Chapter 3

WATER SYSTEMS AND WATER BALANCE

3.1 CHARACTERISTICS OF SURFACE AND GROUNDWATER RESOURCES

The development of water resources and water management, i.e. management of all activities which influence the location and the course of water occurrence, quality and utilization, serves to satisfy social requirements by water availability, both depending on natural, historical and economic factors. The relevant water development stage can be characterized by the innovative utilization of water in the key branch of the developing economic structure (Tab. 3.1).

TABLE 3.1

Stage	Innovation Characteristics (prevailing utilization)	Innovation Tool (means)	Period in Europe
1.	individual consumption	jug	?
2.	collective usage	well	5.mil.B.C.
3.	river navigation	boat	3.mil.B.C.
4.	irrigation	irrigation canal	2.mil.B.C.
5.	human power	bucket wheel	
6.	water power	water wheel	10.c.A.D.
7.	fish breeding	fish pond	10.-15.c.A.D.
8.	minicipal water supply	pipeline networks	12.-16.c.A.D.
9.	mine drainage	pump, driven gears	15.-18.c.A.D.
10.	inland navigation	canals	16.-19.c.A.D.
11.	industrial development	steam engines	19.c.A.D.
12.	hydropower	water turbines	19.c.A.D.
13.	mass usage	reservoirs	19.-20.c.A.D.
14.	multipurpose usage	multipurpose reservoirs	20.c.A.D.
15.	large-scale usage	water systems	end of the 20.c.A.D.
16.	rational usage	water-saving	21.c.A.D.

Characteristic stages of water resources development.

Surface water and groundwater are frequently developed as separate resources. The reason for this rests in the historical and economic conditions, as well as in their physical diversity. This diversity requires not only different modes of utilization but also diverse methods of investigation. Surface water is used and investigated as a dynamic resource depending on natural factors, and groundwater as a renewable raw material. This results in different degrees of cognizance of their physical parameters, having a feedback on their utilization.

Surface water resources are characterized by their shape and size, i.e. volume (m^3) and discharge ($m^3.s^{-1}$). Aquifers, permeable geological formations containing water, are characterized not only by their shape and size, but also by their effective porosity. The effective porosity is usually expressed as a percentage and corresponds to the specific yield, the volume of water which can be removed by the force of gravity.

In addition to this, an aquifer has a specific retention and contains a certain amount of water governed by forces other than gravity. The sum of the specific retention and the specific yield corresponds to the total porosity.

The coefficient of permeability or hydraulic conductivity k_f is defined as a quantity of water flowing in one unit of time through a face of unit area ($m^3.m^{-2}.s^{-1}$) under a driving force of one unit of hydraulic head change per unit length. It depends upon the porosity: Upon grain size, shape and distribution of pores, and compaction of the formation. The product of the hydraulic conductivity and the saturated thickness is the transmissivity

$$k = \int_0^h k_f \; . \; dz \qquad (m^2.s^{-1}) \qquad (3.1)$$

h - saturated thickness

This value characterizes unconfined aquifers. A confined (artesian) aquifer is characterized by the storage coefficient or storativity S. This storativity is dimensionless and corresponds to the volume of water released from the aquifer (or taken into storage) per unit surface area of aquifer and unit change of the piezometric head ($m^3.m^{-2}.m^{-1}$).

Hydraulic phenomena should be assessed over a long period of time on the basis of probability. The likelihood of their recurrence is established without reference to any specific time interval. Reservoirs and aquifers modify the distribution of water resources in time by accumulating water during periods of excess flow and by augmenting natural discharges during periods of low flow.

Their effect can be characterized by the storage coefficient , i.e. by the ratio of the storage capacity of the reservoir or the volume of interstices forming the effective porosity of the aquifer and the long-term mean total annual flow/annual recharge.

$$\beta = \frac{V_e}{Q_a} \qquad (3.2)$$

V_e - useful storage capacity (volume of effective pores) (m^3)

Q_a - long-term mean total annual flow (long-term mean natural recharge) (m^3 per annum)

The development of water resources for maximum utilization requires the co-ordination of surface and groundwater management. Aquifers should be managed in the same manner as surface reservoirs. Depending on the relation between the storage capacity, the fluctuation of natural discharges and water requirements, flow regulation is confined to seasonal redistribution and/or to between-year regulation to satisfy water requirements during years with insufficient water flow.

The guaranteed delivery of a reservoir is the ratio of the minimum discharge secured by the reservoir to the long-term average yearly (monthly, seasonal) discharge

$$\alpha = \frac{Q_{min}}{Q_a} \tag{3.3}$$

Q_{min} - minimum (yearly, monthly seasonal) discharge secured by the reservoir ($m^3.s^{-1}$)

Q_a - average natural discharge ($m^3.s^{-1}$)

The ratio of the surface yield (m^3 per annum) to the average annual recharge (m^3 per annum) of the aquifer expresses the similar characteristics of the groundwater resources.

3.2 SAFE YIELD

Unlike other mineral resources, water resources form a continuous flow which is renewed within the natural hydrologic cycle. Man uses water in that part of its hydrologic cycle which corresponds to the flow of water over the land masses. Any utilization of water changes the course of this cycle quantitatively and qualitatively, and also influences the rate of the relevant hydrological processes (recharge).

Various attempts have been made (see paragraph 5.5) to influence the hydrologic cycle and to increase the quantity of usable water resources. When compiling water balances a distinction has to be made between

- the traditional, conventional water uses and
- the non-conventional uses of water.

Water resources are dynamic and, therefore, the interrelationships between surface and groundwater restrict the number of categories which can be treated separately for the compilation of water balances: Through an accumulation of the dynamic component on the surface or under the ground, the static stock is formed to supplement the lack of the dynamic components, if the need arises (Tab. 3.2).

TABLE 3.2

Component	Physical interpretation	Dimension	Definition
Static	volume	m^3	Amount of water on the surface or under the ground, in the given water management unit, subsequently recharged
Dynamic	discharge (flow)	$m^3.s^{-1}$	Amount of water leaving the relevant water management unit during a given unit of time

Basic interpretation of quantitative aspects of water resources in a defined water management unit.

Interpreted in this way, the surface water resources consist of two parts: the first originating from precipitation and groundwater, the second coming from other water management units. The withdrawn water is partially replenished by increased input of groundwater and reduced evaporation caused by the decrease in water level.

The exploited groundwater resources of a given territory are replenished by increased infiltration from neighbouring aquifers, by increased infiltration from surface waters, as well as by increased infiltration after rainfall and reduced evaporation as ground water level sinks. The safe yield of an aquifer is defined as the amount of water which can be withdrawn annually from the aquifer and which is replenished naturally, without bringing about some undesired environmental legal or other result. To remove some of the ambiguity in meaning of this term, the American Society of Civil Engineers (1961) defined four concepts of yield as follows:

(a) Maximum sustained yield is the maximum rate at which water can be withdrawn perenially from a particular source.

(b) Permissive sustained yield is the maximum rate at which water can economically and legally be withdrawn perenially from a particular source for beneficial purposes without bringing about some undesired result.

(c) Maximum mining yield is the total volume of water in storage that can be extracted and utilized.

(d) Permissive mining yield is the maximum volume of water in storage that can economically and legally be extracted and used for beneficial purposes, without bringing about some undesired result.

In assessing water resources a distinction has to be made between natural and usable water resources. Natural water resources are, on average over a period of years, equal to the mean multi-annual runoff from the defined water management unit, i.e. to the volume of the natural replenishment. The usable water resources of the given water management unit are characterized by the amount of water in a longer time unit (m^3 per year) or by the flow-rate ($m^3.s^{-1}$), which can, with an adequate degree of certainty, continuously supply the relevant water users.

For a precise assessment of usable water resources, the following factors should be taken into account, as they influence the natural recharge rate:

(a) the additional recharge caused by the lowering of the water table: additional infiltration of rainwater, decrease in evaporation, increase or reduction in the groundwater inflow into water courses, infiltration from adjoining aquifers etc.

(b) anthropogenetic influence, caused by land and water development, water utilization etc. and especially by return flow.

Taking into account the natural availability of water and the technical and economic limitations for increasing its supply, water yield, the amount of water which can be withdrawn from the water resource, has different qualities:

Natural yield is the amount of water (m^3 per year) which is supplied by the water resource that is not influenced by anthropogenetic activities. The natural yield of surface resources corresponds to natural discharges. Its minimum value is, therefore, the minimum natural discharge Q_{min}. The natural yield of groundwater resources, the maximum sustained yield, corresponds to the natural recharge and enables water withdrawals which do not decrease natural groundwater deposits in the long term.

Theoretical yield is the amount of water (m^3 per year) which it would be possible to harness in the long term by modifying the occurrence of water in the long term, namely through storage, artificial infiltration and overdraft of groundwater. The theoretical yield of a surface resource corresponds to the average long-term annual runoff. The theoretical sustained yield of a groundwater resource corresponds to the average value of maximum withdrawals under a steady regime of flow, i.e. when the natural groundwater deposit is decreased (development overdraft), thus enabling the maximum recharge from surface and rainwater, also by an artificial recharge, as well as from other aquifers.

The technically utilizable yield of water resources is that portion of the theoretical yield (m^3 per year) which is defined by the possibilities of regulating the flow regime, by the possibilities of locating reservoirs, as well as by the recharge and overdraft possibilities of the relevant aquifers etc. The technically utilizable yield is limited by topographical, hydrogeological and environmental factors, the possibilities of constructing dams, reservoirs and

TABLE 3.3

Classification	Form of interpretation	Measuring unit
Aquifers (water-bearing formations) 1) exploitable en mass 2) local and unimportant 3) utilizable for other purposes 4) unsuitable for any use	Groundwater reserves-volume of water stored in the aquifer, i.e. statistically expressed in the same manner as other mineral resources. Groundwater flow-groundwater resources expressed in the same manner as surface runoff.	m^3 $l.s^{-1}$ $(m^3.s^{-1})$
Induced recharge	Water entering the aquifer from other aquifers and from the surface as a result of water withdrawal.	$l.s^{-1}$ $(m^3.s^{-1})$

Basic characteristics	Categories according to the cognizance of basic characteristics		
	A	B	C
	explored	under investigation	followed up
Aquifer boundary	exactly determined	under investigation	known, not exactly laid down
Source of data	observation network pumping	drilling and short-term pumping	archives
Quantity evaluation	prognosis of the future development	interplay with hydrometeorological factors	hydraulic and hydrological methods
Quality indicators		technology of water treatment, pollution effect	basic information
Protection measures	proved by investigation	determined	not yet laid down
Environmental impact and economy of operation	determined in detail	optimum operation regime	not yet laid down

Groundwater resources offered by a hydrogeological unit, i.e. by a geographically and physically limited system of aquifers and aquicludes. Categories of groundwater according to the adequacy of cognizance of basic data.

structures for artificial recharge etc. It also depends on the flexibility of water management in the sphere of water users.

