2 SYSTEMS IN WATER RESOURCE MANAGEMENT

In developed countries and countries with limited water resources, comprehensive and rational water management is a necessary condition of social and economic development. The bodies of water form extensive natural systems and these natural elements and hydrological relationships are supplemented by artificial relationships, so that the natural watershed ceases to be the boundary of the system.

Water management thus becomes a typical sector where the rational and purposeful utilization of water resources cannot be performed without multi-purpose water resource systems (WRS), including water resources, water users, and further factors related to or influenced by water management.

The optimal solution of problems involving competitive requirements for water needs the systems approach as a methodological procedure that takes all the internal and external relationships into account and utilizes the new theories of systems and modern computer hardware and software.

2.1 WATER RESOURCE SYSTEMS

The concept "water resource systems" can be treated as a real system since its elements are real objects. The system is defined according to the chosen objective and degree of abstraction.

WRS can be defined as a set of water resource elements linked by interrelationships into a purposeful whole.

The elements of the system can be either natural (precipitation, watercourses, lakes, ground water, etc.) or artificial (water management articles and facilities, reservoirs, channels, barrages, weirs, hydroelectric power plants, pumping stations, etc.).

The relationships between the elements are either real (e.g. water diversion) or conceptual (e.g. organization, information). WRS are "open systems" i.e. their elements bear some relation to the environment of the system.

If the link between some elements within the system is relatively closer than that between other elements, inside the system a relatively independent whole exists, which is called the *subsystem*. The selection of the discriminating level for the concept "water resource system (WRS)" is a matter of convention. An example of the discriminating level chosen in Czechoslovak conditions is given in Table 2.1; WRS comprises the total extent of the basins of the main rivers and their tributaries, the supersystem (supreme system) is water management of the whole country (and its supersystem is the whole economy of the country).

These systems are largely artificial and therefore purposeful. Each element, subsystem or system that consists of only one artificial component designed or used for some goal, is a purposeful object.

However, there exist natural WRS, formed by the hydrological networks, without any objectives, and these are not the objects of purposeful human activities (e.g. the system of karst ground water). Only exceptional examples of these purposeless WRS are investigated in this book.

Table 2.1 Hierarchical pattern of WRS (example)

Name	Object
Supersystem	Water management of the country
System	Basin of the main river
Subsystem of the 1st order	Municipal water supply
Subsystem of the 2nd order	Water supply of a town
Subsystem of the 3rd order	Water supply of a big factory
Subsystem of the 4th order	Water supply of a workshop

The interaction between the elements and subsystems of WRS can be local (topographical), hydrological, technological, engineering, etc.

A purposeful WRS is formed by a set of physical (material) items (elements), goals (which the WRS is to achieve) and some operational rules.

On the basis of the goals, WRS can be classified as:

– irrigation and drainage systems, hydroelectric power plant systems, water supply systems, fish-breeding systems, navigational systems, etc.,

– single-purpose or multipurpose systems.

A *single-purpose system* has various physical (material) items (elements) but only one purpose, e.g. a hydroelectric power plant system, or a flood control system, etc. Its goal is defined at the beginning of the investigation, mainly in technical units, e.g. to supply the discharge Q ($m^3 . s^{-1}$) with reliability p_o.

A *multi-purpose WRS* has various elements and a number of goals. The main aim in identifying it is to determine what combination of goals is optimal and what criteria are needed for the evaluation of this optimum.

As the goals are often competitive, optimization is difficult. The optimum-seeking task (determination of the objective function) is simplified if one particular goal (e.g. a municipal water supply) has higher priority than the others. Then this multi-purpose WRS can be treated as a single-purpose system and the "additional" goals are used as constraints.

Together with the basic attributes of a system, i.e. wholeness, unity, etc. the multi-purpose WRS also possesses all the signs of complexity so that a very complicated system can be defined in the following manner:

– it is large-scale in its dimensions, number of components (subsystems and elements), the number of input and output parameters and the number of relationships (e.g. WRS in Chapter 12),

– change in one quantity causes a change in a number of other variables (e.g. a change of hydrological input data),

– it is dynamic (both the water resources and the water demands change with time),

– the nature of hydrological input data and some water demands is random (the values of flows, withdrawals, the indices of water quality, etc. are not known in advance; it is a stochastic process and only its statistical characteristics may be known),

– the demands on the multi-purpose WRS are often competitive (e.g. requirements for higher flood control storage and active storage of reservoirs; the increase in one withdrawal limits the achievement of other goals, etc),

– operation and control of WRS requires many devices for monitoring and information processing, together with computer hardware and software and automation of some activities,

– the multi-purpose WRS requires personnel who measure, monitor, evaluate and control the operating process to ensure the faultless functioning of the WRS,

– the nature of the multi-purpose WRS requires not only technical and economic parameters, but also environmental and intangible aspects for the evaluation of their objectives as they have a profound impact on the environment.

First of all, the WRS has to be analysed in all its complexity. We should not underestimate the danger of oversimplification and try to create a basis for the evaluation of the validity of results of simplified systems (models). A comprehensive analysis of the structure and function of the WRS facilitates the scientifically approved abstraction and simplification.

2.2 WATER RESOURCE SYSTEMS IN THE GENERAL WATER PLAN OF CZECHOSLOVAKIA

"Water Resource Systems" is the heading of an important chapter of the General Water Plan of ČSR and SSR[1])

The General Water Plan (GWP, 1976) states that the creation of WRS in the basins

[1]) Czechoslovakia – the Czechoslovak Socialist Republic (ČSSR) is a federation of two countries, the Czech Socialist Republic (ČSR) and the Slovak Socialist Republic (SSR).

of the main rivers is an objective necessity for the development of water management in the natural, social, and economic conditions of the country. The utilisation of water resources will double by the year 2000, the annual withdrawals will increase to 33% and consumption to 12% of the mean annual flow; in drought years these figures will approximately double. The quantity of waste flow will be approximately proportional to this increase, and requirements concerning conservation and the protection of surface and ground water from pollution will also increase.

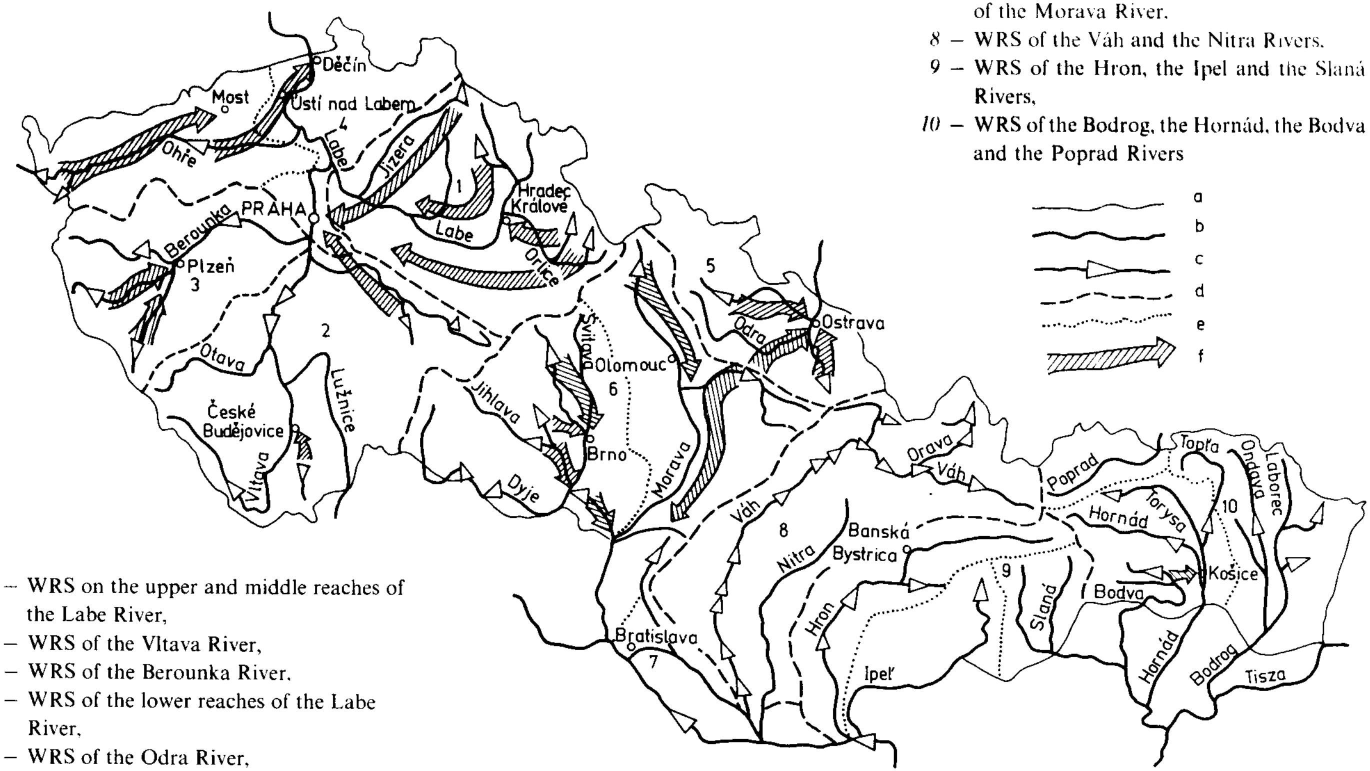
Table 2.2 Survey of WRS in basins of General Water Plan

No.	WRS (basin)	Area [10^3 km^2]	Number of inhabitants (1970) [Thous.]	Mean annual flow [$\frac{10^9 \text{ m}^3}{\text{year}}$]
1	Upper and middle reaches of the Labe River	14.37	1738	3.34
2	The Vltava River (without the Berounka River)	18.30	2330	3.35
3	The Berounka River	9.28	725	1.26
4	Lower reaches of the Labe River	9.54	1183	2.11
5	The Odra River	6.25	1212	1.95
6	The Morava River	21.11	2630	3.14
7	The Danube River and the lower reaches of the Morava River	5.39	739	0.36
8	The Váh River and the Nitra River	16.77	1761	5.31
9	The Hron, the Ipel and the Slaná Rivers	12.30	814	2.92
10	The Bodrog, the Hornád, the Bodva and the Poprad Rivers	14.62	1174	3.84

The traditional classification of the water management sector into divisions (viz. water supply, irrigation and drainage, hydroelectric power generation, etc.) is not comprehensive as the different requirements concerning water in a geographical and administrative area (country, region, basin or parts of them) cannot be coordinated. The methodological prerequisite of the comprehensive and optimal utilisation of water resources and release operation is given by the multi-purpose WRS.

The treatment of the problems of the main WRS consists of the processing of demands and prediction of their growth, and of the estimation of the capacity of water resources and their operation, and it is supplemented by the design of water resource conservation and protection measures. A schematic representation of the

6 – WRS of the Morava and the Dyje Rivers,
7 – WRS of the Danube and the lower reaches of the Morava River,
8 – WRS of the Váh and the Nitra Rivers,
9 – WRS of the Hron, the Ipel and the Slaná Rivers,
10 – WRS of the Bodrog, the Hornád, the Bodva and the Poprad Rivers



1 – WRS on the upper and middle reaches of the Labe River,
2 – WRS of the Vltava River,
3 – WRS of the Berounka River,
4 – WRS of the lower reaches of the Labe River,
5 – WRS of the Odra River,

Fig. 2.1 Schematic representation of WRS in the General Water Plan
a – state frontier, *b* – water courses, *c* – key reservoirs of the WRS, *d* – boundaries of WRS, *e* – boundaries of the subsystems, *f* – the main directions of the influence of the key reservoirs.

extent of WRS in the GWP that cover approximately the area of the main basins, is given in Table 2.2 and Fig. 2.1.

In the first part of the chapter entitled "Water Resource Systems", water management in the main basins is described in the following sections:

– the main tasks of water management in the basin,
– procedures for meeting the main objectives,
– relationships with other basins of the GWP.

In the second part the individual main WRS are described. The comprehensive utilisation of water resources is treated in systems with two discriminating levels – the overall (rough) and the detailed level. The following goals were included in the systems with the rough discriminating level:

– municipal water supply,
– industrial and irrigation water supply,
– flood control and its relationship to water resources,
– water resource conservation, water pollution prevention and environmental improvement,
– hydroelectric power generation,
– inland waterways and navigation,
– water-related recreation and fishing,
– river treatment,
– low-flow augmentation, minimum-flow maintenance.

