, in a monthly cycle (return to the label REP), the flows in gauging stations are read by procedure MGT and transformed by the same procedure to the WRS points.

The output file consists of parameters of reservoirs in WRS, i.e. WZA_i, MON_i and the utilized active storage RWZ_i; in demand centres the parametres (M_j, W_j, C_j) are accompanied by the reliabilities in all three forms discussed above.

The sequence and parameters of procedures depend not only on the configuration of reservoirs and the demand centres but also on the operation of WRS. The system of points numbering and the record of operational policy are illustrated by an example of a program of a simulation model of a simple WRS comprising four reservoirs and nine points (five demand centres).

Table 6.3 Procedures and their parameters

Procedures	Reservoir (RES) No.	River flow regulation at point		Additional release from reservoir (ADDIT1)		Demand-supply integration (DESU) at points		Flow adjustment (FLAD) at points	
		No.	Rank ind.	No.	Rank ind.	No.	Rank ind.	No.	Rank ind.
RDF	1	6, 7	3, 4	–	–	6, 7	3, 4	3, 8, 9	5, 7
RDF	2	5	8, 8	–	–	5	8, 8	3, 8, 9	5, 7
RES, ADF	3	8	6, 6	1, 2	1, 2	8	6, 6	9	7, 7
RDF	4	9	7, 7	–	–	9	7, 7	9	7, 7

The scheme of the WRS is given in Fig. 6.1, and the scheme of its operational policy in Table 6.2. The application of procedures is shown in Table 6.3. The correspondence of serial numbers and rank indices is given in Table 6.4. This relationship is used in Table 6.3 with the limits of rank indices (e.g. instead of 5, 6, 7 only 5,7; instead of 8 the limits 8,8 are used). The sequence of procedures simulating the operation, together with other input, initialization, service and output procedures that

Table 6.4 Rank indices

Serial number i	1	2	3	4	5	6	7	8
Rank indices PO_i	1	2	6	7	3	8	9	5

form the user's program, is given in Table 6.5. The whole program consists of a file declaring the variables, the procedures, and the user's program which is appended to this file. At the end of the program the main and inner blocks are closed by the statements "END"; "END"; (or in reference Algol, end; end;).

Table 6.5 User's program

```
DATA;
ZERO;
REP: MGT;
RDF (1, 3, 4, 5, 7);
RDF (2, 8, 8, 5, 7);
RES (3, 6, 6);
ADF (6, 6, 1, 2, 7, 7);
RDF (4, 7, 7, 7, 7);
YEAR;
"END"; "END";
```

The simplicity of programming by the symbolic SIM-WRS – language is obvious. No time-consuming debugging of the program for new configurations of different WRS is necessary. A further advantage of the symbolic SIM-WRS language is the dynamic allocation of the inner memory for arrays according to the main parameters. That facilitates economical utilization of the capacity of the inner computer memory.

The file of procedures is an open system that can be supplemented by further procedures depending on the specific demands of simulation. The basic operational policy, however, is given by the stated procedures. The simplicity of the programming results in the possibility of multi-modelling. For the same problem, different models can be designed which simulate different WRS operational policy.

Depending on the arrangement of input data, the simulation model is not limited by the length of the hydrological time series. Therefore a program written in SIM-WRS can be used for synthetic sequences of stochastic hydrology in stochastic simulation models.

6.3.8 Verification and Validation of Models

The results of simulation of WRS require verification by various tests (Kos *et al.*, 1971). *Correctness tests* are the first. When the procedures have been debugged, these tests can be reduced to one alternative only. However, these tests must not be omitted, as a combination of procedures can activate certain parts that are not normally used and under some specific conditions the program does not necessarily give correct results.

Further tests analyse the *sensitivity* of the model to input data. These tests are carried out by varying the input data slightly; and observing the response of the output variables.