The economically utilizable yield is a portion of the technically utilizable yield and is defined by the economic criteria (e.g. maximum cost per m^3 of supplied water) accepted by or given to water users in the relevant stage of economic development.

The economic and social development of human society affects and reduces the natural and theoretical yield of water resources, both qualitatively (e.g. by pollution) and quantitatively (e.g. by decreased recharge). On the other hand, technical development results in an increase in the technically and economically utilizable yield (e.g. through bigger reservoirs, or an increase in acceptable costs).

Catchment boundaries (dividing lines) form the natural geographical framework for the compilation of water balances, unless the groundwater straddles the relevant dividing line. The following sum defines, without storage factors, the natural yield $\bar{Q}_n$ for a short term period, whose duration depends on natural retention capacities, and, with storage factors included, the theoretical sustained yield $\bar{Q}_t$, provided the relevant period is a long-term one:

$$\bar{Q}_n = \int_0^t Q_s \, dt + \int_0^t G_g \, dt \qquad (m^3) \tag{3.4}$$

$$\bar{Q}_t = \int_0^t Q_s \, dt + \bar{Q}_{sr} + \int_0^t G_g \, dt + \bar{G}_{gr} \qquad (m^3) \tag{3.5}$$

Q_s - total surface runoff $(m^3.s^{-1})$

$\bar{Q}_{sr}$ - total storage in reservoirs (m^3)

G_g - total groundwater runoff $(m^3.s^{-1})$

$\bar{G}_{gr}$ - groundwater reserve (m^3)

t - time (s)

The preceding equation corresponds to the natural state of the catchment without any anthropogenetic influences. But the harnessing of water resources can never be considered independently of water withdrawals, water pollution and other anthropogenetic activities whose influence can be expressed as follows:

$$\bar{Q}_t = \int_0^t Q_s \, dt + \bar{Q}_{sr} + \int_0^t W \, dt + \int_0^t F \, dt + \int_0^t L \, dt + \int_0^t G_g \, dt + \bar{Q}_{gr} + \int_0^t G_{gi} \, dt - \int_0^t I \, dt - \int_0^t Y \, dt - \bar{Y}_r \tag{3.6}$$

W - water withdrawals $(m^3.s^{-1})$

F - waste water disposal - return flow $(m^3.s^{-1})$

L - water conveyance from (+) and to (-) other catchments $(m^3.s^{-1})$

G_{gi} - induced groundwater reserves $(m^3.s^{-1})$

I - decrease in groundwater recharge, if not recovered in surface resources $(m^3.s^{-1})$

Y - irreversibly polluted portion of runoff $(m^3.s^{-1})$

$\bar{Y}_r$ - irreversibly polluted stored volume (m^3)

The determination of the safe yield is also a problem of the adequacy of the cognizance of resources (Tab. 3.3), categorization, investigation, measurability and a knowledge of the interrelationships of different categories of water occurrence, especially of surface water and groundwater. Water resources can generally be considered as

(a) conventional - i.e. traditional surface and groundwater resources which are withdrawn, pumped, transported, regulated by reservoirs, distributed etc.

(b) non-conventional - geothermal resources, collected (harnessed) dewfall, sea-water, icebergs etc.

Under the second category it is also necessary to consider the increase in conventional resources by non-conventional water use techniques such as artificial rainfall etc. (see paragraph 5.5).

For an assessment of usable groundwater resources it is indispensable to know the hydrodynamic parameters of all the relevant aquifers. The extent to which these resources can be used depends especially on the spacing between wells or galleries (ghanats etc.). To reduce the negative environmental effects, it is necessary to determine the most suitable operating conditions such as pumping rates, draw-down limits etc.

The theoretical yield $\bar{G}_g$ of groundwater resources can be expressed by the formula

$$\bar{G}_g = \int_0^t G_g \, dt + \bar{G}_{gr} + \int_0^t G_{gi} \, dt \qquad (m^3) \qquad (3.7)$$

Groundwater can be deliberately overpumped in the period of high water demand in the knowledge that it will be recharged naturally or artificially in the period of abundant water supply. Such an overdraft has the character of mining minerals and is limited by the volume of the groundwater reserves and by the duration of the overpumping:

$$G_{gm} = \int_0^t G_g \, dt + \int_0^t G_{gi} \, dt + \frac{\bar{G}_{gr}}{t_m} \qquad (m^3.s^{-1}) \qquad (3.8)$$

G_{gm} - overpumping ($m^3.s^{-1}$)

t_m - duration of overpumping (overdraft) (s)

The difference between the theoretical $\bar{G}_g$ and the economically utilizable yield $\bar{Q}_{ge}$

$$\bar{G}_g - \bar{G}_{ge} = \bar{G}_{go} \qquad (m^3) \qquad (3.9)$$

forms the non-utilizable reserve $\bar{G}_{go}$. This reserve consists mainly of low-quality groundwater resources and resources of unstable or low yield. The economically utilizable yield is thus

$$\bar{G}_{ge} = \int_0^t G_g \, dt + \bar{G}_{gr} + \int_0^t G_{gi} \, dt - \bar{G}_{go} \quad (m^3) \qquad (3.10)$$

The equilibrium of input and output of water within a natural geographical area (catchment) over a long period forms suitable conditions for the environmental equilibrium, i.e. for the stability of regional ecosystems. Such a balance of water resources and natural needs can be expressed by the equation

$$\int_0^t Q_s \, dt + \int_0^t G_g \, dt + \int_0^t P \, dt + \int_0^t L \, dt = \int_0^t 0_s \, dt + \int_0^t 0_g \, dt + \int_0^t E \, dt + \int_0^t C \, dt \quad (m^3) \qquad (3.11)$$

Q_s, G_g - surface and groundwater inflow ($m^3.s^{-1}$)

P - precipitation

L - water conveyance from (+) and to (-) other catchments

0_s, 0_g - surface and groundwater outflow

E - evaporation

C - water consumption (of Q_s, G_g, P, L) ($m^3.s^{-1}$)

The majority of these data is measured, systematically collected and processed. Data concerning evaporation E and water consumption C are generally incomplete. Groundwater inflow and outflow cannot be measured directly and have to be determined from the changes in the groundwater reserve. Any inaccuracy in the estimate of relevant values should correspond to the possibilities of regulating the outflow.

The degree of environmental changes and damages depends not only on the degree of disturbance of this balance, on its duration, and period, but also on the tolerance of the relevant ecosystems to changes in relevant components P, G_g, Q_s and L as well as on an induced or hazardous deterioration of water quality.

3.3 BALANCE OF WATER RESOURCES AND NEEDS

The balance of water resources and needs compares the quality and quantity of available water resources, i.e. the economically utilizable yield, with the water requirements, so that the measures which are necessary to satisfy the demands can be analysed. These balances evaluate the actual or planned utilization of water, its localization, course and necessity.

Each balance of water resources and needs relates to a certain geographical unit. The most suitable units for this purpose are catchments, which offer available hydrological data and the possibility of synthesizing surface and groundwater data, as well as partial results from the various neighbouring catchments.

From the hydrological point of view aquifers, reservoirs or their systems are also suitable. Practical purposes require water balances to be compiled for different administrative areas, towns, counties, but also for large farms and industrial estates.

When demarcating the boundaries of such a water management district, the relations to the neighbouring water management units have to be considered in order to incorporate these data hierarchically into those of larger geographical units.

The operational management of water resources utilization requires

(a) a current evaluation of the actual state of the water balance,

(b) a periodic (yearly) evaluation of the balance of the previous year.

Apart from this, medium-term (five years) and long-term (twenty to fifty years) balances should be determined for planning purposes.

In the framework of the planning and investment process long-term, medium-term and short-term water needs arise, i.e. quantities of water intended for a particular use in industry, agriculture, infrastructure or for the population. These needs call for planning or, if short-term, for immediate action. They should be revised as they change and become water demands after their official approval and after the construction of the relevant project. These water needs and water demands exceed the real water requirements (Fig. 3.1).

The water requirement represents that part of water demand which must be supplied for the given technological process. An inevitable water requirement represents that part of the water requirement which must be supplied by applying an optimal water-saving technological process. The water withdrawal and the

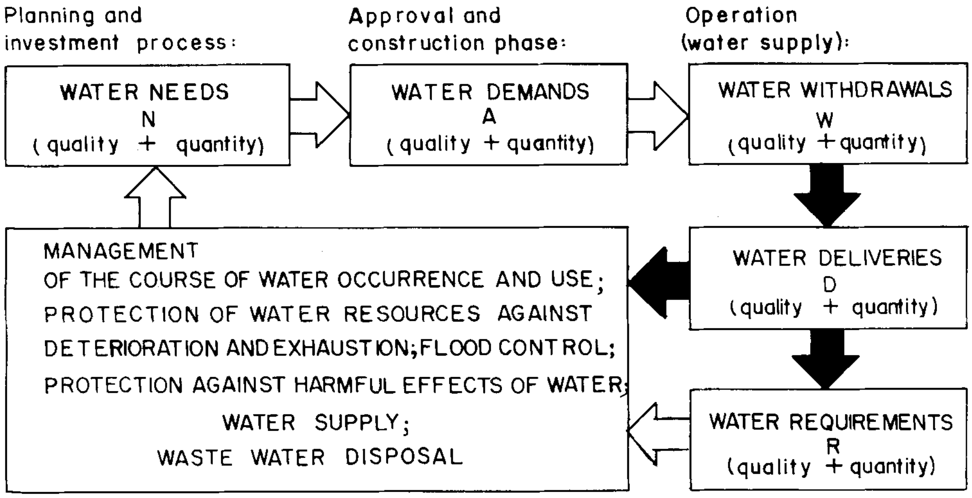


Fig. 3.1. Schematic representation of water needs, demands, withdrawals, deliveries and requirements in the framework of the planning, investment and operation process.

water delivery generally exceed water requirements differing from the amount of water paid for.