The following main goals were included in multi-purpose WRS with a detailed discriminating level:

– municipal water supply,
– industrial and irrigation water supply,
– low-flow augmentation, minimum-flow maintenance,
– flood control,
– water quality improvement,
– water-related recreation.

A simulation model was the main tool for analysis of WRS with the detailed discriminating level. The operational rules of WRS are coded as logical and arithmetical statements that determine the conditions for the storage and release of water from the reservoirs, the allocation of water between reservoirs and for different goals and time periods. This model was used for the investigation of the behaviour of WRS under different conditions. Each change in the operational rules requires a corresponding change in the program.

The input data of simulation models include the parameters of WRS, hydrological time series (i.e. uncontrolled monthly time series in the periods 1931 – 1960 and 1931 – 1970 respectively) and the demands on WRS at control points. These demands are expressed as withdrawal (without consumption), consumption and minimum acceptable flow. The capacity of WRS was tested by data projected for the year 2000 and preliminary data for the year 2015.

In the simulation model the operation of WRS was frequently required without deficits for the period of the observed time series. In the stochastic simulation model, this assumption corresponded to a reliability of 95–97%.

The basic civil engineering activity in WRS in the construction of reservoirs related to water supply and pollution prevention, river training, transbasin diversion and navigation. Water-related recreation was taken into account in the operational rules of reservoirs.

The WRS were subdivided into several subsystems for modelling and evaluating the results. As all the WRS are closely related to the system's environment a water resource supersystem (supreme system) in ČSR has been defined with the following goals:

– the determination of the transbasin diversion to meet water deficits in some WRS,

– the coordination of the operation of the main reservoirs in the supersystem for hydroelectric power generation and flood control on the lower reaches of rivers,

– acceptable water quality at points on the country's borders.

The water resource supersystem was subdivided into three subsystems:

– the basin of the River Labe,

– the basins of the Rivers Morava and Odra linked via the Teplice reservoir by a transbasin diversion channel,

– a water resource system connected to the Danube – Odra – Labe canal.

In the third part of the "Water Resource Systems" chapter in the GWP there is a description of the areas of important water resource conservation defined under the Water Act (No. 138/1973 of the Collection of Acts). This act defined new concepts such as: the conservation of areas with natural water storage (areas of water resource conservation), watercourses and basins for municipal water supply. Conservation also concerns areas with planned utilisation of water resources. Similarly, areas for the conservation of natural ground water resources have been designated.

In a special section of this chapter there is a description of the conservation of watercourses and basins for municipal water supplies and the flooded area of the planned reservoirs.

Preventive water resource conservation is very important for the present utilisation of water and for future trends in water resource development. The resulting constraints are also included in the design of WRS.

The GWP was used as an illustration of the problems of multi-purpose WRS and their importance in dealing with the growing difficulties of water management, and as an illustration of the extent of multi-purpose WRS with a discriminating level in the GWP. The incorporation of systems science in WRS is indispensable, if their design is to be optimized.

2.3 WATER RESOURCE SYSTEM DEFINITION

Concerning water management objects, an infinite number of systems can be defined, which differ in objective, discriminating level, degree of simplification, etc. They are defined as real objects, i.e. the systems are real and not conceptual.

In natural and social sciences, a simplified abstraction (system, model), reflecting only the principal characteristics, is frequently investigated instead of the very complex reality.

The development of scientific knowledge and scientific methods has facilitated the setting-up of systems of ever-increasing complexity in a way that comes closer to reality. However, the simplification of nature, i.e. its adaptation to the possibilities of computer software and hardware capacity (however limited) can exceed the limits of acceptability with results remote from reality. The interpretation of the results of models and systems must be based on the standpoint that not "nature", but its simplified reflection was dealt with directly.

Therefore, in the operation of WRS human control cannot be omitted, since:

– their operation is even more complex and modelling cannot replace reality,

– the behaviour of WRS is not deterministic; it can be predicted with only some degree of reliability.

The human operator remains the principal element even in automated control systems and his profession can be called the "profession of the century" in view of its expected development.

WRS with artificial elements are created with the objective of meeting certain fundamental requirements in an optimal way (if possible), i.e. satisfying some economic or other criteria of optimality.

The task of WRS optimization may be placed in three contexts:

– the WRS exists and its *function* is to be optimized by changes in its *operation*,

– the WRS exists and it is to be *enlarged* (some elements added) in order to meet its present functional requirements better or to fulfil some new functions,

– the WRS does not exist; it is to be *designed* and *constructed*; existing elements can be used along with new ones.

A simplified system is defined for the required objective. This process has three main stages:

– the definition of the WRS units and its schematic representation,

– analysis of the structure and behaviour of the system,

– the design of changes in the system (if any) and their implementation.

The first two stages are the subject of systems analysis, the third requires a synthesis of the system.

A proper definition of the system is the basic prerequisite of the successful solutions of problems in WRS. The correct choice of the main characteristics is indispensable for the achievement of the required objective (or several objectives), and the use of incorrect ones in the system (model) obstructs all efforts, even if the best methods are used. The system in that case does not represent reality, and the results cannot be used in practice since they might lead to incorrect decisions. If the incorrectness of the results is obvious or can be revealed by common sense, no wrong decision is taken and no losses occur. However, the most dangerous case is when an incorrect result seems plausible; then the error is not corrected in time and the wrong decision may be taken.

In defining a WRS it is necessary:

– to verify the correct and accurate formulation of the objectives of the system; this is particularly important if the objectives of the system and the goals of its elements are competitive,

– to choose the discriminating level of the system and by that means to determine its elements, subsystems and environment and their functions in the system,

– to determine the relationships between the parts of the system and between the system and its environment,

– to decide upon a schematic representation of the system (e.g. a graph, matrix, flow-chart, etc.).

The definition of the system is the top creative design activity where human reasoning and intuition are indispensable. The choice of important elements and significant relationships and the adequate reduction of the number of constraints and variety of feasible alternatives determines the validity of system definition but also the adequacy of the simplification and the mathematical tractability of the model.

Although systems analysis includes many methods of system simplification, it cannot guarantee the correct choice of elements and their relationships.

The definition of the system consists of two principal procedures:

– subdivision into parts with defined interrelationships,

– simplification.

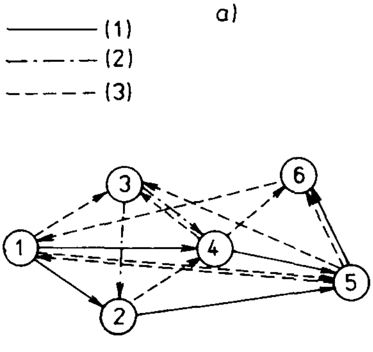
For easier definition of a large-scale system a working procedure was worked out which mechanized some of the steps (Habr and Vepřek, 1972). Hare, 1967, recorded the elements on cards on which the main data were inscribed, e.g. the name and code of the element, the description of the transformations in the element, the relationship of the element to the system and to the system environment, etc. These cards are the basis for the mechanization of the matrix and graphical representation of the system and for the analysis of its structure.

An example of a graphical and matrix representation of a general system is given in Fig. 2.2. The nodes of the graph denote the elements of the system and the directed edges (arcs) represent relationships that are generally material, energy, and information flows. In the matrix representation the starting node is in the row and the final node in the column.

In a simple system with few elements graphical representation and matrix representation are equally suitable; in large-scale systems the information can be more easily extracted from a matrix representation.

In some graphical representations (with the exception of the logical analysis – see 9.4.2), the critical path method (or its modification PERT) can be used for analysis of the time dependence and determination of critical points in the system.

a)



b)

	1	2	3	4	5	6
1		1	3	1	3	
2				3	1	
3		2		2		
4			3		1	3
5	3		3			1,3
6	3					

Fig. 2.2 Schematic representation of the system
a – graphical (flowchart),
b – matrix
Notation of relations:
(*1*) material, (*2*) energy,
(*3*) information

A *simplification* (reduction) of complex and large-scale systems is frequently a compromise between two extreme situations:

– the system is not simplified (accurate results, no costs for simplification, but a very expensive treatment),

– the system is oversimplified (great reduction in costs for treatment but part of the costs is used for simplification; the results, however, may be unreliable).

The increase in the speed and capacity of facilities for information processing makes the choice of less reduced systems possible.

A simpler system can be reduced directly. For simplification of the WRS the following direct methods can be used:

– elimination or aggregation of elements and relationships in the system,
– substitution and transformation of variables and relationships,
– subdivision into subsystems.

Elimination can be performed by "filtering" the components of the system through the given constraints. The following procedures can be employed:

– a reduction of the acceptable range of variables (from among the whole range of the set, values with probability $0.1 \leqq p \leqq 0.9$ are considered),

– reduction of the area of interest; the boundary of the system with the environment is reduced;

– reduction of the number of possible combinations by logical reasoning, or by statistical sampling,

– selection of the inter-element relationships (e.g. by quantity or by frequency of occurence) can eliminate relationships that are above or below a certain value, i.e. the threshold (e.g. withdrawals under a certain limit are omitted); the decrease or increase of the frequency or the number of relationships among the elements can help in the subdivision of the system into subsystems, which simplifies the system.

The use of elimination for simplification of the system is often suitable when the optimization of its function is intended.

Aggregation can be done:

– statistically (i.e. using the statistical characteristics of the set),

– logically (e.g. by change of a continuous variable into a discrete one),

– using prototypes, i.e. elements or subsystems whose properties enable them to represent a group in a system with similar properties.

Aggregation is suitable for the reduction of the system if the relationships between the subsystems and their behaviour are being tested.

Substitution and transformation of variables and relationships are to simplify the description of the system or transform it into a known form. The transformation has to be unique (i.e. possible inversion transformation of the reflection to the original system); the properties of the system that are invariable with respect to the applied transformation should be known.

Subdivisions into subsystems, which are relatively closed, is suitable for large-scale systems; the subsystems are then treated as separate systems and the treatment of the original system is simplified.

All the direct methods of system reduction are based on the assumption that the system is stationary (i.e. with time independent statistical properties). In grouping and selection, the consistency of the system should be maintained (i.e. the same approach by different researchers, the same methods of data collection and processing, etc.).

In the *analysis of structure and behaviour of existing systems* the following items are investigated:

– the principles and objectives of the system,

– the structure of the system and its adequacy for the given objectives,

– the behaviour of the system (whether it corresponds to the assumptions or why not),

– the means of system improvement (if any) with the expected impact on the behaviour of the system.

As the main purpose of this analysis is the diagnosis of weak points in the structure and behaviour of the system, this analysis is called *diagnostics*. It can be classified as (Habr and Vepřek, 1972):

– *qualitative* – the weak points of the present organization are detected, the goals for its improvement are determined, the principles of perfect system are stated, the introduction of new methods and facilities is planned and approved,

– *testing* – the basic information about the analysed system is obtained from by internal and external tests: in *external* tests the system is taken as a black box, the input parameters are varied and the response is investigated (the response test is used mainly in real systems with a flow of material); in *internal* tests discontinuities are detected, and the interface relationships between the elements, the impact of feedback and the alternative function of some parts of the system are investigated.

Simulation of the system is often a successful way of system testing. In principle, it provides the possibility to evaluate a real system before putting it into practice, often evaluation of real systems is not, in fact, possible in complex WRS.

The multi-purpose WRS are often simulated mathematically by the Monte Carlo technique, i.e. the technique of random processes. Computers are necessary and modelling is expensive. Therefore it is necessary to find out if:

– the conditions are suitable for simulation,

– there is a cheaper and easier method for solving the problem than simulation,

– the human role in the control process does not eliminate the possibility of using the simulation technique,

– the low frequency of task computation does not prevent the setting-up of a special simulation program,

– the conditions in the simulation model and in the real system are the same.

2.4 METHODOLOGY OF WATER RESOURCE SYSTEM DEFINITION

From among the many possibilities of defining a WRS, an example of a multi-purpose WRS where one goal has priority is presented.

2.4.1 Task Formulation by Water Resource System Analysis

A system of reservoirs in a basin is to be completed and its operation optimized. The system is multi-purpose with the following objectives:

– municipal and industrial water supply,

– flood control,

– low-flow augmentation,

– hydroelectric power generation,

– water-related recreation.

In Fig. 2.3 there is a schematic representation of
- water resources and existing and designed reservoirs,
- larger, suitably aggregated withdrawals of water,
- watercourses and canals.