If the system meets all the demands with the required reliability, these tests can result in a reduction of surplus capacities in excess of the required goals. If, however, input parameters acquire their maximum values and undesirable deficits still occur, a correction in the WRS is necessary and new water resources must be incorporated to meet the demands. If there are no additional water resources, or if acquiring them would be too expensive or even impossible due to other reasons (e.g. legal), the requirements on the WRS must be reduced and the simulation repeated.

Verification tests include comparison with the results obtained by different approaches and methods, e.g. balancing, on the basis of the sum of the effects of individual reservoirs (a WRS should give better results), critical period approach (simulation performed for a drought year only), etc. The stochastic simulation model can be compared with deterministic simulation.

These *logical tests* include the service output, e.g. the print of the reservoir storage at the end of each month in the period analysed, the print of flows influenced by the functioning of the WRS at all its important points.

Testing the *validity* of simulation models is the most difficult methodological problem of each simulation technique. The critical issue is confirmation that all the important properties of the system investigated have been reflected in the model and that all the criteria have been properly defined.

The main aim of simulation models is the prediction of some characteristics of a WRS development plan. Each plan rests on a series of assumptions and a change in one of them can substantially influence the validity of the simulation model. The validity of the simulation model is therefore a relative concept and testing it is a continuous process in which convergent and sometimes divergent stages of the relationship between reality and the model may occur. The goal of the simulation model is to ensure that the results of the model can be used at all stages of this development and that they can be used to promote decisions that are correct in principle and can be adapted in future development.

6.4 ANALYSIS OF RESULTS AND DESIGN OF OPTIMIZATION METHODS

In the analysis of the results of simulation models criteria must be formulated for evaluation of simulation outputs. Sometimes these criteria are corrected and reformulated in the process of evaluation of simulation runs. In WRS there are elements whose function cannot be measured (e.g. in economic terms). In that case, an economic comparison of WRS alternatives for the determination of the optimal alternative cannot be performed. Sometimes these functions can be measured, but in units which are not comparable. Therefore, the results of a simulation model may be presented as a *set of alternatives*, optimal according to different criteria. Comparison of the alternatives in this set can be made by the methods of *decision analysis*, with due consideration for and weighing up of different criteria, e.g. costs, power output, economic efficiency, environmental impact, development adaptability, construction and operational stability and reliability, political considerations, etc.

Analysis of the results of simulation models in complicated by the stochastic nature of the problem and evaluation of the results includes the methods of decision-making in circumstances of *risk* and *uncertainty*. The stochastic nature is caused mainly by hydrological data and demands on WRS. The probability distribution of hydrological data is often known. However, the statistical properties of demands and their extrapolation into the future is a more complicated futurological problem that is difficult to solve (IIASA, 1979).

In some cases, probability characteristics of past events of this stochastic process are not a reliable basis for the prediction of demands (non-stationary stochastic process). Therefore hydrological data and demands lead to decision-making in circumstances of risk and uncertainty, respectively.

The risk of failure caused by hydrological conditions in connection with operational policy is the main component of the output of simulation models. Often its counterpart, viz. *reliability*, is examined instead of the risk. The limit of this risk, the acceptable risk, should be determined by an economic and environmental analysis of the WRS. However, the problems of multiobjective optimization and ill-defined WRS structures cannot be solved by these methods. The acceptable risk is then often given by standards or as a result of application of decision theory.

In the General Water Plan (GWP, 1976) in Czechoslovakia the problem of acceptable risk and reliability was solved in the following way: Based on the observed time sequence of flows in the system of gauging stations, operation without dangerous failures is required. Some small deficits were permitted, i.e. deficits such as do not cause an interruption in the functions of the WRS but only some reduction (e.g. a reduction of water supply for irrigation demands to 80% in a critical period, Kos, 1968). This aim was achieved by variation of the WRS parameters, especially of designed active storage of reservoirs. The minimum flow requirements were used as constraints. If this target was not reached with maximum values of active storage, the simulation model representing water quality was re-run with altered parameters reflecting a reduced requirement on water quality and reduced minimum flow requirements.