The relation between the mentioned categories can be expressed in this way:

$$N \gtreqless A \gtreqless W \gtreqless D \gtreqless R \gtreqless R_i \gtreqless U \gtreqless Q_p \qquad (3.12)$$

The relation between the water quality indicators in these categories can be expressed in a similar way:

$$n_i \gtreqless a_i \gtreqless w_i \gtreqless d_i \gtreqless r_i \gtreqless r_{ii} \gtreqless u_i \gtreqless q_i \qquad (3.13)$$

N, $n_{1\ldots n}$ – planned water needs and planned water quality indicators,

A, $a_{1\ldots n}$ – officially approved water demand and approved quality indicators,

W, $w_{1\ldots n}$ – water withdrawal, amount of water diverted from a stream or a groundwater resource and its water quality indicators,

D, $d_{1\ldots n}$ – water delivery, amount of water supplied to the water user and relevant water quality indicators,

R, $r_{1\ldots n}$ – water requirement, the amount of water required by the water user under the given economic and production conditions,

R , $r_{i1\ldots in}$ – indispensable water requirement, the amount of water which is indispensable to ensure the technological process, by applying all known water-saving techniques,

U, $u_{1...n}$ - water use, the amount of water really used for the relevant purpose and actual water quality indicators,

Q_p, $q_{p1...n}$ - amount of water paid for and corresponding water quality indicators.

The economy of the water development process depends on the mutual relations between the above values. The necessary water supply can be determined from the (indispensable) water requirements with a reserve for losses etc., deducing the amounts supplied from in-plant resources such as water re-use and re-cycling, storage etc.

A certain reserve, marked by the sign $>$ between water demand, water withdrawal, water supply and water requirements forms the conditions for a future extension of the production. When the sign $<$ occurs between these values, operational troubles may occur. With regard to water quality indicators, a reserve is necessary in each case for manifold and multipurpose water use, or to treat water for any of these different purposes.

The problems with the present practical compilation of the balance of water resources and needs mainly arise from their inadequacy in respect of the following points:

(a) relevant surface and groundwater resources are not analyzed from the point of view of their economic feasibility, but in the hierarchy of their cognizance/present utilization, depending mainly on the inertia of the past development and on the external influences of other braches of the national economy,

(b) the motivation of relevant water needs is not sufficiently analysed, resulting in the approval of the excessive water demands and in an extensive development of industrial or agricultural production on account of the water (and overall) development, financed generally from state financial resources,

(c) different methodological conditions of occurrence and statistical interpretation of the surface water and groundwater (e.g. groundwater and surface water including re-use of waste waters both from surface water and groundwater are analysed separately. The overdevelopment of one of these resource categories may be a consequence of or the reason for this practice).

(d) non-conventional water resources are not taken into account sufficiently.

The problem of the compilation of the balance of water resources and needs does not concern surface and groundwater resources only, but also soil water and rainfall. Soil water safeguards the majority of plant water requirements. In arid and semi-arid areas, the problem of the maintenance of the vegetative canopy has to be included in the relevant water balance considerations.

The water requirements of the vegetative canopy can be included in the framework of the irrigation water requirements. Soil water including the stock of the capillary rising groundwater can also be excluded at the beginning of the compilation process, because the water which is available for the evapotranspiration depends on local conditions, thus forming a closed system of local water supply and production, and water balances are generally compiled for superior land complexes.

The heterogeneity of the available data, the differences in the extent and frequency of measuring, and the different methods of data recording and statistical evaluation all tend to complicate the common compilation of surface and groundwater balances.

The basic inequation for the compilation of water balances and needs is

$$Q \gtreqless N \qquad (m^3.s^{-1},\ m^3) \qquad (3.14)$$

Q - available water resources $(m^3.s^{-1},\ m^3)$

N - water needs (water withdrawals W) $(m^3.s^{-1},\ m^3)$

This basic inequation can be formulated for both the surface and groundwater resources of a certain geographical unit for a limited period in the following way

$$Q_s + Q_{sr} + G_g + G_{gr} + L + F \gtreqless W + MQ + G_{go} \quad (m^3 \text{ per period}) \qquad (3.15)$$

Q_s - surface water inflow

Q_{sr} - surface water in reservoirs

G_g - groundwater inflow

G_{gr} - groundwater reserve

L - water conveyance into the area

F - return flow - waste water

W - water withdrawals including water conveyance from the area

MQ - required minimum discharge

G_{go} - groundwater outflow

The balance for surface water is expressed as follows:

$$Q_s + Q_{sr} + L - I + F = W_s + MQ \qquad (m^3 \text{ per period}) \qquad (3.16)$$

and for groundwater resources

$$G_g + G_{gr} + I = W_g + G_{go} \qquad (m^3 \text{ per period}) \qquad (3.17)$$

I - infiltration into groundwater resources from surface resources, waste water and water conveyance

W_s - water requirements covered by surface water resources

W_g - water requiremets withdrawn from groundwater resources.

TABLE 3.4

Class	Water quality	Characteristic suitability	Usage
I.	a. very clean	drinking water	urban and rural supply, food and pharmaceutical
	b. clean	domestic uses	industry, swimming pools
II.	slightly polluted	livestock breeding	livestock breeding, water sports and recreation
III.	intensively polluted	other uses	industrial supply, irrigation
IV.	deteriorated	selected in-stream uses	not suitable for withdrawal uses, only for navigation, hydropower generation, waste disposal

Categories of water quality according to its efficient usage (see Tab. 1.24).

TABLE 3.5

Group	Characteristics
A.	Water acceptable for relevant purposes of usage without treatment or after simple pre-treatment
B.	Water acceptable for relevant purpose of usage after inexpensive, simple treatment
C.	Water acceptable for relevant purpose of usage after special, but economically feasible treatment
D.	Water acceptable for relevant purposes of usage after an economically unfeasible treatment

Groups of water quality according to the feasibility of water treatment for the required purpose of usage.

The purpose of the compilation forms the basic difference between the hydrological balance and the balance of water resources and needs: The hydrological balance analyses the quantity of water in the hydrologic cycle, i.e. the inflow into and the outflow from certain geographical unit and simultaneously the increment or decrement of water inside.

The balance of water resources and needs analyses the quality and quantity of available water resources and their seasonal fluctuation, comparing them with the course or development of the relevant water needs (demands, withdrawals, requirements) in relevant categories of water quality (Tab. 3.4).

In addition to this available water resources can for water development purposes be categorized according to the feasibility of water treatment for the required purpose of usage (Tab. 3.5).

3.4 MINIMUM WATER TABLE AND MINIMUM DISCHARGES

The functions of water are manifold and any utilization of water resources must not be allowed to hinder either the natural functions of water or its general utilization by human society. It is, therefore, of paramount importance to safeguard the social functions of water and its essential ecological functions, especially for

(a) the conservation of the natural ecosystem in the rived bed,

(b) the conservation of the sediment transport,

(c) the conservation of the hygienic and aesthetic functions of water,

(d) the conservation of the natural vegetative canopy within the sphere of influence of groundwater withdrawals,

(e) conservation of the groundwater table and the natural ecosystems along water courses.

The water regime has a basic influence on the biological balance in ecosystems. Changes in the water regime occur as changes

- in flooding, the season of its occurrence, its duration and frequency, the depth and velocity of flow in the flooded area, the water and sediment quality,
- in the groundwater regime: in the groundwater recharge, groundwater level fluctuation and quality, especially if this water supplies the soil moisture of the superficial layer.

The occurrence of a minimum water table in a river, and a minimum groundwater table along its course, depends on the occurrence of minimum discharges, provided that the water table is not impounded artificially.

Therefore, during minimum discharges a criticial situation occurs, whose long-term influence on the existing natural conditions determines the composition of the relevant ecosystems. When the values of water discharges influenced by human activities such as reservoir operation or water withdrawals exceed the yearly minimum, the balance of ecosystems may not be disturbed, even in the case of an increase in the frequency of the occurrence of low discharges or in the case of an extension of their duration.

In many cases, depending on the natural conditions and adaptability of ecosystems, even a decrease in natural discharges below the value of the yearly minimum need not necessarily have a significantly harmful effect. Taking this into account, the value of the admissible minimum discharge can be derived from the minimum yearly discharges in the following way:

$$MQ = r \cdot Q_{min} \qquad (m^3.s^{-1}) \qquad (3.18)$$

MQ - minimum admissible discharge (minimum acceptable flow)

Q_{min} - the natural minimum yearly discharge, usually Q_{355d}

r - the rate of minimum discharge reduction ($r \leqq 1$)

In this way the minimum acceptable flow can be derived from the minimum monitored discharges only (Tab. 3.6).

In many cases such an oversimplification does not lead to appropriate results. The rate of minimum admissible discharge reduction is a function of

- climatic factors X_c
- geomorphological factors X_m
- biological factors (adaptability, drought resistance) X_b
- groundwater regime and surface water regime X_w
- water quality (natural pollution) X_q
- anthropogenic factors (artificial pollution, required water utilization etc.) X_x

It goes without saying that the minimum admissible discharge often depends on the season and may, therefore, differ for each month

$${}^{m}Q_{min} = f_m\,(X_c\ , X_m\ , X_b\ , X_w\ , X_q\ , X_x)\ .\ {}^{m}Q_{min} \quad (m^3.s^{-1}) \qquad (3.19)$$

m - month (1,2,3,.......12) (t_m

Furthermore, the maximum admissible duration of the minimum discharges also depends on the season and can be expressed as a function of the degree of the discharge reduction

$$t_m = F_m\,(X_c\ , X_m\ , X_b\ , X_w\ , X_q\ , X_x)\ \frac{{}^{m}Q_m}{{}^{m}Q_{min}} \quad (\text{days}) \qquad (3.20)$$

${}^{m}Q_{min}$ - natural minimum discharge in the month m

The above factors or the rate of the minimum discharge reduction and its admissible duration has, therefore, to be derived on the basis of three groups of criteria:

(1) criteria of environmental protection,
(2) criteria of in-stream water utilization,
(3) criteria of withdrawal priorities.

The criteria of environmental protection include:

(a) the criterion of biological equilibrium in the stream channel, i.e. complicated problems with regard to the undistrubed development of aquatic life,

(b) the criterion of the external equilibrium in the landscape, i.e. conservation of natural terrestrial ecosystems,

(c) the criterion of the physical equilibrium i.e. determination of minimum discharges which do not upset the balance of the erosion and sedimentation processes in the river bed,

(d) the first criterion of water quality, i.e. not allowing it to exceed the maximum admissible chemical, biological and heat pollution levels, in order to protect groundwater resources

(e) the first criterion of water table altitude, required for aesthetic enjoyment.

The criteria of in-stream water utilization include:

(a) the criterion of hydrological balance, i.e. determination of minimum discharges which limit excessive drainage of groundwater or permit the inevitable infiltration,

(b) the second criterion of the water table, required for the general water utilization in the river channel, as well as for navigation and recreation.