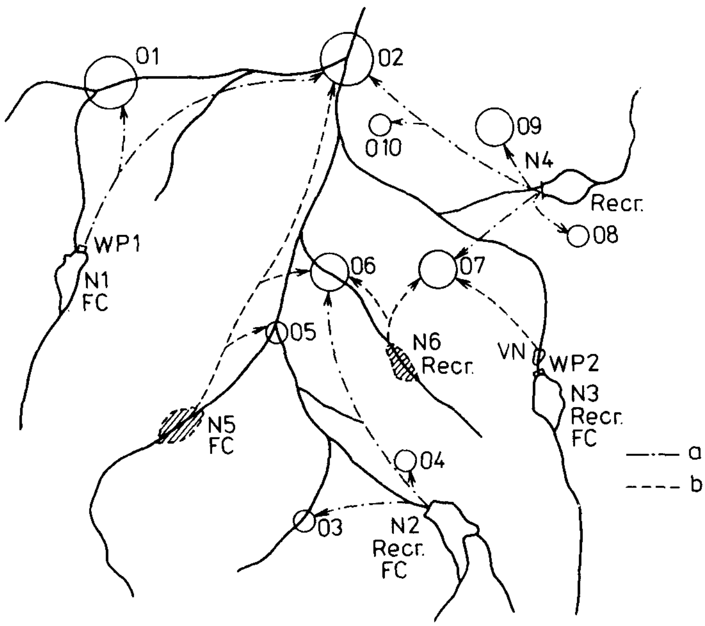


Fig. 2.3 Schematic representation of a multipurpose WRS
N1 to *N4* – existing reservoirs, *N5*, *N6* – designed reservoirs, *VN* – buffer storage reservoir, *01* to *010* – withdrawals of water, *a* – existing water mains, *b* – designed water mains, *Recr.* – water related recreation, *FC* – flood control, *WP* – water power plant

At present, there are four reservoirs in operation. Their goals, together with the water supply, are given in Table 2.3, the designed reservoirs are denoted *N5* and *N6*.

Since the aim was to obtain only a reflection of the relationships among the elements of the WRS, the simplest representation by a zero-one matrix was used.

A system with six water reservoirs and ten aggregated water withdrawals is relatively simple; the matrix representation is more suitable than the graphical one (Fig. 2.3) even if it is simplified.

One can read directly from the matrix representation that:

– the existing reservoirs are mainly used as isolated reservoirs (i.e. independent, isolated subsystems) with the exception of reservoirs *N1* and *N4* whose purpose is to supply water for withdrawal *O2*,

– water for withdrawal *O5* is not supplied from the reservoirs,

– reservoir *N3* is not utilized for the municipal water supply yet; its utilization

Table 2.3. The purpose of reservoirs in the system

Reservoir	Purpose of the reservoir				Withdrawals of water									
	Water supply	Flood control	Power generation	Recreation	*01*	*02*	*03*	*04*	*05*	*06*	*07*	*08*	*09*	*010*
N1	1	1	1		1	1								
N2	1	1		1			1	1		1				
N3	(1)	1	1	1							(1)			
N4	1			1			1				1	1	1	1
N5	1	1				1			1	1				
N6	1			1						1	1			

for this purpose (see (1) in Table 2.3) can relieve water resource *N4* which is the only resource for withdrawals *O8*, *O9* and *O10*,

– the recreational function is combined with the municipal water supply and hydroelectric power generation,

– reservoir *N5* is an important complementary resource for WRS for the following reasons:

a) it supplies water for withdrawal *O5*,

b) it increases the quantity and reliability of the water supply for *O2* and *O6*,

Table 2.4. Matrix of the competitive purposes of the system

Purpose	*Z*	*O*	*H*	*R*
Z – water supply	–	1	1,3	2,3
O – flood control	1	–	1	–
H – hydropower	1,3	1	–	3
R – recreation	2,3	–	3	–

1 – Competition in reservoir storage requirements
2 – Competition in water quality
3 – Competition in operation requirements

c) via *O2* and *O6* the system is linked with *N1*, *N2* and *N4*, which forms a compact water supply system,

d) it increases the degree of flood control (flood alleviation).

– reservoir *N6* is a planned versatile element of the water supply system. If it delivers water for large withdrawals *O6* and *O7*, water resources *N2*, *N4* and *N5* can be relieved; its location makes it suitable for recreation.

To simplify the defined WRS and the treatment of the problem, a logical analysis is carried out:

The system has four objectives, i.e. it is a multi-purpose system. Firstly, a *reduction in the number of aims* should be achieved, since the multi-purpose nature of the system greatly complicates its optimization, especially if the aims are competitive; a matrix of competitions has been set up (Table 2.4):

This matrix is, of course, symmetrical around the main diagonal. It is clear that all the four purposes are to some degree competitive, with the exception of recreation and flood control (in this example). Competitions (1) and (3) are approximately equally frequent, competition (2) occurs only once.

The respective priorities of the purposes can be determined in this relatively simple case by a comparison of their social and economic impacts in the context of the plan for economic and water management development of the area, e.g. in this way:

The most important demand on water resources in this region, as compared with other requirements (represented by three purposes), is the *municipal and industrial water supply*; the question is, if the other three purposes can be considered as the constraints on the main demand.

Flood control: if the necessary flood control volumes A_r in the reservoirs are determined, the single existing conflict (1) is thus resolved; if the reservoir has a carry-over volume (i.e. large active storage $A_{\underline{z}}$) and storage $A_{\underline{z}}$ is also used for a reduction in flood discharges, conflict (3) can be resolved by unconstrained requirements for the water supply. If there is no provision for the construction of the storage volumes of reservoirs for both purposes Z and O, some new alternative serving both these purposes will have to be found.

Hydroelectric power generation: the conflict between purposes Z and H concerns requirements on storage of the reservoirs (1) and their operation (3). As the reservoirs are on small watercourses equipped with hydroelectric power plants of limited capacity and of minor significance in the power system, the hydroelectric power requirements can be subordinated to purpose Z; in this way the conflict has been resolved. The economic efficiency of purpose H should be determined under these constraints; e.g. the adverse impact of peaking of hydroelectric power plants on the water quality would restrict their peaking operation.

Recreation: the conflict between purposes Z and R concerns the water quality requirements (2) and operation (3). In the present situation, in principle, the combination of recreation and municipal water supply is possible. A detailed analysis is to be used to decide if this combination of purposes Z and R in a reservoir is effective or if it would be more advantageous to separate these two important purposes (both have a high environmental impact).

Further relationships between the *various purposes* are treated, e.g. between purposes O and H: the conflict between purposes O and H is of type (1) and it has been dealt with by resolving the conflict between purposes Z and O, since purpose H is subordinated to Z. If there is a conflict between O and H, the social and economic analyses will, under the given conditions, give higher priority to flood control O.

The conflict between purposes H and R concerns operation (3); for R a constant water level is advantageous, H requires a variable water level due to peaking operations which are, however, constrained by Z.

The result of this short analysis is the transformation of a system with four purposes into a system with a single main purpose, with the remaining three purposes being

Table 2.5 The relation among the resources and withdrawals of water in WRS

Element of WRS	*N1*	*N2*	*N3*	*N4*	*N5*	*N6*	*O1*	*O2*	*O3*	*O4*	*O5*	*O6*	*O7*	*O8*	*O9*	*O10*
N1	–	0		*A*	*A*	0	1	1			0	0	0	0	0	0
N2	0	–	0	0	*A*	*A*		0	1	1	0	1	0			
N3		0	–	*A*	0	*A*		0				0	1	0	0	0
N4	*A*	0	*A*	–	*A*	*A*	0	1			0	0	1	1	1	1
N5	*A*	*A*	0	*A*	–	*A*	0	1	0	0	1	1	0	0	0	0
N6	0	*A*	*A*	*A*	*A*	–	0	0	0	0	0	1	1	0	0	0
O1	1			0	0	0	–	*a*								
O2	1	0	0	1	1	0	*a*	–			*a*	*a*	*a*	*a*	*a*	*a*
O3		1			0	0			–	*a*		*a*				
O4		1			0	0			*a*	–		*a*				
O5	0	0		0	1	0		*a*				*a*				
O6	0	1	0	0	1	1		*a*	*a*	*a*	*a*	–	*a*			
O7	0	0	1	1	0	1		*a*				*a*	–	*a*	*a*	*a*
O8	0		0	1	0	0		*a*					*a*	–	*a*	*a*
O9	0		0	1	0	0		*a*					*a*	*a*	–	*a*
O10	0		0	1	0	0		*a*					*a*	*a*	*a*	–

Notation of relations:

1 – direct relation between the water resource and withdrawal

A – direct relation among the water resources supplying the same withdrawal

a – direct relation among the withdrawals from the same water resource

0 – indirect relation among the water resources and withdrawals via one intermediate withdrawal

used as constraints on this main one. The conflicts among these three subordinate purposes have been analysed.

The *discriminating level* in the definition of the WRS was expressed in Fig. 2.3 where the elements and relationships (directed edges giving the flow of water) were drawn.

The graphical representation in Fig. 2.3 together with Table 2.5 can be used for a possible subdivision of the WRS into *subsystems*. The direct relationships, denoted in the matrix as 1, *A*, *a*, will play the decisive role. The indirect relationships, denoted as 0, will be taken into account in the second order as a characteristic of the interrelationships between the elements of the system.

A look at Table 2.5 shows:

– a high degree of interrelatedness among the elements of the system; the definition of WRS was therefore necessary and the systems approach is therefore methodologically correct,

– the relationships involving the functions of water resources are mainly direct or via one intermediate withdrawal (with the exception of *N1* and *N3*),

– water resources *N5* and *N6* were well chosen; they are directly or indirectly (0) related to all the other elements of the system,

– the following subsystems can be defined: *N1* and *O1* (the environment of this subsystem is the constraint on *O2*), *N2*, *O3*, *O4* (the environment of this subsystem is the constraint on *O6*).

The *relationship between the system and its environment* is reduced to O_N, i.e. the reliability of low-flow augmentation in the river that leaves the system under withdrawal *O2*.

This analysis having been carried out, as was briefly discussed, the *formulation of the task* is possible: Design an optimal completion of the multi-purpose WRS by additional water resources, considering primarily sites *N5* and *N6*. The system is to serve four main purposes (*Z*, *O*, *H*, and *R*), purpose *Z* being the main one and the other three constraints on it. The relationship to the system environment is given by reliability requirements for discharge O_N under withdrawal *O2*. In the treatment of the system it is necessary to delimitate two subsystems of the WRS, (*N1*, *O1*) and (*N2*, *O3*, *O4*), which are relatively loosely related to the other parts of the system.

2.4.2 Water Resource System Definition

In a multi-purpose WRS different subsystems can be defined:

– a subsystem of watercourses and reservoirs,
– a subsystem of drinking-water consumers,
– a subsystem of gauging stations,
– a subsystem of power transmission,
– a subsystem of communication, etc.

On the basis of the preliminary analysis the multi-purpose WRS was transformed into a single-purpose system with some constraints. The main purpose was water supply. Therefore this WRS was defined mainly as a water supply system.

The problem was precisely formulated to allow definition of the system, the system was quantified, i.e. subdivided into parts (viz. elements, subsystems), the relationships were determined, as given by the flow of water (Fig. 2.3). In the graphical representation a desirable and reasonable simplification was made and a system abstraction prepared.

The *elements and subsystems* are (*N1, O1*), (*N2, O3, O4*), *N3, N4, N5, N6, O2, O5, O6, O7, O8, O9, O10*; they include water resources and water withdrawals (canals and pipelines that facilitate linkage are considered as relationships).

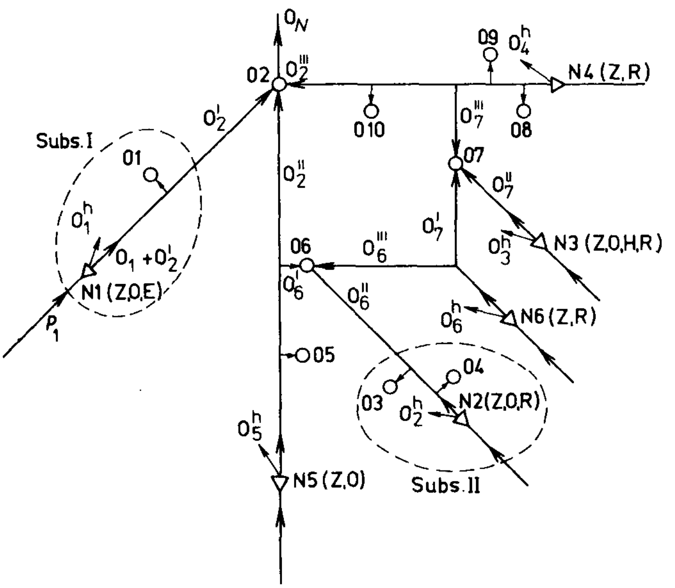


Fig. 2.4 Graphical representation of the water supply system

The river downstream of site *O2*, where O_N is to be maintained, is considered as an *element of the environment*.