As stated earlier, the operational policy for flood control is modelled in two kinds of simulation models. The first of these uses the flood control storage in a monthly simulation for water supply and other goals, the second determines the flood control storage of reservoirs and the requirement for river training in an hourly simulation.

In some cases the requirement for flood control storage may conflict with the active storage requirements when the sum of active, flood control and dead storage is greater than the total storage given by the morphological and hydrological conditions of the reservoir site.

In simulation models for water supply, the flood control storage is often taken as a constant. If competition for use of reservoir storage is strong and the total storage is limited, an optimization model is necessary and a new simulation with a water supply operational policy involving reduced flood control storage is performed, or a reduction of water supply demand takes place (or some reduction in both objectives).

If the differences are relatively small, a better multiobjective operational policy may be found to enable the WRS to serve these objectives, i.e. water supply, low-flow augmentation and flood control.

One kind of operational policy that can be used is the dispatching operation. In simulation models this method is reflected by a rule curve giving the necessary storage (dispatching storage) for each month of the year (an annual cycle is considered). For the planning stage of WRS analysis this approach is too detailed and a fixed or flexible operational policy (Maass, 1962) is often tested. In most cases this operation gives a good approximation of the operational adaptability of the system.

If the level of water requirements on WRS is relatively high (e.g. more than 70% of the annual mean flow) and the required reliability is also high (e.g. 97%), the assumption that the observed flows provide a good basis for reliability and risk estimation, is questionable. For example, with a required 97% reliability the result of the simulation model corresponds to the most serious critical period that occurred once in 40 years. This single realization of a stochastic process may be a very inaccurate approximation of possible sequences of flows that can occur under stationary conditions of the stochastic process.

In such cases, a deterministic simulation model should be supplemented by a stochastic simulation model or by another model that includes a stochastic evaluation of the functions of WRS.

Analysis of the result of *stochastic simulation models* is more difficult than that of a deterministic model. If the sections (e.g. 50 years) of the synthetic flow series are investigated in separate simulation models, the output consists of a series of values that can be treated by the methods of mathematical statistics (i.e. parameters and functions such as mean values, standard deviations, cumulative distribution functions, probability density functions, etc. are investigated).

The second approach uses the complete hydrological series generated e.g. 500 years or more and the long-term characteristics of operational policy and design of WRS are investigated.

6.5 DESIGN OF SAMPLING STRATEGY

The basic sampling strategies in simulation models used for optimization are: systematic sampling, random sampling and the gradient methods (e.g. the steepest ascent method).

In *systematic sampling*, a survey of the response surface is carried out at points systematically distributed according to the input parameters. This response surface is given by the values of the objective function (e.g. the costs of the alternative). For example, an alternative in systematic sampling uses all combinations of parameters with their maximum values, and with values corresponding to one third and two thirds of their range, respectively. As the number of combinations in systematic sampling is very large, a combination of this sampling with *heuristic sampling* is often used. Obviously inefficient combinations of parameters are excluded in advance. This method can be used for relatively simple relationships in WRS, where the behaviour of the system can be estimated beforehand.

In *random sampling*, some points are chosen at random from a systematic grid and the objective function is computed. This method is suitable at the beginning of computation when the behaviour of a system is completely unknown and preliminary information is being acquired. Computation of an obviously bad combination is prevented by a heuristic approach or by some screening method of operation research for complex systems.

In a detailed investigation of the behaviour of a system and its response to input parameters, the *method of steepest ascent* is often used. By small variations of parameters the partial differentiations in the direction of the varied parameters are estimated and on the basis of these differences the steepest ascent on the response surface (i.e. the surface formed by the values of the objective function in *n*-dimensional space) is evaluated. The parameters are changed in the direction of the steepest ascent and a new value of the objective function is computed. This algorithm is repeated until the region of the optimum is reacted. In this area, systematic sampling is often preferred.