(c) the first criterion of discharges, necessary for power generation,

(d) the second criterion of water quality, i.e. determination of the necessary dilution of waste waters to safeguard the undisturbed course of natural self-purification processes and enable general water utilization, fishery, recreation etc.,

The criteria of withdrawal priorities include:

(a) the second criterion of discharges to cover relevant downstream water withdrawals,

(b) the third criterion of water quality, i.e. determination of the waste water dilution which would permit safe and economic water treatment processes for further water utilization by the pollution and industry.

All these criteria depend on local conditions. The established values may differ, depending on the above factors ($X_c, \dots X_x$). The problem of minimum admissible discharge is generally considered as a hygienic and economic one. In such a way, the environmental factors are not accordingly taken into account. The appropriate determination of the minimum admissible discharge is hampered by inadequate information, in addition to the economic obstacles, legislative and institutional problems and the lack of responsibility of the authorities towards the needs of the society.

Depending on the given economic possibilities, the approved minimum admissible discharge can be used to serve environmental purposes, or to cover essential withdrawals, i.e. to fulfill only some or all the above-mentioned criteria. Taking mainly economic factors into account, minimum admissible discharges are determined on the basis of a compromise between the cost of waste water treatment on the one hand and the economic losses which may occur as a result of the deterioration in water quality and the subsequent limitations of water supply to lower riparian users on the other hand.

A practical assessment of the minimum acceptable flow depends inter alia on water requirements for effluent dilution to achieve the requested water quality, characterized e.g. by 8 mg of the biological oxygen demand BOD_5 in effluents, whose quality depends on the admissible waste water pollution in the area in question. Discharges within the limits of Q_{355d} to Q_{270d} can also be assessed, depending on the type and state of geological formations which do not destroy the groundwater regime and/or which safeguard the conservation of the characteristic ecosystem etc. (Tab 3.6).

TABLE 3.6

Water course	Minimum discharge
Mountain creeks	$0.2\ Q_{min}$
Water courses with a relatively steady flow	$0.5\ Q_{min}$
Other water courses	$0.8 - 1.0\ Q_{min}$

Minimum acceptable discharges MQ according to the recommendation to the Economic Commission for Europe of the United Nations (1970).

When the minimum admissible discharge is established, not respecting the criteria of in-stream water utilization and the criteria of withdrawal priorities, practical discharge limits should be determined for each stream sector to safeguard all essential requirements for in-stream water utilization and essential water withdrawals.

In such a way a minimum value of not less than Q_{355d} can be accepted as limiting just below the dam profile. Corresponding to this in a sector of a stream not influenced by the effect of a reservoir the minimum admissible discharge may be assessed within the limits

$$\frac{1}{2} Q_{364d} < MQ < Q_{364d} \qquad (3.21)$$

In the intermediate sectors, the relevant values decrease down to the profile, where the reservoir impact is not apparent. In any case, the minimum admissible discharge should also depend on the water quality, i.e. be higher for low water quality, e.g. Q_{355d} instead of $\frac{1}{2} Q_{364d}$.

An assessment of the minimum admissible discharge may make it necessary to take measures to change existing reservoir operation and to limit water withdrawals so as to respect this value etc. Authorities might approve of a drop below these values in exception cases, but limit it to some lower values. Every appropriate measure should be taken to safeguard the necessary minimum discharge including the construction of reservoirs or conjunctive use of groundwater and surface water discharges whenever the possibility of further water withdrawals occurs.

3.5 ACTIVE AND PASSIVE WATER BALANCE

The equilibrium of water balances and needs signifies that no action has to be taken to satisfy existing needs if no further uses are planned. For such a state an interval of ± 10% has to be introduced to make allowances for the elasticity of demand and its adaptation to water shortages and also for the uncertainties of data collection and processing. Water demands can be cut by up to 20% without any important negative operational and economic consequences (Fig. 3.2).

The minimum admissible discharge for environmental protection and in-stream water utilization (not including any withdrawals) has to be regarded as an indispensable water need. Bearing this in mind, the balance of water resources and needs may be considered to be in equilirbium if

$$0.9\ Q - MQ \leqq \sum_{i=1}^{n} W_i - \sum_{i=1}^{n} F_i \leqq 1.1\ Q - MQ \qquad (3.22)$$

in each of the localities (river sectors) considered

W_i - water withdrawals ($W_i < Q - MQ$) (daily - m^3 per day)

Q - daily discharges/groundwater yield (m^3 per day)

F_i - outlet discharge (return flow)

MQ - minimum admissible discharge (m^3 per day)

$(Q - MQ)$ - usable water resources (m^3 per day)

This balance is therefore favourable (active) if

$$\sum_{i=1}^{n} W_i - \sum_{i=1}^{n} F_i < 0.9\ Q - MQ \qquad (3.23)$$

and unfavourable (passive) if

$$\sum_{i-1}^{n} W_i - \sum_{i=1}^{n} F_i > 1.1\ Q - MQ \qquad (3.24)$$

A favourable balance of water resources and needs indicates that abstraction for existing water uses can be extended and new uses can be satisfied, including water conveyance into neighbouring areas with passive balances. The unfa-

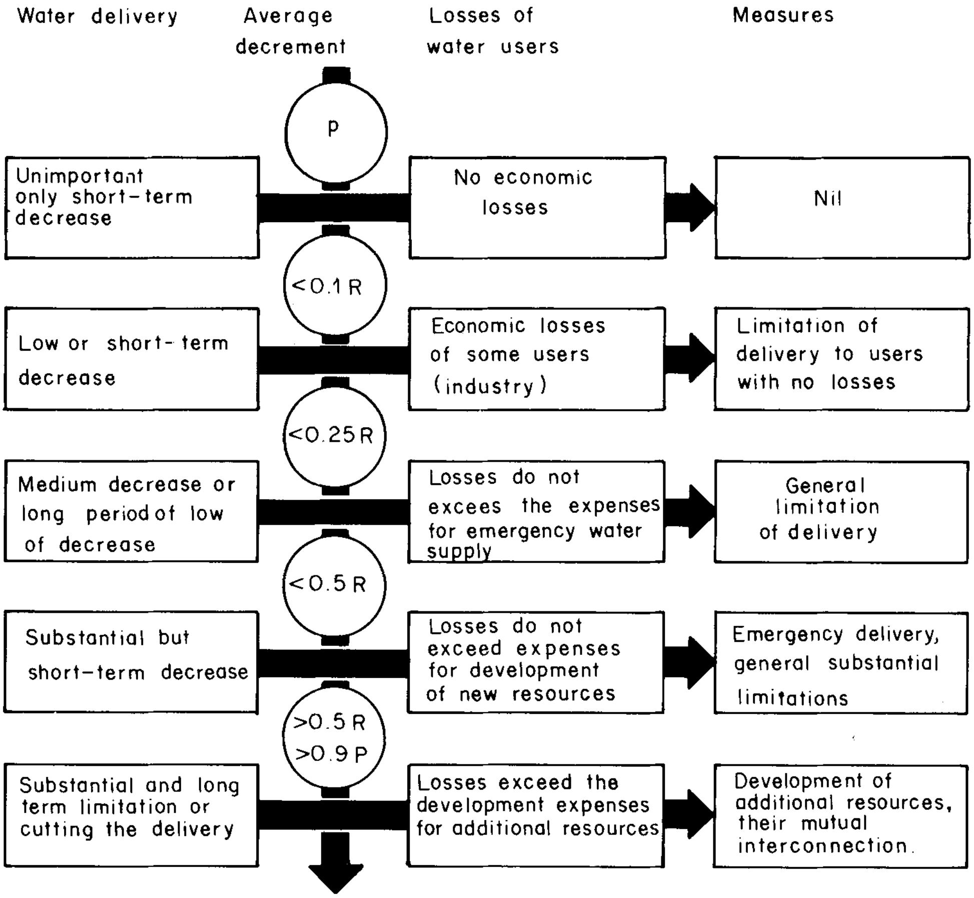


Fig. 3.2. Consequences of a decrease in water delivery and necessary operational or investment measures (p - rate of guarantee, R - water requirements).

vourable (passive) water balance indicates the need for a development of new water resources or for water conveyance from neighbouring catchments with an active water balance. From the operational point of view it indicates the need for restricting present water uses and for cutting down existing water uses e.g. by excluding inefficient uses and through the introduction of water-saving techniques.

When compiling balances of water resources and needs, the balancing effect of outlet discharges should be taken into account

$$F = W - C \qquad (m^3) \qquad (3.25)$$

C - water consumption (m^3)

The compilation of statistics of the interrelationships between water supply (amount of water supplied) and water consumption gives a basic picture of development possibilities by the application of water re-use and recycling techniques in the sphere of water users. Nevertheless, it does not mirror the possibilities of other water-saving techniques which are to be considered separately, in connection with relevant technological processes (Tab. 3.7).

TABLE 3.7

Balance of water resources and needs	Basic equation	Water surplus or deficit	Coefficient of usage of water resources	Measures
Favourable (active)	$Q > 1.1\,W$	$X > 0$ $X > 0.1\,Q$	$\mu < 0.9$	New water uses can be developed
In equilibrium	$0.9W \leq Q \leq 1.1W$	$\lvert X\rvert < 0.1\,Q$	$0.9 \leq \mu \leq 1.1$	No action necessary
Unfavourable (passive)	$Q < 0.9\,W$	$X < 0$ $\lvert X\rvert > 0.1\,Q$	$\mu > 1.1$	Water use restriction, water resources development

Quantitative indices of the balance of water resources and needs.

In practice, the difference between usable water resources and demands is often used as an important quantitative indicator. It is called water surplus if positive, or water deficit if negative, and is to be derived from statistical records in the following manner

$$X = Q - W + F \qquad \text{i.e.} \qquad (3.26)$$

$$X = Q - C \qquad (m^3,\ m^3.s^{-1})$$

X – water surplus (+), water deficit (–) $(m^3,\ m^3.s^{-1})$

On this basis, the rate of usage of a water resource is to be defined by the ratio

$$r_u = \frac{\sum_{i=1}^{n} W_i - \sum_{i=1}^{n} F_i}{Q} \qquad (3.27)$$

The ratio $$r_r = \frac{\sum_{i=1}^{n} W_i}{Q} \qquad (3.28)$$

expresses the degree of water re-use of relevant resources. The reversed value of this ratio, applied to the whole country and covering an average year, was introduced by Balcerski (1968) for comparing water resources utilization in different countries:

$$c_{wm} = \frac{\sum_{j=1}^{k} Q_i}{\sum_{j=1}^{n} W_i} \tag{3.29}$$

c_{wm} - index of water management

$\sum_{j=1}^{k} Q_i$ - mean annual surface and groundwater runoff of the whole country (m^3 per year)

$\sum_{i=1}^{n} W_i$ - annual water needs of the whole country (m^3 per year)

This index of water management does not express the activity or passivity of water balances and needs. It characterises the ratio of surface and groundwater resources development and utilization

- at the beginning of economic development and
- the re-use of water at further stages of development.