The relationships between the elements of the system and with the environment are graphically represented in Fig. 2.4.

Further treatment is only outlined roughly; a detailed explanation is more suitable for a concrete case (see Chapter 12). The schematic representation in Fig. 2.4 or in Table 2.3 is not sufficient for an unambiguous (unique) procedure as it does not include e.g. the capacity of water resources, the dimensions of storage volumes of reservoirs, the quantity and importance of the withdrawals, water quality, etc.

The water supply system has dynamic inputs and outputs. It is an extensive system with six reservoirs so that further simplification would be necessary for optimization by dynamic programming:

– alternatively, the system is treated with different time horizons, (e.g. for the time level 1990, and 2000 with consideration of further development),

– for each time level a number of alternatives are dealt with and from the chosen criteria an optimum alternative is selected.

Firstly, both subsystems are considered (Fig. 2.4):

a) Subsystem (*N1*, *O1*): The relationships between the stochastic inflow $P_1 = P_1(t)$ and its statistical characteristics are known, assuming a similar knowledge of the municipal water supply $O_1 = O_1(t)$ and a given minimum flow O_1^m. Using these data and assumptions the storage volume A_{z1} of the reservoir *N1* can be calculated for a given reliability p_1.

$$A_{z1} = f(P_1, O_1, O_1^m, \mathrm{p}_1) \tag{2.1}$$

It was assumed $O_2' = 0$. In addition, the flood control storage A_{r1} and dead storage A_{s1} are determined and then (omitting the hydropower generation) the total storage volume of the reservoir *N1* is calculated (A_{p1} is the volume corresponding to spillage):

$$A_{1\,\mathrm{total}} = A_{s1} + A_{z1} + A_{r1} + A_{p1} \tag{2.2}$$

The possibility of allocating this volume in the given geomorphological conditions is determined and the technological and economic indices etc. are calculated.

If the hydrological and geomorphological conditions are suitable for $O_2' > 0$, then the corresponding indices are determined for several values of O_2' and compared with indices for O_2'' and O_2''' to optimize the water supply for O_2 from different water resources.

b) Subsystem (*N2*, *O3*, *O4*) is dealt with in a similar manner to subsystem (*N1*, *O1*) as the two cases are equivalent in principle, if withdrawals (*O3* + *O4*) are combined and constraints *H* and *R* are omitted.

In this subsystem a relationship between O_6'' and the water reservoir *N2* is obtained and expressed in appropriate indices.

We could further simplify the system by forming a subsystem (*N4*, *O8*, *O9*, *O10*), which has two relationships with the environment: *O2* and *O7*.

Having sufficiently and acceptably simplified the system, we can start to deal with the system in technological and economic units.

The optimum alternative is determined, using economic indices relating to the main goal and taking into account the secondary goals and intangibles as constraints.

In this way the problems of the system are solved for one time level. The system is then treated similarly for the second time level, using the same intermediate results from the first time level (e.g. the technical and economic parameters for O_2', etc.).

The results of both time levels are used in the choice of a final alternative.

2.5 WATER RESOURCE SYSTEM EVALUATION

The evaluation of a WRS and the decision-making concerning the optimum alternative for the system's development are difficult and possess some special characteristics, so that the usual ("classical") methods may fail. The decision-making process involves various institutions which prefer different criteria for evaluation. Even one decision-maker has a difficult task in a multi-purpose WRS with incompatible goals or in evaluating a single-purpose WRS using various criteria. In addition, such decisions are often irreversible, cause considerable impact, and involve great uncertainty in input data and prediction of development. A special, and in WRS a typical, problem is the combination of economic and intangible criteria.

In spite of many references to the subject (see e.g. Haimes, Hall, and Freedman, 1975), and attempts to formalize the decision-making and optimization process, subjective heuristic reasoning is still often an indispensable part of it.

The "Recommendation" of the Ministry of Forestry and Water Management of the ČSR on the evaluation of the effectiveness of structures in water management, 1976, includes methods for and examples of the evaluation of alternatives for water engineering structures by a procedure which includes relative and absolute efficiency, an evaluation of construction by stages, and the allocation of costs in a multi-purpose WRS. For the evaluation of WRS the method of decision analysis can be used as it is useful for the evaluation of alternative structures when a significant proportion of the requirements and consequences cannot be expressed in terms of money. This method reduces the subjective part of the evaluation (Novotný and Polenka, 1973).

2.5.1 Water Resource System Evaluation by Decision Analysis

The decision-making process consists of four steps:

1) definition of the criteria for the evaluation of the extent to which the alternative fulfils the purpose,

2) a simple evaluation of alternatives on a point scale,

3) mutual comparison of criteria in pairs using Fuller triangle,

4) a weighted evaluation of the alternatives by combining steps (2) and (3).

The *criteria* should express the principal purposes of the system and should not overlap. They are chosen according to the case being analysed:

a) *Cost* criteria include the initial costs, or a comparison of initial costs with a given limit. An alternative that requires lower initial costs may be preferred, using the objective function

$$Y = \sum_{i=1}^{n} I_i \overset{!}{=} \min \tag{2.3}$$

where H is the time horizon under consideration (e.g. Five-year plan), I_i – initial costs in time interval i.

b) *Production* criteria are concerned with the quantity and quality of water management production and services. The quantity is stated in technical units or in dollars, if adequate prices or unit costs are available. The quality is evaluated separately if price cannot express it (e.g. reliability of water supply, increase in water temperature in summer, etc.).

c) *Environmental* criteria are used for

– conservation and enhancement of the environment (the positive and negative effects of the alternatives on the present state of the environment and possibilities for reducing negative effects are evaluated),

– town planning and architectural evaluation of the water engineering structures,

– impact on the working and living environments,

– the use of water engineering structures for water-related recreation and sports,

– changes in land use (it is assumed that the economic value of the ground is expressed in costs for land, which are included in the initial costs),

– the extent of displacement of the inhabitants,

– preservation of buildings of cultural or historical value.

d) Criteria of *economic effectiveness* can include:

– the present value of initial costs and OMR costs (operation, maintenance and repair), if the outputs of the alternatives do not differ too much,

– the average discounted net benefits (if the outputs of the alternatives differ significantly and if it is possible to express the output in monetary units).

e) *Construction* criteria apply to the evaluation of positive and negative factors relating to construction that are not included in the initial costs such as the following items:

– duration of construction work,

– uncertain foundation conditions which have not yet been described by a geological survey,

– the dependence of the construction work on parts imported from abroad,

– the precision requirements for products which the producer can guarantee only with great difficulty,

– local climatic, transportation, manpower, etc. conditions,

– the use of standardization and prefabrication,

– the possible use of free construction capacity of the contractor.

f) Criteria of *optimization* include:

– the reliability of operation,

– the ability to rectify operational failures,

– the frequency of maintenance and repairs,
– the quality requirements for the supply of fuel, energy, and material, which are not included in their costs,
– the climatic conditions of operation,
– the operational constraints imposed by repair and replacement of construction parts.

g) *Development* criteria include:
– coordination with water resource development of the region, e.g. with respect to the development of superior WRS, General Water Plan, etc.
– development adaptability to changed conditions,
– conceptual reliability with reference to possible failures,
– the degree of continuous utilisation of the designed capacities with possibilities for construction in stages.

h) *Other* criteria, e.g.
– conflicts with activities of other sectors, which are mutually exclusive or constitute certain constraints,
– preparation for construction (design, land use, projects, operation, etc.),
– international conditions of construction in cases involving extention across borders into neighbouring countries, national defence, etc.
– coordination with the political interests in the region.

Table 2.6 Fuller triangle

Evaluated criteria	Criteria	Number of preferences
1 1 1 1 2 3 4 5	1	3
2 2 2 3 4 5	2	4
3 3 4 5	3	0
4 5	4	2
	5	1

a – with couples of rows

2 3 4 5	Criteria	Number of preferences
2 1 1 1	1	3
2 2 2	2	4
4 5	3	0
4	4	2
	5	1

b – with a single row

From the above-mentioned criteria those items are chosen that best characterize the effectiveness of the designed alternatives (or some new criteria are added).

A *simple evaluation of alternatives* is carried out by awarding each alternative and each chosen criterion a number of points, e.g. 0 (does not satisfy) to 5 (satisfies best). The total number of points gives the simple score of the individual alternatives.

The *mutual evaluation of the criteria* is carried out by comparison in pairs of all the criteria used and it is represented in a tabular form called Fuller triangle.

The Fuller triangle is composed of pairs of rows; the first row of each pair contains the serial numbers of the criteria being processed and the second row contains the numbers of other criteria that are compared with the criteria in the first row. The pairs in the column are compared and the preferred criteria are underlined. The number of preferences (underlined numbers) of the criteria score in the whole triangle determine their respective weights. To eliminate the case of a zero weight, all the weights are increased by one.

The Fuller triangle is substantially simplified (to half the rows without underlining) if instead of double rows only a single row with preferred criterion is used (see Table 2.6 for five criteria).

The *weighted evaluation of alternatives* is obtained by multiplying the figures resulting from the simple evaluation of alternatives in the second step by the weights of the corresponding criteria in the third step. The sum of all the weighted values of the criteria for each alternative yields the total weighted score, the highest of which determines the most advantageous alternative from the standpoint of the criteria used.

Evaluation of the method of decision analysis

The whole procedure is formalized and therefore objective. The choice of criteria and their evaluation is, however, heuristic. Both these properties tend to be advantageous but are sometimes disadvantageous.

The advantage stems from the fact that the procedure is unambiguous, and that the calculation is preceded by reasoning and deliberation that leads to a deeper understanding of the individual characteristics of the alternatives, which can be numerous and would otherwise be hardly commensurable.

The disadvantages pertain to the fact that the formalized procedure need not express in the way described the proper proportions of the relative advantages of the alternatives, and that in a choice of alternatives and their evaluation, a subjective standpoint might prevail.

Therefore the chosen criteria should exhaust all the important properties of the alternatives investigated. In particular, properties that differentiate the alternatives must not be omitted. On the other hand, criteria which are not important for the investigated structure can be omitted.

The subjective element can be diminished by first having the evaluation performed by several researchers individually. Their different views are then discussed, the effect of different conclusions on the results is determined and the evaluation is repeated.

The result of this analysis is not identical with the final decision of the decision-maker, but such an analysis is a very important decision-aiding tool.

An example of decision analysis

We are to decide between two alternatives using the following steps:

1st step – definition of criteria: they are listed in Table 2.7. (in this case, eight criteria).

2nd step – determination of the number of points (scale 0 to 5 points), the simple evaluation of both alternatives being given by the total number of points (Table 2.7).

Table 2.7 The list of criteria and the simple evaluation of alternatives

Criterion	Alternative	
	I	II
1 Economic effectiveness	5	4
2 Quantity and reliability of water supply	4	3
3 Flood control	2	4
4 Environmental impact	3	1
5 Land use and its change	1	2
6 Requirements of construction	3	1
7 Operational reliability	4	2
8 Adaptability to changed conditions	2	3
The number of points by simple evaluation	24	20

It is clear that the evaluation of some criteria by points and their interrelationships depend on the expert's judgement. In a real case, a greater number of criteria would often be used. Adding more alternatives causes no trouble. In our case, the simple evaluation seems to indicate that the first alternative (I) is the more advantageous, even if it is less advantageous from the standpoint of flood control, land use and change and adaptability to changed conditions.

3rd step – the comparison of pairs in the Fuller triangle (Table 2.8) is used in a simplified form (see Table 2.6.b). A subjective element also appears in this comparison in pairs.

4th step – the weighted evaluation of alternatives (Table 2.9) is obtained by multiplication of the values from the second and third steps (see Tables 2.7 and 2.8), the weight being the number of preferences increased by one.