The method of steepest ascent requires computation of a large number of alternatives. Therefore, it is used in detailed WRS studies where the results obtained by preliminary investigation in planning models are corrected.

The above-mentioned sampling strategies are used for internal optimization of simulation models. Another type of sampling strategy concerns the relationships between the various WRS models, e.g. models of flood control, water quality, water power, water transport, etc.

In view of the difficulties involved in the explicit formulation of these relationships, the *method of trial and error* is often used in a computation process in which the constraints and prerequisites of individual models and the requirements of higher systems converge.

6.6 IMPLEMENTATION OF SIMULATION MODELS

The main problem in the implementation of models in the process of decision-making is to establish if the prediction obtained on the basis of simulation models is correct, or at least better than predictions made by the implementation of other models or methods of investigation. It is, in other words, a question of the *credibility of the model* and its results. Therefore, it is necessary to analyse how to persuade the decision-makers that the simulation model offers correct results that can be used in decision-making.

Simulation models of WRS have some advantages over mathematical models, as they use the same principles as the traditional methods of water resource research, especially in yield-storage relationships. This applies particularly to the deterministic simulation models where the results can be confirmed by partial calculations using some part of the historical records. For instance, it is well-known that the years 1933, 1934, 1947 and 1954 brought periods of drought in many regions in Czechoslovakia and they may, therefore, be a good basis for the verification of results and operational policies of water supply simulation models.

An actual operational policy of a WRS based on the same principles as the operational policy of the simulation model would be the best proof and simplest verification of the model's correctness. This can be done to some extent in simulation models of existing WRS when optimal operational policy is investigated. The assumption is a sufficiently frequent occurrence of drought periods. In WRS planning and in the design of structural changes in WRS where simulation models are used most, the modelled system does not exist and such a *direct test* cannot be carried out.

In such cases different types of verification tests should be performed. The *adaptability of the model* can be used as one such test, i.e. the ability of the model to react to various situations caused by hydrological input values and also by variations and *changes in demands.* The ability of a multipurpose WRS to adapt and react to such changes is much better than that of a single-purpose system.

In cases where the planned development of water supply demand is hindered by obstacles, the free capacity can be used for some other goal (e.g. flood control, recreation, etc.). In this way there is no unused investment. These properties can be easily reflected in a simulation model as alternatives of demands on WRS.

"Common sense" is often used for the verification of the results of simulation models. The results of simulation models rarely fall outside the limits assumed by engineering experience. If an exception occurs, the print of reservoir contents at the end of each month, releases from reservoirs, changes of flow at all points of the WRS, etc. help to detect possible errors and reveal the cause of the exceptional behaviour of the WRS. If no error is detected, several operational rules can be used and the reaction of the output can prove the correctness of the original operational policy.

The test of the sensitivity of output to input values helps to prove that a simulation model reacts logically, e.g. an increase in demand is related to an increase in storage etc.

An adequate *degree of simplification* is given by the assumptions of model implementation. If a simulation model reflects the main features of WRS only, no description of detailed behaviour can be obtained, e.g. a detailed comparison of different operational rules with and without some small reservoirs in the system, or the problems of weekly operation in a simulation model with a monthly time step. On the other hand, a high degree of detail can be misleading, if the main variables are not thoroughly analysed and all the necessary sensitivity tests are not performed.

At the beginning of the development of WRS simulation models, the validity tests were mainly carried out on the basis of their inner structure, modelled by a sequence of algorithms and coded in a computer program. An example of a simple situation, given in Chapter 4 (Fig. 4.5), illustrates this structure and the simulation method. Examples of simulation technique for more complicated WRS in river basins will be given in Chapter 12.

In simulation models of WRS not all the factors affecting WRS and all the relationships can be reflected; therefore, a simulation model cannot be considered the only tool in decision-making. It is obvious that in the design of WRS, where capital costs are very high, all the known models and their results are used. The results of simulation models are used as a very important element in the process of decision-making. The implementation of simulation models of WRS can therefore be considered a success.