This index does not include the internal recycling, i.e. the repeated use of the same water inside a closed circuit of different water users. It characterizes the development of water management in the relevant country/area and the coordination of the repeated use of the same water by the different users, but does not characterize the efficiency of water use by relevant water users.

Quantitative indices of water utilization depend on the season, especially if irrigation requirements prevail. This unevenness can be expressed by the ratio of a summer r_s (April to September) and winter r_w (October to March) withdrawals or by the ratio of summer c_s and winter water consumption c_w:

$$r_s = \frac{\sum_{i=1}^{n} W_{si}}{\sum_{i=1}^{n} W_{ai}} \qquad r_w = \frac{\sum_{i=1}^{n} W_{wi}}{\sum_{i=1}^{n} W_{ai}} = \frac{\sum_{i=1}^{n} (W_{ai} - W_{si})}{\sum_{i=1}^{n} W_{ai}} \tag{3.30}$$

$$c_s = \frac{\sum_{i=1}^{n} (W_{si} - F_{si})}{\sum_{i=1}^{n} (W_{ai} - F_{ai})} \qquad c_w = \frac{\sum_{n=1}^{n} (W_{wi} - F_{wi})}{\sum_{i=1}^{n} (W_{ai} - F_{ai})} \tag{3.31}$$

W_{ai} - annual water withdrawals (m^3)

W_{si}, W_{wi} - water withdrawals in the summer and winter season (m^3)

F_{ai} - return flows (m^3 per year)

F_{si},F_{wi} - return flows in the summer and winter season (m^3 per season)

3.6 PROBABILITY OF THE SATISFACTION OF WATER REQUIREMENTS

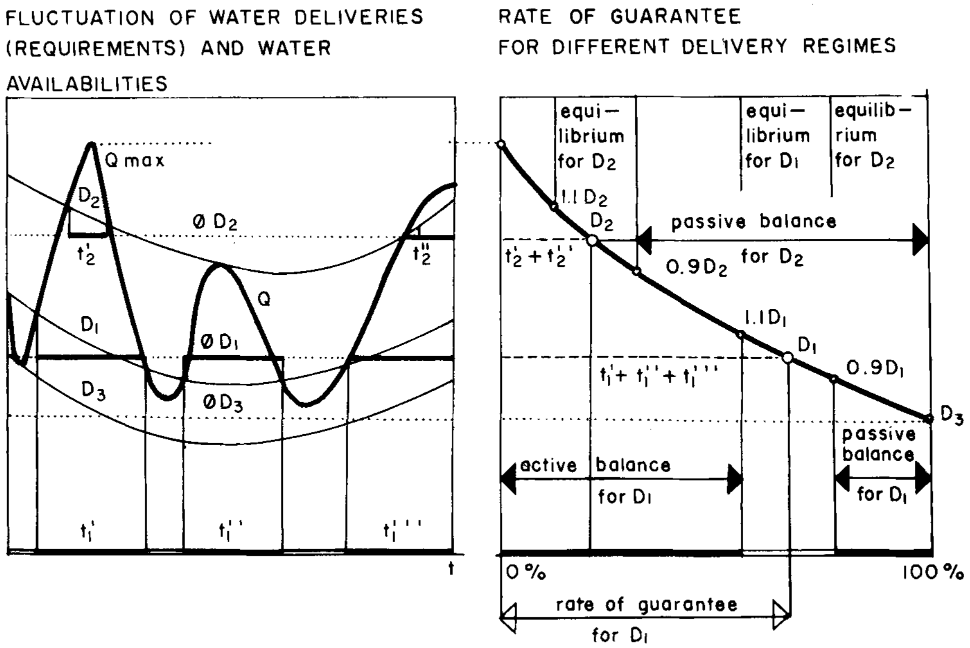
The course of water availabilities Q and of water consumption C can be expressed as a function of time

$$Q = f_1(t) \qquad C = \sum_{i=1}^{n} (W_i - F_i) = f_2(t) \qquad (3.32)$$

Their difference water surplus or deficit X is, therefore, also a function of time

$$X = Q - C = f_1(t) - f_2(t) = f_3(t) \qquad (3.33)$$

The points of intersection of the time function of available water resources and the time function of their consumption divide the period of the active and passive water balance. The duration of the passive balance, i.e. of non-guaranteed water supply, depends not only on the quantitative variation of water resources in time, but also on the course of water withdrawals and consumption, i.e. on the structure of water users. Similar structures of water users under the same climatic conditions produce similar time functions of water consumption.


FLUCTUATION OF WATER DELIVERIES (REQUIREMENTS) AND WATER AVAILABILITIES

RATE OF GUARANTEE FOR DIFFERENT DELIVERY REGIMES

Fig. 3.3. Chronological representation of the course of water deliveries (requirements), water resources availability and the duration curve of relevant water balance states: D_{1-3} - water deliveries (requirements), ø D_{1-3} average values, Q - available water resources, t - time.

Fluctuation in water consumption can therefore be characterized by average values and by the rate of the non-guaranteed water supply evaluated in the same manner as the course of discharges in hydrology: by the duration curve. Such a duration curve indicates the duration of the non-guaranteed water supply (%) in the given long-term period for the relevant course of the water consumption, characterized by the average value (Fig. 3.3). The decrease in water requirements increases the rate of guarantee and extends the duration of the favourable balance of water resources and needs (requirements).

Practically, the interval ± 10% for the equilibrium of water balances and needs has to be considered and relevant curves derived from values corresponding to the increased values of water availability by 10% and average values of water consumption (or for characteristic water resources data and water consumption) decreased by 10%.

The rate of guarantee of the water supply has to be economically considered from the point of view of

- the water user,
- the water supply organisation,
- the national economy.

The cost of water for its user can be expressed as the function

$$M = f(W) \tag{3.34}$$

M - cost per unit of production ($ per t)

W - amount of water supplied to the water (per unit of product m^3 per t , m^3.etc. water withdrawal W, delivery D, or water demand A, depending on methods of payment and masurement)

Agriculture and industry can operate without restriction or interruptions, i.e. at full capacity, when

$$D \geqq R_i \leqq R \qquad (m^3.s^{-1},\ m^3.t^{-1}) \tag{3.35}$$

R_i - the minimum discharge with which the user is able to operate without limiting the production (indispensable water requirement) ($m^3.s^{-1}$, $m^3.t^{-1}$)

D - water delivery ($D < W$) ($m^3.s^{-1}$)

R - the discharge which meets the user's requirements without using water-saving techniques ($m^3.s^{-1}$)

A limitation or interruption of the water supply causes economic losses in industry and agriculture. A decrease in the water supply beneath the lower limit R_i results in an immediate, non-proportional increase in costs per unit of production (M_2). The production rate decreases, also often influencing the quality of production, both in agriculture and in industry. A further decrease in water supply can result in a similar non-proportional increase in costs (M_3), because production can be ensured e.g. by an emergency water supply only, and in agriculture by cutting down the area under irrigation. It is quite obvious that a decrease in water supply below a certain limiting value definitely interrupts the production process, but a minimum discharge R_{min} may still be required for the maintenance of some processes in industry and for conservational purposes in agriculture (Fig. 3.4).

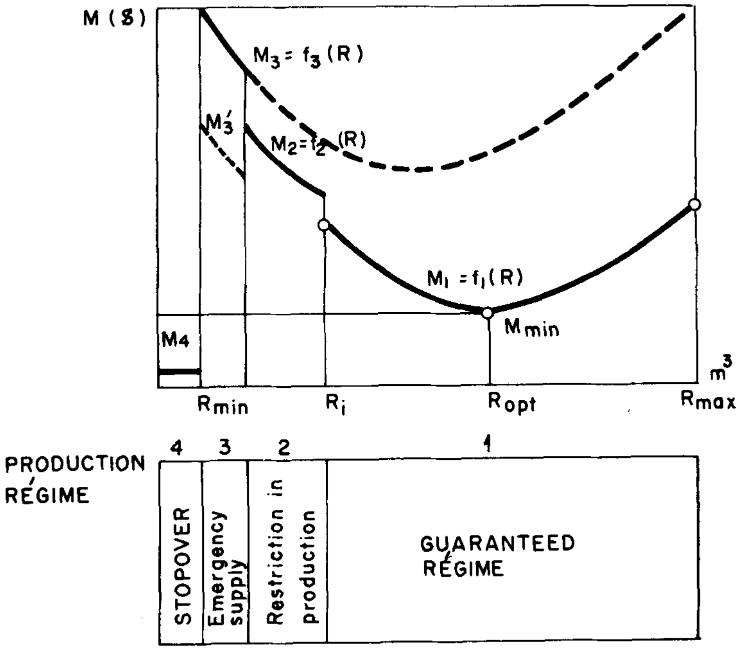


Fig. 3.4. Graphical representation of the influence of limiting water deliveries on operating cost: R_{min} - indispensable water requirements (e.g. with maximum recycling), R_{max} - water requirements with no recycling, R_{opt} - optimum discharge to be abstracted from the users viewpoints, M_1 - M_4 - operating costs under different production and water delivery regimes, M_{min} - minimum cost for the user.

The guarantee rate of water requirements satisfaction is simply the probability of satisfying the quantitative conditions of water requirements

$$p = \frac{t_1}{t} \,.\, 100\% \qquad (3.36)$$

p - the guarantee rate of water requirements satisfaction

t_1 - the duration of the satisfaction of water requirements (days)

t - the analysed long-term period (days)

By optimizing water use in agriculture and industry, an optimum discharge can be determined, thus safeguarding the required production at minimum cost for the user, i.e. optimum discharge to be abstracted from the user's viewpoint, or for the national economy, i.e. from the superior nation-wide point of view (R_i). The overall efficiency of the water supply does not depend on the water cost borne by the water user, but on the relevant cost of the water resources development and operation and on the losses resulting from the cutting down of production borne by the national economy.

But the economic relations between the water users and organisations responsible for the water supply are one-way. Relevant economic and legal feedback is not sufficient to project accordingly the losses to the water supplier: These organisations are only affected by the decrease in income from restricted water supply or by the possible duty to safeguard a compensatory emergency water supply. A decision on the rate of guarantee has to be taken from the over-all point of view of the national economy: Supplementary water resources development, generally borne by the national economy, is economically feasible if the total losses cause by the interruption or the decrease in the water supply exceed the total construction and operation costs.