Table 2.8 Evaluation in pairs in the Fuller triangle

2	3	4	5	6	7	8	Criterion	Number of preferences
2	1	1	1	1	1	1	1	6
	2	2	2	2	2	2	2	7
		3	3	3	7	3	3	4
			4	4	7	4	4	3
				6	7	8	5	0
					7	8	6	1
						7	7	5
							8	2

Table 2.9 The weighted evaluation of alternatives

Criterion	Weight	I		II	
		simple	weighted	simple	weighted
1	7	5	35	4	28
2	8	4	32	3	24
3	5	2	10	4	20
4	4	3	12	1	4
5	1	1	1	2	2
6	2	3	6	1	2
7	6	4	24	2	12
8	3	2	6	3	9
Total			126		101

It is clear that in a weighted evaluation a difference in the effect of the individual criteria is more pronounced than in a simple evaluation.

In this case also, alternative (I) was more advantageous.

In view of the nature of the evaluation the result must be considered as a preliminary one. It is necessary to return to the decision criteria, to the uncertainty in the preferences, and to determine the effect of possible changes on the resulting final evaluation. (Sýkora, 1980). However, only one part of the decision-aiding information will be obtained in this way[1]).

The weights of criteria are very important in the methodology applied. The deterministic approach using the Fuller triangle in fact does not determine the "weights" according to the meaning of experts but their significant order based on mutual comparison. Bečvář, 1986, suggested to use instead of the point evaluation a linguistic one based on the evaluation of criteria and their values for the individual alternatives analysed.

The experts are given a sufficient number of statements describing the quality (e.g. 25 statements for evaluation from "excellent" or "extraordinary" to "catastrophic") and approximately the same number of statements for expression of the quality (from "giant" to "zero") and about nine sentences for different combinations of both individual evaluations. The variability of the possible evaluations is sufficiently rich.

For an objectively justified transition of the verbal statements to the numerical evaluation about two hundred experts were interviewed by Bečvář in order to transfer the imagination of the numerical evaluation of the statement into a 50-point scale. The graphical evaluation by a subjective function of the relationships of the point scale elements to the statements and the sentences was added. The central "gravity" points and the "width" of each statement were the results of these data processing.

[1]) The method of decision analysis described above was used by a team of eleven members of the research institute, the university of technology and the water board responsible for WRS operation, for the determination of the optimal alternative for the capacity of the Slezská Harta reservoir (see Chapter 12). The capacity designed by various projects varied from 150 to 330 mil. m^3. The table shows the results of six typical respondents, including the whole capacity range. About half of the thirteen criteria show profound differences. Nevertheless, the weighted evaluation tends to favour the lowest capacity *A* or the middle capacity *B*. The results of respondents 4, 5, 6 reveal little difference between alternatives *A*, *B* and *C*:

Respondent		1	2	3	4	5	6
Weighted	*A* (150 mil. m^3)	1.00	1.00	1.00	0.99	1.00	0.99
score of	*B* (210 mil. m^3)	0.74	0.86	0.91	1.00	0.94	0.99
alternatives	*C* (250 mil. m^3)	0.64	0.80	0.88	0.99	0.93	1.00
(final values):	*D* (290 mil. m^3)	0.35	0.69	0.71	0.77	0.71	0.88

This method was used with a good result in comparing four alternatives of a big pumping water plant in Czechoslovakia where the environmental ciriterion of an ecological area protection was applied. Using the Fuller triangle the ratio of the lowest criterion to the highest would be 1 : 11, according to the verbal evaluation of the experts this ratio was approximately 1 : 2 only.

2.5.2. Economic Evaluation of Water Resource Systems

The economic evaluation of WRS is always a fundamental one and no decision-making process can do without it. Economic and other evaluations are used in the rational design of WRS not only in the final stage of the project but during all its stages. Only in this way can a project that is feasible and sufficiently close to the optimal alternative be obtained.

The evaluation of effectiveness from the standpoint of society as a whole is more difficult than a mere cost-benefit analysis. A cost-benefit analysis using only market prices for monetary evaluation of effects is not acceptable as it does not include all those social consequences which cannot be expressed as relationships between supplier and consumer.

Therefore, not only market prices but also "shadow" prices (Krutilla, 1962; Maass *et al.*, 1962; Vitha and Doležal, 1975; Recommendations, 1976) are recommended for the evaluation of products and services, which are not used in relationships between supplier and consumer.

Vitha and Doležal, 1975, describe the method of calculation of these shadow prices (price equivalents). For products where the amount of human labour involved can be calculated, the two prices must be the same. For multi-purpose production an iterative procedure is recommended.

In the first step of the calculation, it is assumed that the total value of the benefits, CV, of Water Boards and engineering organisations all over the country has to correspond to the total costs, SNN, that must be paid by society over the given period (e.g. five years plan or an annual average of this five year period), then

$$CV = SNN \tag{2.4}$$

and

$$CV = V_1 + V_2 + \dots V_n = \sum_{i=1}^{n} V_i \tag{2.5}$$

where V_i are benefits from the individual water-related products and services, for which the following relationships is valid

$$V_i = SNN_i \tag{2.6}$$

Since, in this step, the prices for the determination of the benefits are not known, they are determined on the basis of replaceable products (e.g. electric power from thermal power plants, transportation by railways, etc.) or by prices that the consumer is willing to pay (e.g. the shadow price of water-related recreation). These benefits are denoted by $\bar{V}_i$ and $\overline{CV}$; it is possible that

$$\overline{CV} = \sum \bar{V}_i \gtreqless CV \tag{2.7}$$

If $\sum \bar{V}_i$ is greater than CV, the multi-purpose treatment is effective; if $\sum \bar{V}_i$ is less than CV, this treatment is not advantageous.

Since equations (2.4) and (2.5) must be satisfied, the benefits $\bar{V}_i$ may be reduced to $\bar{V}_{ir}$, as the total cost of replaceable products and services should be greater than their socially necessary costs:

$$\sum \bar{V}_{ir} = CV = SNN \tag{2.8}$$

Since up to this point an equal effectiveness for all the products was assumed,

$$\bar{V}_{ir} = k\bar{V}_i \tag{2.9}$$

where

$$k = \frac{CV}{\sum \bar{V}_i} < 1.0 \tag{2.10}$$

The calculated price of the product or service in the first step will be

$$C_i = \frac{\bar{V}_{ir}}{P_i} \tag{2.11}$$

where P_i is the quantity of the product or service for one year (in technical units).

The prices obtained in this way in the first step are corrected by common and individual costs of the corresponding common and individual parts of the multi-purpose water engineering construction.

There are many methods for the allocation of costs of a multi-purpose project among the individual benefits (Votruba and Broža, 1966). "Recommendations", 1976, allocates the costs in proportion to the benefits and side effects expressed in monetary units. If there are significant side effects among the inputs and outputs of the multi-purpose water engineering project, which cannot be evaluated by shadow prices, these effects may be evaluated by the initial and OMR costs of the substitute or they may be determined by agreement among the users. The result depends on the precision of the econometric measurement of products and services.

2.5.3 Multi-Objective Optimization

In the optimization of multi-purpose WRS several criteria are applied and the problem of multi-purpose optimization arises. Studies on such subjects have been published since the early seventies[1].

Treatment of multi-purpose optimization by means of a mathematical model requires a definition of the individual objectives, the relationships between them and the goals of the system and, based on them, a global objective of the system leading to a unique algorithm for the selection of the optimum alternative. Often, ideas of desirable and feasible values of the criteria are modified during this treatment; this leads to a compromise solution, which takes into account the interrelationships of criteria in feasible solutions and the requirements of the decision-makers.

The partial goals require their maximum or minimum values (extreme goal) or they are expressed in the form of the constraint (constrained goal). The analysis of their relationships to the objectives of the system should be followed by a synthesis to form a selection method.

The multi-objective task can be treated in such a way that the most advantageous is selected from among several solutions, or that this task is transformed into a single-purpose problem. Molnár, 1976, considers as promising the development of heuristic convergent models which combine both these approaches. Their principle is iterative and the decision-maker reduces, in a series of steps, the set of feasible solutions on the basis of information about the criteria gained in the previous steps. Each objective in this procedure is interpreted as a constraint (principle of satisfaction), and step by step the individual constraints are loosened until the resulting value of the objective is unaffected by the loosening in the previous step. The values of the objectives obtained in each step express the "degree" of satisfaction of the decision-maker. The iterative treatment gives a sequence consisting of the non-decreasing "values" of satisfaction so that, at the end of this sequence, a solution with a maximum "value" of satisfaction (utility) is obtained. The treatment can be applied to the model of the theory of games (Belenson and Kapur, 1973), the parametric model (Fandel, 1972), the eliminating model (Banayoun and Tergny, 1970) and others.

If in WRS one goal (e.g. economic effectiveness) is ranked above the other goals, a single objective can be used (e.g. the standpoint of the national economy), and the optimization can be performed using mathematical decision-optimization models; the secondary goals can be used as constraints with estimated values. Lately, however, there has been a tendency to give intangible goals the same priority and the same weight as economic efficiency.

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[1]) They include the following: Banayoun and Tergny, 1970; Roy, 1970; Lebedyev *et al.*, 1971; Fandel, 1972; Belenson and Kapur, 1973, etc. The multi-purpose optimization of WRS: e.g. O'Riordan, 1973; Monarchi *et al.*, 1973; Cohon and Marks, 1973; Haimes and Hall, 1974; Haimes *et al.*, 1975.

The application of a vector of objective functions creates a new quality in modelling, mathematical programming and optimal control, especially if there is no numerical estimation of optimal solution. In water resource analysis, a number of studies of systems with several goals have been carried out. O'Riordan, 1973, when planning basins in Canada, introduced the objective of economic growth and an environmental objective. Monarchi *et al.*, 1973, developed an iterative method that leads to a solution on the principle "not less than". Cohon and Marks, 1973, tried to find the best solution from the standpoint of the gross national product and regional reallocation of the product in a developing country. Haimes *et al.*, 1974 and 1975, developed a new approach, viz. the surrogate worth trade-off method. This method is based on the assumption that in the optimization theory the relative values of increments of different intangible goals, given the value of each objective function, are more important than their absolute values. The decision-maker can more easily estimate the relative values of the increments and decrements between any two goals than their absolute values.

A great advantage of the surrogate worth trade-off method is that intangible goals can be evaluated quantitatively. Therefore, they can be used for the multi-purpose analysis of water resource utilisation when questions of the design, construction and operation of reservoirs or water quality are involved.

Multi-purpose optimization, although not yet completely worked out, is one of the most important issues of systems analysis, including the analysis of WRS. In this book some literature references are given and some approaches are discussed which are promising and which should be developed in general and in application to WRS.

2.6 APPLICATION OF HEURISTIC METHODS IN WATER RESOURCE SYSTEM ANALYSIS

Heuristics[1]) is an interdisciplinary science that deals with the investigation of methods of treatment and reasoning that optimize (e.g. by reduction) the solution of problems as compared with less effective random procedures or highly specialized methods (Linhart, 1976).

Heuristics (i.e. the theory of heuristic methods) takes into account logical, mathematical, cybernetic, psychological and philosophical aspects. It investigates the psychological and logical conditions necessary to make the treatment of a problem

[1]) Definition of heuristics in Webster's Third New International Dictionary (G & C Merriam Co., Springfield, Mass. U.S.A., 1963): heuristic is the science or art of heuristic procedure valuable for stimulating or conducting empirical research but unproved or incapable of proof – often used for arguments, methods and constructs that assume or postulate what remains to be proven or that lead a person to find out for himself.

by an individual or by a team more effective, it rationalizes mental activity and helps in its planning by heuristic programs.

The *heuristic process* treats a problem in terms of a certain probability and the researchers use analogy, intuition, additional questions, etc.

The new method that can help to reduce the number of alternative approaches to the problem under consideration, with unknown procedures leading to the solution, is often called heuristic. On the other hand, algorithmic methods can be used if the method leading to the solution of the problem is known (an algorithm is a unique, precisely determined procedure of problem solving).

The selection of the method depends on the type of problem: If the problem is well defined and thoroughly logically described, it can be solved by some algorithm on a computer; the vaguely defined problem, however, can be solved only by a human being, since the treatment includes some gnostic activity that is, by definition, a non-algorithmic process. The heuristic treatment of a problem or control of activities starts at the moment the goals and methods used are inadequate for the requirements and a new plan of activities needs be set up.

The heuristic method consists of three main stages (Linhart, 1973):

- formulation of the problem and analysis of the conditions and constraints,
- treatment, i.e. generation of hypotheses, selection of strategies and operations,
- verification of the correctness of hypotheses and adequacy of the method, implementation of the results in practice.

Six main heuristic methods can be distinguished:

- "generate and test" (GT),
- method of adaptation (MA),
- "hill-climbing" (H),
- heuristic search (HS),
- inductive method (IM),
- hypothetical-deductive method (HD).

These methods can be combined and new ones added (Newell *et al.* 1958, 1959, 1969; Pushkin *et al.* 1969, 1971, etc.). All these methods involve the creation of an internal model of the problem by a hypothetical-deductive process (Rubinstein, 1960), when the hypothetical causes of the phenomena appear in the mind of the researcher and he makes deductions from them. In this creative thinking, which is one of the basic heuristic approaches, there is a dialectical unity of analysis and synthesis, generalisation and abstraction. Depending on the state of the treatment, synthesis can procede analysis or vice versa, so that synthesis is an indispensable tool for analysis and analysis for synthesis.

The six above-mentioned heuristic methods were arranged according to the degree of activity of the hypothetical-deductive model, complexity, strength, and generic properties of the methods. GT is the simplest method, as appears from its flow-chart (Fig. 2.5, Linhart, 1976). The researchers generate at random an element x

from the set X; it becomes an input of a decision test which shows whether x has the property P; if it has, the loop ends and a further element can be generated; if it does not, the element is omitted. The GT method is used for the determination if the property P is satisfied in the set X. It is clear that the heuristic strength of this trial and error search of the GT method is low.

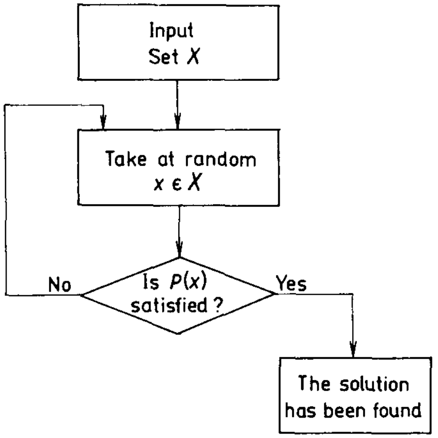

Fig. 2.5 Flowchart of the method "Generate and test" (GT)

The strength of the method is evaluated from three standpoints:

– what is the probability that it will yield a solution?

– what is its quality? how does it optimize the solution?

– what variability of procedures does it have (e.g. different methods of calculation, etc.)?

The universality of the method is given by the variety of problems that can be solved in this manner. Frequently new information that increases the strength of the method decreases its universality.

Experiments to integrate the logical – formal procedures of mathematical models and human activities on the subject of decision-making in heuristic models produced the heuristic convergent models used for multi-objective optimization (see section 2.5.3). The main working tool is the mathematical model. Comparison of alternatives is possible if there are measurable consequences of the decisions taken in accordance with the given goals. In the final estimate of the consequences in complex technical and economic systems, e.g. WRS, a decisive role is played by the "individuality" of the decision-maker with his knowledge and his priorities. The grading of goals is significantly influenced by the subjective attitude of the decision-maker.

2.7 PROGNOSTICS IN THE DESIGN AND OPERATION OF WRS

The nature of water management (i.e. limitation of water resources, the long-term consequences of water engineering structures for man and the environment, their irreversibility and long-term economic life, etc.) forces the water resource planners to deal with the distant future, which is not possible without long-term, medium-term and also short-term predictions. Systems science, therefore, includes prognostics as a scientific field that investigates the general principles of development, methods of prediction for arbitrary objects and the laws involved in process of making predictions (Gvishiani and Lishichkin, 1968).

The causal dependence between social development and water demands, with the necessary development of the utilisation of water resources, necessitates making water management predictions related to the development of society, i.e. the number of inhabitants, their standard of living, the development of industry, agriculture, etc.

Therefore, the General Water Plan (GWP) of Czechoslovakia is based on the development plan of the national economy till the year 1990 and the known or predicted number of inhabitants for the time horizons 1970, 1985, 2000 and 2015. For these time horizons the following data were collected and predicted:

– structure of the settlement (i.e. the movement and concentration of the inhabitants, the proportion of the population living in towns and villages of up to 2000, 5000, 10 000, 100 000, and above 100 000 inhabitants),

– the standard of living and the facilities available (e.g. category of flats, municipal water supply, sewage, etc.).

Trends in industrial production, allocated to the individual sectors, were given till 1985, the long-term trends in agriculture and environment till the year 2000. The general evaluation includes the prediction that the greatest industrial and urban development will be concentrated in the present industrial and population centres. In other regions the development of recreational utilisation can be envisaged.

Water resource predictions are related to social and economic predictions that are typical for centrally planned economies. Specific predictions precede the planning stage, but they need not be incorporated in the plan[1]).

Predictions are integral components of every theory, particularly of systems theory. Management and control (the subject of cybernetics) include two integral parts: the forming of predictions and plans. Prognostics as a scientific field is in a state of rapid development. The stage of creating working methods has not yet been completed; Pearce, 1973, enumerates eighteen possibilities.

Prediction stems from past development; therefore a thorough knowledge of that is a necessary but not the only condition of reliable prediction. In social, econ-

[1]) In this sense the GWP is more of a prediction than a plan, as it does not determine the tasks that have to be performed but rather provides an outline ("scenario") of the further development of water resources in the whole country and in its individual regions.

omic and natural phenomena the deterministic components are accompanied by many random factors; even the best prediction, therefore, has a limited degree of accuracy.

Even if a diagnostic analysis of the past and present states has been performed from a prognostic standpoint, the bounds of variability of the future development may be found to increase with the distance of the time horizon of the prediction.

In economics, predictions are often classified according to the distance of the time horizon into short-term (1 – 3 years), medium-term (3 – 7 years), long-term (10 – 20 years), and perspective (30 years and more). The definitions of these terms are not clearcut (Kozák and Seger, 1975) and in water management and in GWP mainly long-term and perspective predictions are used. A great problem in water management, therefore, is the danger of extrapolation of trend curves into the distant future.

Prediction, including its exactness, depends on three sources:

– the results of observation and monitoring of the past period and their correct processing (*input data*),

– *prognostic theory* (model), describing the effect of individual factors,

– *predictor*, i.e. the method of prediction determination used for calculation of the prediction from the input data.

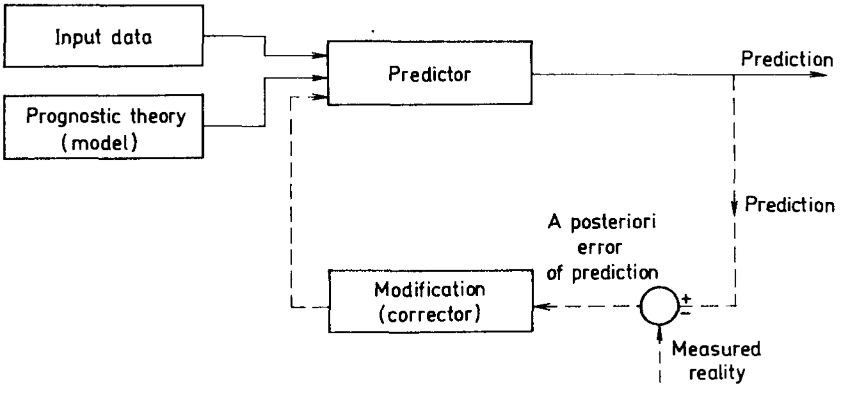

Fig. 2.6 Schematic representation of the prediction process

The flowchart in Fig. 2.6 shows the basic scheme of the predictive process marked by a solid line (Kozák and Seger, 1975). This flowchart indicates that prediction is the estimation of the future level of an unknown quantity according to a model which uses a certain predictor and observed input data.

The prediction may be *quantitative* (numerical) or *qualitative*. In technical and economic problems, quantitative predictions are fundamental; they are expressed by single values (*point* prediction) or by ranges (*interval* prediction). The difference between the predicted value and the real value is the *error of prediction.*

Together with general scientific methods and methods from other fields, interdisciplinary methods are used in prognosis.

The predictions in water management employ mainly the following methods:

- interpolation and extrapolation methods,
- methods based on the probability theory and mathematical statistics,
- methods of analogy,
- modelling methods,
- methods based on the estimation of experts.

Interpolation and extrapolation methods

The elements of a dynamic sequence are determined by *interpolation* using the analysis of relationships between the existing elements. The problem of interpolation is often solved by the determination of a regression function which includes a degree of deviation of empirical values from theoretical ones.

Extrapolation serves for the estimation of the values of the selected function outside the known interval based on the known values inside this interval. In technical and economic predictions, errors of prediction always occur because:

– the regression function of past development is only an approximation to reality,

– at the time of prediction there is no knowledge of the difference between future and past development,

– only a limited number of random effects can be included in the regression function; other random effects not included in its determination cannot be estimated.

No prediction model can eliminate all the sources of error but it can minimize them.

In economy and water management, an *extrapolation of trend curves* into the future often occurs. Besides the trend (long-term tendency), the development in water management includes a *seasonal* component (oscillation), often with annual periods, and a *random* component that is not a function of time. The choice of the trend has the greatest impact on the predicted values, and this influence grows with the distance of the time horizon.

The applied trend curves have three forms:

– monotonically increasing, unbounded for $t \to \infty$ (e.g. linear trend $y = a + bt$, quadratic trend $y = a + bt + ct^2$, exponential trend $y = a + b\,e^{ct}$, logarithmic trend $y = a + b \log t$);

– monotonically increasing or decreasing (without inflection point) to a non-negative asymptote for $t \to \infty$ (e.g. a simple exponential trend: $y = b\,e^{-ct}$, hyperbolic trend $y = a - b/t$; Törnquist' curve $y = at/(b + t)$ etc.);

– having one inflection point and a non-negative asymptote (S – shaped curve, e.g. Gauss–Laplace integral curve $y = \int_{-\infty}^{t} F(x)\,dx$, logistic curve $y = a/(1 + b\,e^{-ct})$ etc.).

The shapes of the trend curves are given in Fig. 2.7a. The trend functions are compared by means of the functions of growth rate that are given by the first derivative of the trend function $y' = dy/dt$ (Fig. 2.7b).

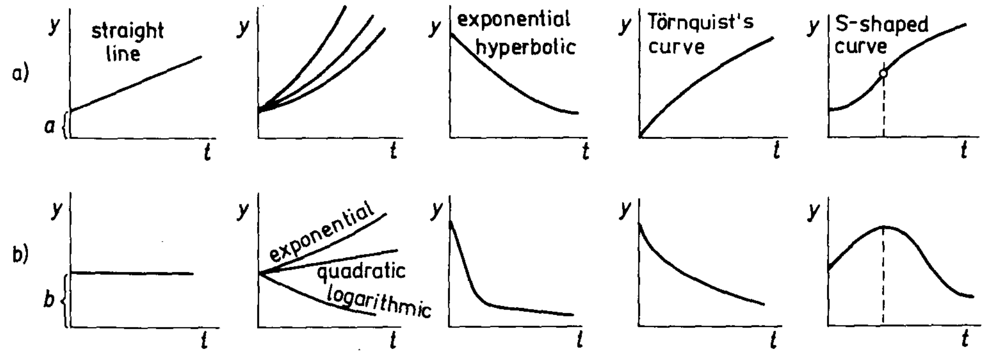

Fig. 2.7 The forms of functions
a – trend function, b – growth rate

The choice of the trend and the growth rate function need to be verified by analysis of the nature of the extrapolated phenomenon, and empirically (i.e. statistically); the former is the basic verification, the latter is an auxiliary one.

The final verification of the exactness of extrapolation (and other) predictions is a comparison of reality with prediction. The errors of prediction can be clearly seen in the Theil P-S diagram (prediction – reality) as deviations from the line of "errorless predictions" that crosses the origin of axes and has a 45° slope – on the abscissa the predictions and on the ordinate the observations are drawn to the same scale.

Using errors thus revealed, the prediction model can be modified (corrected) step by step and the adapted prediction can be attained. The basic flowchart of prediction can therefore be supplemented by modification or by feedback (in Fig. 2.6 drawn by a dotted line).

Methods based on probability theory and mathematical statistics

Although probability calculus is used in other methods, too, statistical estimation methods are classified as an individual group since they have a common basis in a correlation relationship between real phenomena (that need not necessarily be causal). The correlation between two phenomena may be caused by the common influence of a third factor; e.g. the correlation between the time series of flows in two gauging stations is caused by similar meteorological and morphological properties of both basins.