TABLE 3.8

Water user	Rate of guarantee (%)	Water user	Rate of guarantee (%)
Population:		Power production:	
Big cities	95	Interstate system	99
Small centres	80	Local system	90
Agriculture:		Industry:	
Field crops	75	Interstate importance	97
Intensive cultivation	85	Local importance	90
Water transport:		Recreation	80
International	95		
National	85		
Local importance	60		

The recommended guarantee rate of water requirements satisfaction for basic categories of water users.

The full satisfaction (100%) of water requirements for the national economy is completely uneconomic, requiring a disproportionate development of water resources, in certain cases also emergency reservoirs and networks. It is very important that an increase in the guarantee rate of a few per cent within the limits from 80 to 95, and especially from 95 to 99 per cent results in a disproportionate increase, in a doubling or even in a higher increase of construction and operation costs. It is therefore indispensable to accept that the water supply could be decreased and even interrupted during periods of a lack of water or during necessary maintenance and reconstruction works. The limits of this guarantee rate depend on the relevant economic and social losses (Tab. 3.8).

The rate of guarantee does not only depend on quantitative, but also on qualitative parameters. The conditions for satisfying the quality requirements with the necessary degree of probability are of two types; i.e. for quality indicators, which must

(a) be greater than the necessary concentration

$$q_i \geqq q_{io} \qquad \text{(oxygen content etc.)} \qquad (3.37)$$

(b) not be greater than the allowable concentration

$$q_i' \leqq q_{io}' \qquad (3.38)$$

(i = 1,2..., n-1,n thermal, chemical, biological and bacteriological pollution).

The rate of guarantee for qualitative conditions represents the probability of exceeding the necessary and not exceeding the admissible indicators.

The guarantee rate of water requirements satisfaction is therefore a function of many random variables

$$f(R) = \text{probability } (Q \geqq R\ ,\ q_i' \geqq q_{io}\ ,\ q_i' \leqq q_{io}'). \qquad (3.39)$$

To determine this probability with the necessary accuracy requires daily records of quantitative data concerning water resources and water requirements. The density of water quality data need not be even, but must embrace any occurrence of pollution which exceeds the accepted limits.

The guarantee rate of water requirements satisfaction may be practically expressed in three ways:

(a) guarantee of duration	x_t
(b) guarantee of volume	x_v
(c) guarantee of frequency	x_f

The guarantee of frequency, expressed by the ratio of the number of years (or days) with active balance or balance in equilibrium and the total number of years of the given period, defines neither the real frequency of the interruption of the water supply, nor the depth of the water deficiency, nor its real duration.

The economic effect is quite different if these days are spread or accumulated. The rate expressed by the ratio of the number of years, though used quite often, is almost without practical use (Tab. 3.9).

TABLE 3.9

Rate of guarantee	Formula	Remarks
Guarantee of duration	$x_t = \frac{t'}{t}$	t – total duration of the period t' – accumulated duration of the periods in which the use is satisfied
Guarantee of volume	$x_v = \frac{W'}{W}$	W – total volume of water requirements W' – volume of water actually supplied
Guarantee of frequency	$x_f = \frac{Y'}{Y}$	Y – total number of years in the period Y' – number of years in which the water use is completely satisfied

Rate of guarantee for qualitative water requirements expressed as a percentage or fraction of the whole according to the Economic Commission for Europe (1973).

The guarantee of duration and of volume have the same disadvantage, namely that of expressing neither the frequency nor the duration of the relevant disturbances of supply. The relation between the three mentioned rates is:

$$x_f < x_t < x_v \qquad (3.40)$$

The rate of guarantee of volume may exceed 1 (one), exceeding the guarantee of duration in all cases. The guarantee of frequency, expressed by numbers of years, represents the smallest value, illogically accepting the total annual period as passive, if only a few days occur with a passive water balance.

To characterize the guarantee rate of water requirements satisfaction by mostly appropriate figures, it is necessary to determine the characteristics interrelations between the three indicators mentioned in the following way:

- to find the year with the highest number of days with a passive water balance,
- to select the longest period of the passive balance within this year,
- to determine the guarantee of volume during this period,
- to check whether a lower value of guarantee does not occur in some other period.

The appropriate value of the guarantee rate of water requirements satisfaction is expressed by the figure selected in this way.

3.7 FLOW CONTROL AND OPERATING SCHEDULES

The desired daily equilibrium or active balance of water requirements and water availabilities has to be achieved by flow and groundwater abstraction control. Schedules and guides for both surface and groundwater withdrawal and the regulation of flow and reservoir operation should be developed in advance in order to determine the most effective methods of water utilization.

Operating procedures form a complex of fixed and conditioned rules, whose aim it is to influence the location and the time distribution of water occurrence and its quality. These operating procedures include rules for surface and groundwater withdrawal, the storage of excess water in reservoirs and aquifers, its infiltration, pumping and conveyance, the release of stored water, the control of its quality by the control of the return flow and its beneficial use for the sake of the society.

Surface water bodies differ from underground water bodies by their flood detention effect. River beds, reservoirs, polders and river valleys offer storage for the immediate accumulation of water discharges, prism storage and, during the advance of a flood wave, also wedge storage. The degree of flood control offered by the reservoir depends on the ratio of the flood volume to the detention storage offered at the moment of any harmful overtopping of the natural and artificial banks in a given reach of stream. The degree of flood control can be characterized by the frequency of the flood volume occurrence, when the storage

$$V = \int_0^t (Q_f - Q_o)\, dt \qquad (3.41)$$

V - storage volume of the reservoir (m^3)

Q_f - flood discharges ($m^3.s^{-1}$)

Q_o - maximum discharge, not causing harmful overtopping of river banks ($m^3.s^{-1}$)

t - time (duration of the flood)

Almost all modern reservoirs are multipurpose. The effective storage capacity of such a reservoir can be theoretically divided into the flood-control storage and the storage capacity reserved for beneficial use. It is essential that the reservoir capacity reserved for the storage of flood water should be emptied as soon as practicable after a flood. Insufficient flood-storage capacity may result in a concentration of maximum discharge from tributaries, thus increasing the maximum flood discharge instead of decreasing it. The storage filled up before the arrival of the peak flood reduces the duration, but not the extent of inundation.

To optimize the operating procedures for the multipurpose utilization of reservoirs, the modifying effects on discharges including floods passing through a reservoir, polder etc. have to be determined by routing on the basis of

(a) collected chronological sequences of hydrological data and data on water use,

(b) chronological sequences of synthetic hydrological data and water needs,

(c) general probabilistic data on water requirements and water availabilities,

(d) frequency analysis of the storage volume at the boundary of the time intervals.

Operating schedules, rules and guides depend on the lay-out and technical equipment of relevant projects and systems. Depending on the relevant lay-out and equipment, the function of water development projects and systems is

(a) controllable and thus controlled or uncontrolled,

(b) uncontrollable, i.e. rigid and not dependent on the decisions of the operating personnel.

Consequently, the operating rules are either rigid or flexible. Rigid schedules depend mostly on ungated structures or on unconditional binding operations. The day-to-day operation is often based on semi-rigid schedules, on conditional rules dependent on the flow and the water requirements, on their current and forecasted state. The decision can be determined beforehand and expressed in the form of graphs and tabulation, formulated by the operating centre or done on site by relevant decision-makers or by the operating personnel, as this should be laid down beforehand on the basis of the theoretical studies or of previous experiences.

To increase the flood control effect of a reservoir, the active storage capacity reserved for beneficial use may be partially emptied, depending on the flow forecast. Such a release and beneficial use of water is also useful for limiting the expected but not beneficially usable spill (for power generation), which may occur especially when the reservoir is full before the beginning of the new cycle of reservoir operation.

Under such circumstances, the release of water is economically feasible if the economic effect from the beneficial utilization of such water balances the risk of losses which may occur in the next period of reservoir operation (Fig. 3.5). According to Hugh-Blair Smith (1960), this condition may be formulated as follows:

$$O_{k+} = Q_{m-k} - (V - V_k) - O_{m-k} \qquad (m^3) \qquad (3.42)$$

O_{k+} - additional release of water during the month k (m^3)

Q_{m-k} – forecasted inflow in the remaining (m-k) month period of the operation cycle (m^3)

V – total active storage (m^3)

V_k – volume available in the reservoir in the month k

O_{m-k} – outflow from the reservoir according to the basic operation (m^3)

When $O_{n+} < 0$, the additional release of water = 0. An additional limitation for water power generation is

$$O_{k+} \leq V_k \qquad Q_{ke} \geq O_{k+} \leq V_k \qquad (m^3) \tag{3.43}$$

Q_{ne} – unused capacity of the power plant according to the basic operation

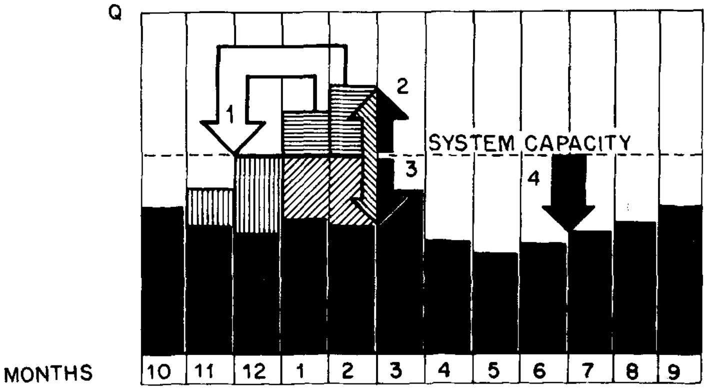


Fig. 3.5. Supplementary outflow from a reservoir on the basis of a medium-term inflow forecast increases the efficiency of water utilization in comparison with a rigid operating schedule, based on actual water availabilities.
1 – supplementary outflow, 2 – water surplus (nonavailable operatively),
3 – water surplus available operatively, 4 – unused capacity of the system (reserve for seasonal increase in requirements).

The additional release of water is not economically feasible if the economic effect from the filled reservoir exceeds the economic effect from the beneficial utilization of water downstream.

The economization of reservoir utilization can also be achieved by the reduction of withdrawals to safeguard water in storage for later use. The feasibility of such a decision has to be proved on the basis of the benefits arising from the decreased risk of a water lack in the next period. The efficiency of such operation can be proved when the function of the economic losses is not linear. Under such circumstances, the lowering of water withdrawals in the period preceding the period of the expected water deficiency is motivated by the higher benefits to accrue from the same amount of water.

Such a reduction of water withdrawals is justified in the period of reduced useful storage (Fig. 3.6) and is useful in the course of a short-term period, because hydrological and meteorological forecasts for longer periods are not sufficiently reliable.