The correlation relationship can be described by some statistical characteristics, or by regression equations that can be used for the determination of data concerning one phenomenon on the basis of data for a second one.

Formal mathematical correlation analysis must always be combined with physical analysis to avoid the danger of *spurious correlation*, i.e. when, numerically, the "existence" of a correlation relationship between two phenomena is proved, but, in fact, they are not related (e.g. exponential growth of electric power production and growth of criminality in a social group etc.).

In some cases, a correlation with some *time lag* is possible when the dependent variable is to be correlated with the independent (factor) variables shifted back by some time interval (lag). For example, the water temperature at a particular point in a river can be correlated with the temperature at point upstream, which was measured earlier in time, i.e. time reduced by the time of travel between these two points. These questions are investigated by factor analysis of the time series.

Correlation analysis among more variables is performed by *multiple regression* (see Chapter 3).

The reliability of statistical predictions depends on the reliability of the input data and the logically approved validity of the probability method (model).

Method of analogy

Methods using analogy have often been used in water management problems (e.g. hydrological analogy, electronic and hydrodynamic analogy, etc.). Analogous phenomena are governed by the same laws. Physically they need not be related, e.g. electrical current and water infiltration are both described by the relationship $z = k(\partial y/\partial x)$, the increase of some biological parameters and the growth of scientific information both by an S-shaped curve, etc. In view of the physical independence of analogous phenomena, the reliability of prediction by analogy has to be proved by an alternative method.

In management, sometimes, the *method of historical analogy* is used when the prediction of future development is based on the development of an analogous past phenomenon. For example, the development of water demand in an area with a designed municipal water supply is derived from the growth of demand that occured in another area where the municipal water supply was installed earlier.

The basis of the success of this method is the proof of the likelihood and validity of the analogy under consideration (e.g. analogy of social, local, historical or other conditions).

Modelling method

With the increasing complexity of the problems and the phenomena being predicted, the importance of modelling is increasing. Instead of real objects, models of them are investigated and the results are then transferred from the model to reality. Modelling (i.e. mathematical modelling) of WRS is an integral part of the methods with which they are treated (see Chapters 5, 6, 7, 8).

Technical, scientific and economic predictions often require computer-based models. Four steps have been worked out for such models (Gvishiani and Lishichkin, 1968):

a) Representation of a future reality in technical, economic, social or other areas with regard to national requirements; the trends are extrapolated at the upper and lower levels,

b) probability calculation of relative frequencies,

c) systems correction of errors,

d) integration of the previous stages by computer modelling (sometimes without computer); the result is the prediction of development trends and alternatives for planning strategies.

Methods based on the estimation of experts

Predictions of phenomena that have no analogy in the present or in the past and that cannot be formalized are often based on the predictions of experts, who are assumed to be able to estimate the trends of future development in their own fields. These estimates can be obtained in different ways:

a) *Brainstorming* aims to reveal new ideas through the intuition of experts "in the process of brain tension". It is assumed that among the many ideas of the individuals and groups of experts some important ones may be discovered. For the success of the method the following points are recommended:

– the basic features of the problem should be delineated from one preferred standpoint;

– no idea should be omitted as being incorrect; it should be developed, even if it does not seem realistic;

– open discussion should be stimulated and the intellectual tension should be maintained.

b) The method of *group tension* is based on the consensus of views on some question in a group of experts,

c) The method of *operation creative activity* aims at the most probable solution in the situation where only the chief officer of the project is thoroughly informed about its nature and possible methods of treatment.

d) The *Delphi* method tries to predict future development by a statistical evaluation of the views of the experts on expected development in their own and marginal fields. The experts receive a questionnaire on these issues which is (a) formulated in such a way that the answer may be quantitative, and (b) used in iterative cycles with increasing precision of questions and answers.

Every expert with a specific point of view has to explain and justify it. The method is carried out in writing which excludes direct discussion but facilitates a continual exchange of views. The result combines the prevailing views on the given question expressed quantitatively in terms of means, quantiles and correlation between the time horizons of the events (e.g. discovery).

Computers are used for the prediction of long-term development trends. The computer prediction programme of the British chemical concern ICI (Pearce, 1973) includes six basic trend curves: straight line, parabola, simple exponential curve, logarithmic parabola, modified exponential curve, and the Gompertz curve, where the growth rate decreases to the final value given by the user.

In the light of ICI's experience, these trend curves are more suitable for the prediction of total consumption in a country than for the sales of any particular firm. For a good prediction the past series has to be longer than 7 years; better 12 to 15 years, and, for very variable data, 25 years give reliable results.

Non-linear extrapolation is sensitive to the most recent values. In short-term predictions over one or two years, deviations from the trend have a decisive influence. The selection of input data and the interpretation of the results require a good insight into the problem.

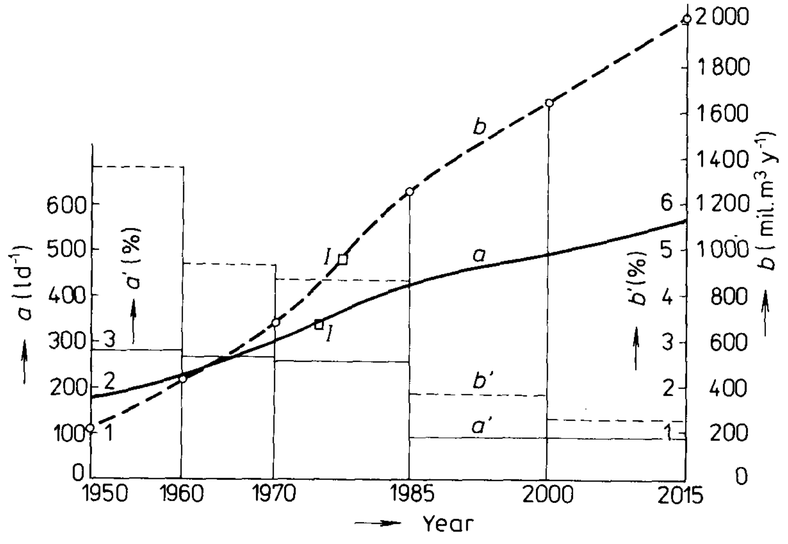

Fig. 2.8 The development and prediction of municipal water supply in ČSR
a – specific demand (litres per day per inhabitant), *b* – annual prediction of drinking water ($10^6 . m^3$ per year), *a'* – average annual increment of specific demand (%), *b'* – average annual increment (%)

The prediction of water resource demands in the GWP was derived from the prediction of social development and from other research papers. In alternatives obtained from processing the data from all over the country, the differences between the extreme values were so small that, with the exception of water pollution, the trend of the development of all the basic requirements could be characterized in each time horizon by a single value. Regional correction of the requirements is part of the continuous prediction-conception activity that follows the GWP.

The prediction of the development of the municipal water supply in ČSR in Fig. 2.8, is expressed in specific demand, its average annual increment, total production of drinking-water, and its average annual increment. The trend curves are flat S-shaped curves with the inflection point expected in the years 1976 to 1980: the average annual increments (growth-rate function) have an irregular but steadily decreasing tendency.

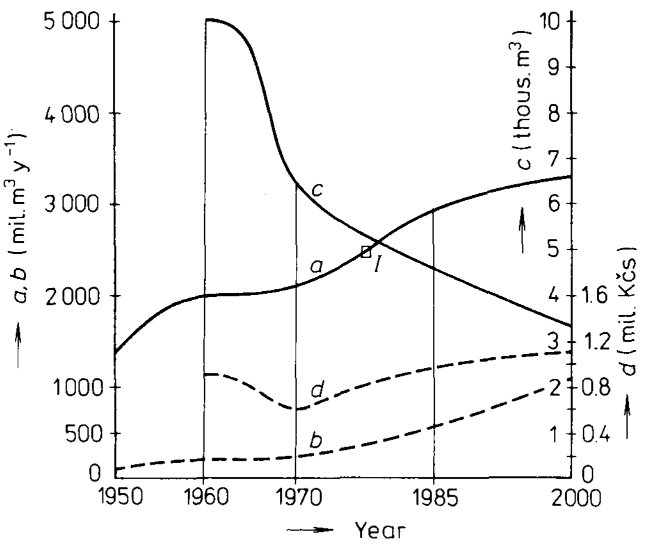

Fig. 2.9 The development and prediction of trends of withdrawals and consumption of water in industry of ČSR
a – withdrawals of water resources, *b* – consumption of water, *c* – withdrawal of water per 1 mil. Kčs of production, *d* – consumption of water per 1 mil. Kčs of production

Similar trend curves of withdrawals and consumption of water in industry are given in Fig. 2.9 (curves *a*, *b*). The further development curve (*a*) has an expected inflection point in the years 1975 to 1980; curve (*b*) monotonically increases. The same figure (curves *c*, *d*) shows the predictions of the development of withdrawals and consumption of water per 1 mil. Kčs (monetary unit in Czechoslovakia) of industrial production in ČSR.

The specific withdrawals decrease monotonically while specific consumption, after decreasing until the year 1970, increases again, and it will double in 30 years.

Similarly, trend curves can be analysed for water supply for agriculture, development of water quality, flood control, etc. Plans for the development of water management activities and the requirements of other sectors that form the necessary conditions were based on these predictions.

Similar analyses were carried out for the main basins which approximately coincide with the areas where WRS were defined on the discriminating level of GWP.

2.8 FUNCTION OF CREATIVE TEAMS AND WORK GROUPS IN THE DESIGN AND OPERATION OF WRS

The origin and development of WRS and the necessity of their rational design and operation require a qualitatively new activity that goes beyond the boundaries of any one discipline. In the treatment of interdisciplinary problems, the coordination of experts on different subjects is necessary; e.g. the problems of WRS require experts in the following fields: hydrology, hydrogeology, water quality and water pollution, environment and wildlife, probability theory and mathematical statistics, numerical analysis and computers, systems analysis, economics, operation of water engineering structures, town planning, etc. According to the nature of the problem and the relative importance of different fields, the set of experts may form either a creative team (also called a consulting panel, task force group, advisory committee) or a work group.

A *creative team* is a group of highly qualified experts from selected backgrounds whose aim is to tackle and solve a particular problem, or to design a method for a given task, a set-up which is not possible in a project or planning organization. Unlike a work group, this team deals with the problem as a whole and therefore its responsibility is collective.

In a *work group* (e.g. of authors, department) work is allocated to members, the results are put together, perhaps coordinated, and this is the end of the work on a given task.

In a creative team there is a distribution of work, but the main point is its integration.

In homogenous as well as in heterogenous teams, no one discipline is predominant, all are equally important. The team is free to determine the content of the work and the direction the investigation of a roughly outlined problem should take. Its success depends on team interaction, the exchange of information inside the team and a climate of friendship and trust, where everybody can express his own views and influence or oppose the views of the others.

When there are different views, decision by voting is not acceptable; the problem has to be discussed and explained and the alternatives optimized, using the approved criteria, until agreement is reached. If it is not possible to decide which of two alternatives is the better, both must be followed up.

Sládeček, 1973, describes typical approaches to creative team activities:

– *brainstorming*, in order to generate, in a short time, as many alternatives for the treatment of a given problem as possible,

– a *morphological* approach when the problem is split into various elements, after which relationships and mutual combinations for the set-up of the new functions, relationships, etc. are derived,

– *synthesis* when a special method of connecting seemingly unrelated elements is used, together with analysis and analogy,

– the use of *control lists*, i.e. listing the interrelationships of particular elements and their transformation in accordance with certain rules,

– the *optimization* method, generating alternatives and selecting the best one,

– the use of *lists of properties*, suitable for tasks which aim to improve the functioning of the system,

– the use of *models*,

– an *operations research* approach,

– a *systems engineering* approach,

– *heuristic* methods.

The probability of finding a successful solution to the problem depends on the quality of the methods applied and on the number of original ideas which can be generated.

The team cannot do without a leader, whose authority has to be based on the trust of all the members of the team and not on his power or social position. A good leader must be outstanding in his own field and he has to have original ideas; he has to be able to differentiate between good and bad suggestions, he has to stimulate work and create a favourable atmosphere. The success of the work of the team will be endangered if its composition is unsuitable, if the task is beyond its professional or time capacity or if its style of work is not effective.

The work on WRS problems can be performed by a creative team and a work group: the former for scientific research and the latter for the design and operation of concrete WRS, using known methodology. The creative teams are often composed of employees of different organizations and institutes, whereas the members of the work groups come from the same organization. The head of the team is usually a well-known expert with informal authority; the head of the work group is the formal head of the organization or one of its departments. In the team there is no hierarchy, but in the work group this does exist. The team is led, the work group is managed or controlled. There are, therefore, better conditions for the development of creativity in the team than in the work group. However, neither type of internal organization is in itself a guarantee of a good working style and good results. There are work groups where the management, style of work, and results are on the level of a good creative team and, conversely, there are creative teams full of "comedies of errors" (viz. administrative, personal or actual errors) which hinder the success of the work.

In the selection of the team members, not only professional orientation should be taken into account but also personal character. Egocentric individuals (who are far from scarce in research or science) are not suitable people for team work. Team cooperation is not a temporary fashion but an integral part of the scientific and technological revolution, and as such it should be promoted and its foundations laid during school education.

An example of a creative team in WRS

The investigation is related to the nature of the task and the problem is outlined roughly so as not to restrict the creative freedom of the team – e.g., "Set up a methodology for the design and evaluation of a WRS with water supply its first priority".

Table 2.10 Formation of creative team for the design of WRS with water supply having priority

1 Conception of the structure of system and definition of WRS	Experienced water resource planner with education in systems sciences	Water resource research institute
2 Determination of municipal water supply subsystems	Experienced water resource engineer with education in water supply and systems analysis	Hydroproject
3 Water balance of the system	Hydrologist and water resource engineer or planner 1 or 2	Hydrometeorologic institute
4 Assembly of mathematical models of WRS	Mathematician with education in systems science or systems engineer with mathematical education	Research institute of computer science or water management
5 Optimization of alternatives	Economist with systems education	Water management or economy research institute
6 Consultative cooperation of experts	– for land use plan – for environment – for the objectives of WRS – for operation of WRS	Terplan (territorial planning) various organisations various organisations Water Board

A schematic representation of the development of the team is given in Table 2.10. First, a list of activities necessary for the solution of the problem is compiled. Then, the types of experts are added to this list and possibly the organisations and institutes where these experts are to be found. To facilitate cooperation and communication inside the team, the number of members should be kept low.

For this reason, the types of activities and types of experts are divided into two groups:

– basic permanent activities which participate substantially in the problem solving during the whole period of the work,

– auxiliary activities necessary for dealing with the problem but not on a permanent basis.

The experts in the first group should be members of the team, the experts in the second group should be consultants. However, the formation of the team is ultimately adjusted according to the ability and character of the individuals involved.

In our case, a team with five members, supported by some consultants, will be formed. The natural head of the team should be an experienced water resource planner with a training in systems sciences. The table shows that every member of the team for WRS should have some knowledge of systems sciences (analysis); the applied systems sciences should be a normal part of the basic training in water resource engineering and planning.

2.9 AUTOMATIC CONTROL OF WATER RESOURCE SYSTEMS

2.9.1 Subjects of the Automatic Control Theory and Its Relationship to Cybernetics

Control as a specific human activity is understood as a purposeful impact on an object with the aim of attaining a given objective (Kubík *et al.*, 1972).

The principles of control, its forms and technical means of implementation are related to the nature of the controlled system.

Scientific research of the control system requires the analysis of the controlled system, an important and integral part of it being the control function.

The general principles of control systems and processes are investigated by cybernetics and originated on the borderlines between mathematics, logic, electronics, physiology and other fields. The theory of automatic control and computers contributed to the formation and development of cybernetics as a new field of science using the results of the theories of communication and information and their investigation by the theory of mathematical probability. These fields provided cybernetics and its components with its basic method and procedures.

The theory of control and decision-making is sometimes considered as an extension of operations research, which is, in this respect, interpreted as a set of specific ways of decision-making (Sládek, 1974).

New branches of technology came into being, together with the development of the theory of cybernetics, e.g. automatic control that investigates the use of technical facilities and devices to free man from the tedious mental and physical work involved in control.

Although automatic control has been developing since the end of the last century, the systems approach has been stressed only recently. Its basic feature is a comprehensive understanding of the system with all its internal and external relationships, with the objective of optimum effectiveness on the basis of a comparison of alternatives. The theory of automatic control was involved and has become an important and promising branch of technical cybernetics.

Initially, the theory of automatic control dealt with the problems of automatic protection of technical devices, automatic signalling and automatic regulation. The intensive development of the theory of automatic control in recent years, together with the intensive development of computer hardware and software and methods of mathematical programming, led to the formation of the theory of optimal control systems.

This theory investigates systems of automatic control with different properties and under different conditions of technical realisation. For example, the optimal control of systems with complete and incomplete initial information, deterministic and stochastic systems, adaptive, learning systems, etc.

The theory of optimal control systems has penetrated into various human activities. It can be predicted that automatic control systems will develop in all branches of the national economy as subsystems of the central economic control systems. In water management, too, suitable conditions for their implementation exist. The multi-purpose WRS with their characteristic properties (e.g. territorial extensiveness, dynamic and stochastic character of input data, their great number, their reliance on modern computer hardware and software for dispatching operations, etc.) represent a typical example of possible implementation of the optimal control theory, which can be considered as a significant improvement on the previous approaches to control.

Further basic information is available concerning the principles and methods of automatic control, the theory of optimal control of automatic systems and information about the possibilities of their implementation in WRS problems. Development is far from complete but there is plenty of literature on the subject (Švec and Kotek *et al.*, 1969; Kubík *et al.*, 1972) with many references.

2.9.2 Principles and Methods of Automatic Control Theory and Optimal Systems Theory

Automatic protection, signalling, control and regulation were mostly applied in the comprehensive automation of technological processes in machinery, energetics, steelworks and chemistry. Automation includes the issues of control in the given technological process; a prerequisite is a knowledge of the properties of the controlled technology and objects and the control functions, i.e. a knowledge of the effects of the control action on the process.

An especially important kind of control is regulation, which maintains some physical quantities at predetermined values. The actual values are monitored during the regulation process and compared with the required ones; the goal of regulation is the attainment of minimum deviations.

The automatic regulation theory has been extensively and broadly developed. The subject includes the design of elements and loops of automatic control, investigation of their static and dynamic properties in connection with the problem of stability, investigation of special regulation circuits (e.g. multi-branch, multivariable, non-linear control). Impulse and digital control is studied as the basis of the control of complex systems by computers, and the problems of identification of the regulated systems, which is the basis for the construction of mathematical models of them, are also important.

In the theory of automatic control an important place belongs to the methods of the theory of probability and the theory of random processes. They are used for the investigation of dynamic characteristics of control systems, which are influenced by random noise, and the theoretical relationships from which the effective design of these circuits are derived. Research in this area is not complete: important applications of the theory of automatic control can be dealt with by statistical methods, e.g. statistical prediction, filtering (of the information signal from noise), statistical linearisation of non-linear systems of the problems of adaptive control systems.

The application of the methods of the theory of probability and the theory of stochastic processes in tasks of automatic control has been developed in recent years and has generated a new extension of the theory of automatic control, which is now called statistical dynamics of regulation circuits (Beneš, 1961; Švec and Kotek *et al.*, 1969).

The requirement of optimization of automatic control systems is often combined with the problems of their control. It is concerned with that form of automatic control which has the best properties of control as evaluated by some optimization criterion. It can, for example, be the requirement of the optimal form of the transients of the controlled quantity or other quantities in the control loop caused by a change in the control or noisy variables (i.e. dynamic optimization) or the requirement to attain other optimum values of quantities in the steady state to optimize the technological and economic results of control, e.g. maximum energetic effectiveness, the best quality of production etc. (i.e. static optimization). In optimization control some extreme value of the optimization criterion is frequently required (maximum or minimum).

The theory of optimal control now covers a more extensive area than the treatment of optimal regulation loops, which had been the main subject of the traditional theory of automatic regulation. Nowadays, the general problems of complex systems are investigated, under different conditions, and control computers are used for automatic control. Control is carried out by a system of programs of varying importance. An adequate program is selected depending on the behaviour of the system and the momentary values of the parameters monitored. The control computer should include in its software several programs with different priorities. The requirements of real-time systems control implies requirements for the speed and reliability of the control computer.

The development of mathematical methods facilitated the treatment of deterministic and stochastic problems. Frequently, the basis is formed by the methods of mathematical programming, but other systems fields are promising, too, e.g. the theory of games, the decision theory, etc. For WRS contexts, the theory of statistically optimal systems and adaptive systems are important since the properties of the system can be adapted to changing conditions. These properties can be maintained or improved on the basis of experience gained in the search for optimum behaviour (e.g. adaptive learning systems).

Adaptive systems can be classified into several types according to the aim of the activity and the realization of change in it. A change in activity can be derived from change in the external signals influencing the system or from changes in the parameters of the system and it can be realized by a change in the structure of the control system. However, both the structure and the parameters of the controlled system may change.

A characteristic feature of algorithms of adaptivity and learning is the ability to find the optimum solution under conditions of uncertainty in initial input data. The control system must continually monitor the behaviour of the controlled system, influence it and decide on the further strategy of control.

Design of a control system which realizes optimum control involves the performance of a relatively extensive set of tasks which that can be subdivided as follows (Kubík *et al.*, 1972):

– the problem of optimal identification of the control goals, the solution of which provides an optimum formulation of the control objective,

– the problem of optimal identification of the controlled object, the solution of which provides the mathematical model,

– the problem of optimal identification of the constraints which are related to the conditions of the object,

– the problem of the determination of the optimum algorithm of control and its realization.

One of the most difficult tasks is the determination of the optimum control algorithm, which has to satisfy the criteria not only of optimum control but also of all the constraints.

2.9.3 Prospects of Application of Optimal Systems of Automatic Control in WRS

The scientific and technical problems of automatic control systems are complex and difficult to solve. In their implementation in the operation of WRS the following fundamental problems of a general and applied nature need to be taken into account: the design of the control centre, a system of computer software, a monitoring system, a system of data collection, processing and communication with the centre including remote transmission and control and the problems mentioned above concerning the design of the control centre. The experience of other technical sectors can be put to advantage. In water management the development of these systems has just started. It can therefore be assumed that their realization and full operational functioning is a long-term task for the institutions responsible for water research design and operation.

The first conditions for optimal control of WRS in the main basins have been satisfied. In accordance with the general trends, the Water Boards prepare the fundamental conditions for the comprehensive water resource dispatch centres, which are to be in charge of the scientifically based operation and control of water resources.

In WRS the main problems of the design of optimal control include the construction of a mathematical model (or a set of models), its verification under real operational conditions and implementation on a control computer. It is an extraordinarily complicated task whose solution has, as yet, no precedent. It is clear that the process of construction of systems software includes the problems of systems analysis and synthesis; the design of the system, the construction of models and control algorithms and their verification in operation all have to be developed.

The difficulties that arise in the development of mathematical control models are related to the specific conditions of implementation of systems and stochastic methods in WRS. Actual problems are to be treated, e.g. multi-objective optimization of the competing interests of water users, classification of decision (operation) situations in non-stationary conditions, integration of continual and discrete simulation, etc. For WRS control systems, particularly applicable are the automatic adaptive models with random input, which keep the important control parameters within certain limits, derived from optimization analysis of WRS objectives.

In the main basins, water resource control by control computers in real-time operation is an important task, which can be considered a final stage in the implementation of automatic operation of WRS. It is assumed that the control computer in a dispatch centre will produce the control instructions in a system of control algorithms, based on concrete, monitored data describing the situation in the basin (i.e. flows in watercourses, levels in reservoirs, water and air temperatures, precipitation, water quality at selected points, etc.).

It is a favourable circumstance that an investigation of all the main tasks and problems associated with the application of cybernetics in WRS was initiated in the Czechoslovak State Program of Task of Basic Research and Applied Technical Development.

The Water Board in the Ohře River basin is an example of a highly developed water resource dispatch centre (Chomutov, ČSSR). Here, the aspect of WRS operation control involves the following devices:

– automatic monitoring stations in the basin,

– transmission devices for the transmission of data from the monitoring stations to the regional dispatch points and to the dispatch centre,

– communication devices linking the monitoring stations with the regional dispatch points and dispatch centre,

– regional dispatch points in Cheb and Karlovy Vary (ČSSR),

– a central dispatch centre in Chomutov (ČSSR) with a control computer RPP-16-S.