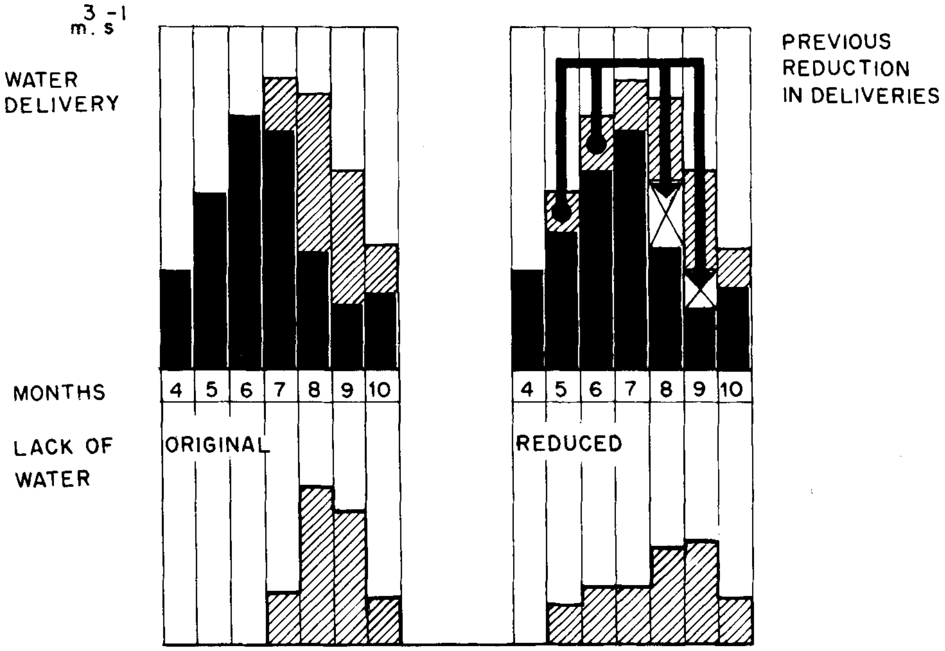


Fig. 3.6. The decrease in economic losses from water deficiency by reducing water deliveries before the period of unfavourable balances of water resources needs: a. original values without previous reduction in water deliveries, b. reduced values of water deliveries before the period of the forecasted drought, resulting in a reduction in the lack of water in the period of water deficiency. (Water deliveries marked black, deficiency hatched).

For the optimum utilization of the maximum volume of water in water reservoir systems it is necessary to distribute the release of water among the relevant reservoirs, so that the empty part of the useful storages is in relation to the inflow expected on the basis of a statistical and probability analysis in the remaining period before the beginning of the next operation cycle.

Shoemaker (1960) expressed this principle mathematically on the basis of the quality of the ratio of the empty storage of one reservoir to the empty storages of all the reservoirs, and the ratio of the expected inflow of one reservoir to the expected inflow of all the reservoirs in the system as follows:

$$\frac{V_j - \bar{V}_{jk} - Q_{jk} + O_{jk}}{\sum_{j=1}^{n} (V_n - V_{jk} - Q_{jk}) + O_r} = \frac{Q_{j(m-k)}}{\sum_{j=1}^{n} Q_{j(m-k)}} \qquad (3.44)$$

n – number of reservoirs

m – number of months in the operation cycle

V_j – useful storage of the reservoir j (m^3)

$\bar{V}_{jk}$ – the volume of water in the storage of reservoir j in the month k (m^3)

Q_{jk} – the inflow of water into reservoir j during the month k (m^3)

O_{jk} – outflow from the reservoir j during the month k (m^3)

O_r – controlled increase of runoff in the rest of the period (m^3)

$Q_{j(m-k)}$ – the expected inflow into the reservoir j in the rest of the cycle of the reservoir operation (m^3)

Supposing that

$$Q_r = O_{jk} = (\bar{V}_{jk} + Q_{jk}), \qquad (3.45)$$

the release from reservoir j during the month k is

$$O_{jk} = \bar{V}_{jk} + Q_{jk} - V_j + \sum_{j=1}^{n} \left[(V_j - \bar{V}_{jk} - Q_{jk}) + O_r \right] \cdot \frac{Q_{j(m-k)}}{\sum_{j=1}^{n} Q_{j(m-k)}} \qquad (3.46)$$

The benefits from operation on the basis of this principle arise in practice only if the hydrological forecast is sufficiently reliable, i.e. mainly during spring discharges caused by the melting of snow.

The formulation of a similar analog for water power generation requires programming, because relevant dams offer different heads, resulting in the differences in the benefits to arise from a utilization of the same amount of water by the power stations of different dams.

For the efficient use of the useful storage capacity it is indispensable

(a) to release water either for beneficial uses or to increase the flood-control storage in the period of the expected surplus of water, to decrease the extent of floods or the amount of water not beneficially used,

(b) to decrease water withdrawals in the period before the water deficiency, carefully balancing the restricted benefits against the decrease in expected losses,

(c) to manage the operation of all reservoirs which are capable of controlling and increasing the discharges in the relevant water management profile in such a way as to balance their empty storage against the inflow expected in the next period,

(d) to increase the yield by a conjunctive use of surface and groundwater resources, to meet most needs in normal and wet years by surface storage, to retain groundwater for use during years of low surface runoff and also recharge this artificially in periods of excess surface flow.

In reality, reservoirs and water resources systems are managed on the basis of incomplete knowledge. Operational decisions are taken on the basis of what the future state is expected to be, rather than of what it is known to be. The optimal control of the outflow depends

(a) on the ability to forecast future flow sequences,

(b) on the influence of the intermediate catchment: the prism and wedge storage of the river bed, inflows from unmeasured tributaries, gains and losses due to groundwater drainage, losses and evaporation, water withdrawals etc.

(c) on the useful storage available at the right moment,

(d) on the control of the reservoir sluices.

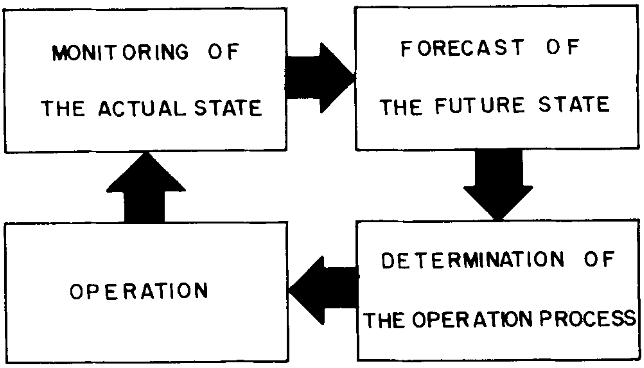


Fig. 3.7. Schematic representation of a cycle for tuning the reservoir operation on the basis of results achieved by single steps of operation.

Success in managing a multi-purpose reservoir or a reservoir system in real time depends on a minimal delay between the measured change of state and the implementation of the appropriate control decision implemented (Fig. 3.7).

This delay depends above all on the equipment and the state of

(a) the signalling system (hydrological and meteorological)

(b) the decision making system (programming, simulation or brain-trust only),

(c) the operation system (communication, press-button control on site or remote, centralized remote-control etc.)

The degree of water losses arising from current control in comparison with the data of computerized centralized remote-control often exceeds 20%. The extent and technical standard of the signalling, decision-making and operation system safeguarding the real flexibility of operation schedules should be determined by analyzing the relevant purchase and operation costs. The sum of these costs should exceed neither the increase of the induced benefits, nor the investment and operation costs of the emergency water supply.

3.8 SYSTEMS IN WATER RESOURCES MANAGEMENT

The framework in which water management activities exist forms a complex of river network systems, groundwater strata systems, water supply systems, irrigation systems, drainage and water disposal systems, flood control systems, water transport systems, water power generation systems etc., but also the abiotic, biological, legal, economic, administrative, informational and other systems of the environment (Fig. 3.8). This complex can be characterized by and subdivided into

(a) the natural systems of catchments and aquifers,

(b) technical systems of inlet works, wells and galleries, reservoirs, canal and pipeline networks etc. with relevant signalling and control systems,

(c) water supply, distribution and disposal systems of water users, situated either inside or outside water resources systems,

(d) economic and administrative systems of water management,

(e) natural, technical and socio-economic systems of the environment.

A system is a set of elements whose interrelationship is far more important than their relations to the elements of the other systems which form its environment. The set of elements and links forms the structure of a system (Fig. 3.9). Important links in water resources systems can be distinguished as

- material (hydraulic and hydrological - Fig. 3.11)
- energetical (enabling the operation)
- immaterial (economic, legal, informational etc.)

n elements of a system can be connected mutually by not more than n . (n-1) links of the same type. An open system has at least one link with the environment. A closed system has no links with the environment and can be characterized by the Cartesian product

$$S = \{X \ast R\} \qquad (3.47)$$

$X = \{X_1 \quad X_2 \ldots \quad \ldots X_n\}$ X_i - sets of elements x_i

$R = \{R_1 \quad R_2 \ldots \quad \ldots R_n\}$ R_i - sets of elements r_i

$$(x_1 \in X_1,\ x_2 \in X_2, \ldots \qquad \ldots, x_n \in X_n)$$

$$(r_1 \in R_1,\ r_2 \in R_2, \ldots \qquad \ldots, r_n \in R_n)$$

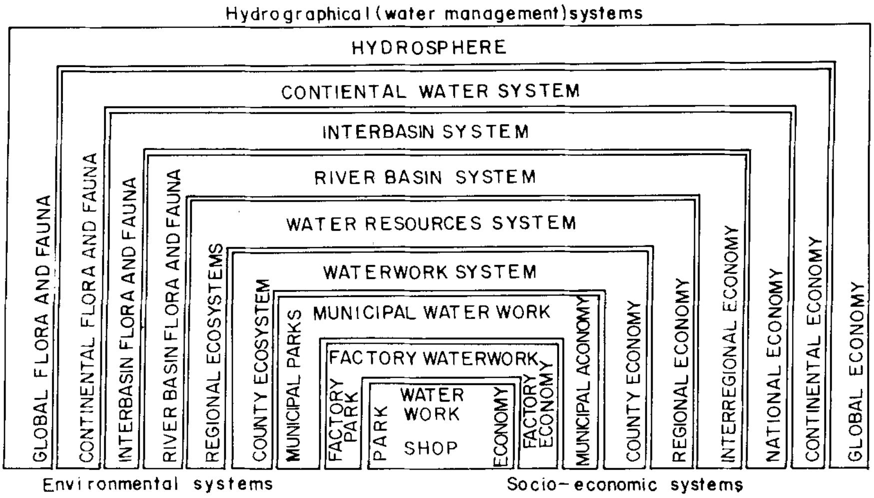


Fig. 3.8. Hierarchy of basic systems for water supply in relation to the natural and social systems which form the environment of the water supply and disposal systems.

To achieve the optimum satisfaction of the defined objectives of water resources systems, to find their most economic lay-out and function and to achieve their harmony with their environment, water resources systems and their function should be optimized at three different stages of their development:

(a) at the planning stage - to identify the optimum structure of the system which satisfies the needs within the constraints imposed, i.e. to allocate resources so that relevant preconceived goals are attained as far as possible,

(b) at the design stage - to optimize the size of the components mainly on the basis of the topographic and hydrological data, e.g. to select the least-cost solution imposing minimum constraints on the future development, or the solution of creating an integral component of the final development stage,

(c) at the operational stage - to manage a system in such a way that the actual needs are satisfied up to the design standard and the economic losses (sometimes also operational costs) are minimized and the maximum benefits achieved.

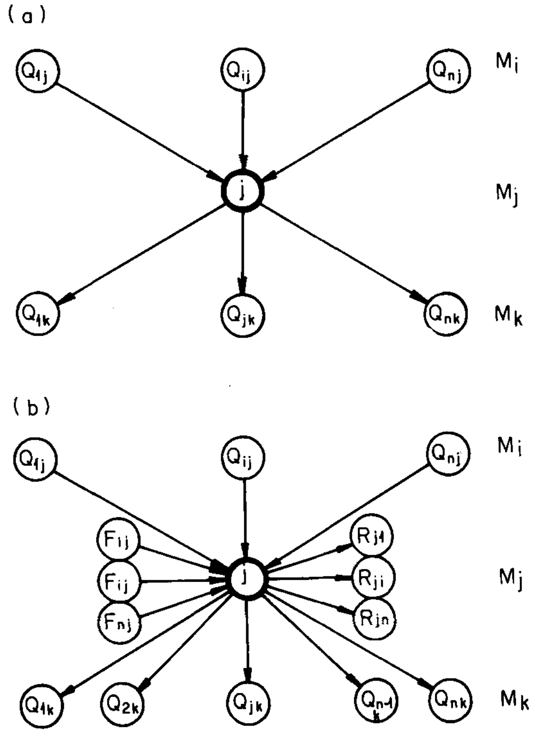


Fig. 3.9. Schematic representation of hydraulic interrelations of one element in a water resources system: a) with the water users who form the environment of the system, b) with the water users incorporated into the system. Q - water resources, R - water withdrawals, F - effluent.

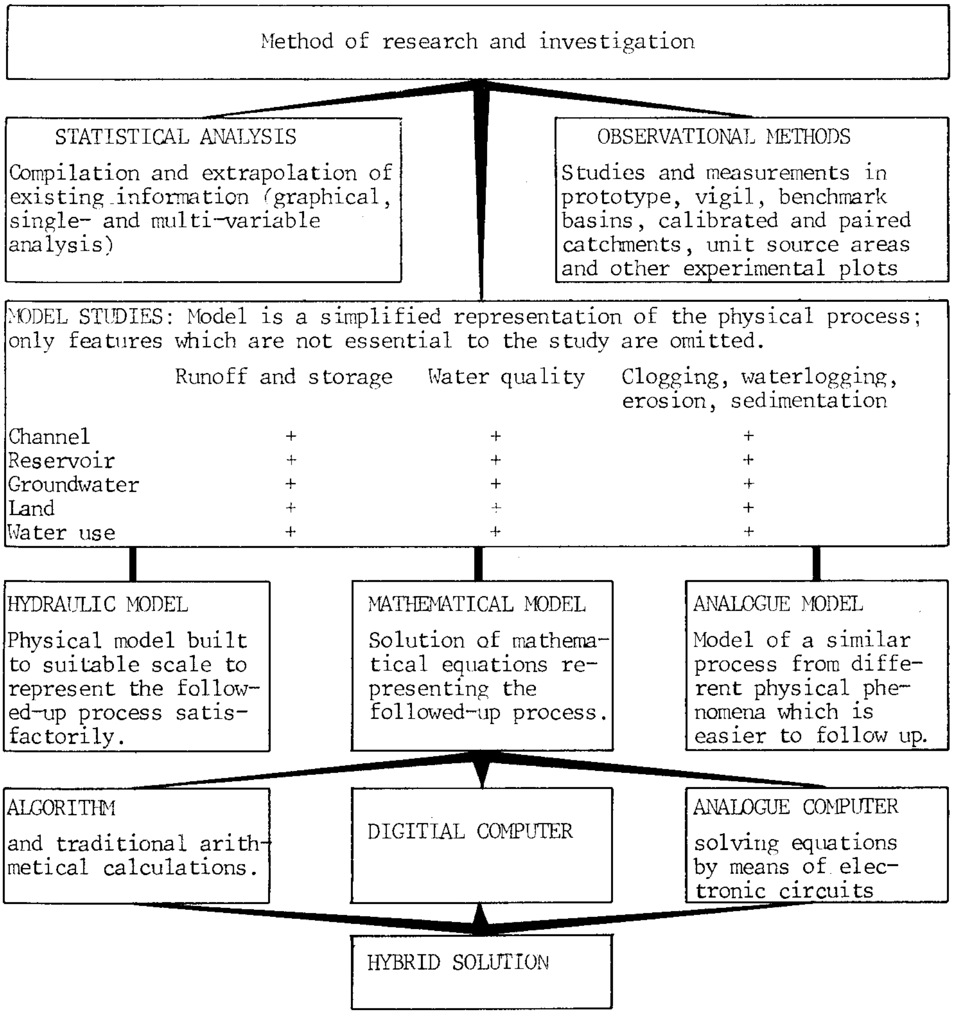
3.9 ANALYSIS AND MODELLING OF WATER RESOURCES SYSTEMS

Desirable functions of water resources systems can be achieved in balanced interrelations in their subsystems only, simultaneously fulfilling different functions in other systems, especially in the technical and economic ones and in the administrative system of water resources management.

To achieve these desired goals in an optimum way, heuristic methods have to be used. These methods, restricting the extent of searching and helping to formulate the solution, include scientific appraisals in the first extreme and exact algorithms in the second. In this specific case it is unlikely that any algorithm, a prescription for a series of calculations to be performed one after another, or any similar analytical technique, would be capable of leading from the entry data to the optimum solution.

A hierarchical approach is needed, enabling many alternative solutions to be considered without attention to detail, in order to examine the best of them in detail during subsequent stages. The complex problems of water resources require the use of different research and investigation methods (Tab. 3.10) and various other techniques such as probability theory, modelling and mathematical programming, operation research/systems analysis etc.

TABLE 3.10



Method of research and investigation

STATISTICAL ANALYSIS

Compilation and extrapolation of existing information (graphical, single- and multi-variable analysis)

OBSERVATIONAL METHODS

Studies and measurements in prototype, vigil, benchmark basins, calibrated and paired catchments, unit source areas and other experimental plots

MODEL STUDIES: Model is a simplified representation of the physical process; only features which are not essential to the study are omitted.

	Runoff and storage	Water quality	Clogging, waterlogging, erosion, sedimentation
Channel	+	+	+
Reservoir	+	+	+
Groundwater	+	+	+
Land	+	+	+
Water use	+	+	+

HYDRAULIC MODEL

Physical model built to suitable scale to represent the followed-up process satisfactorily.

MATHEMATICAL MODEL

Solution of mathematical equations representing the followed-up process.

ANALOGUE MODEL

Model of a similar process from different physical phenomena which is easier to follow up.

ALGORITHM

and traditional arithmetical calculations.

DIGITIAL COMPUTER

ANALOGUE COMPUTER

solving equations by means of electronic circuits

HYBRID SOLUTION

Research methods and models in water resources management.

Relevant methods are appropriate to different circumstances: Simulation methods use mathematical systems analogous to the physical systems under study, which may be manipulated to produce output data similar to observed data. The variables of interest in the former correspond to physical variables. Mathematical programming is a technique for finding the optimum way to accomplish the given purpose.

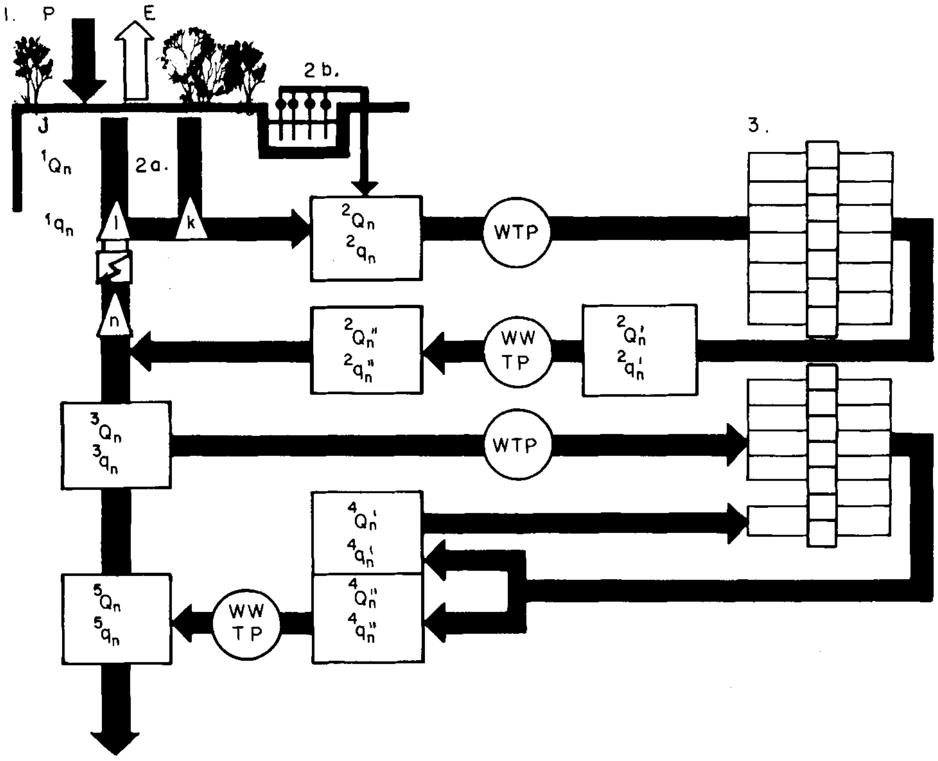


Fig. 3.10. Basic inputs and outputs in systems of water resources and users: P - precipitation, J - energy, Q - runoff, q - water quality indicators, E - evaporation, WTP - water purification plant, WWTP - waste water treatment plant. 1 - natural systems, 2 - water resources systems: a) channel and reservoir network, b) well systems, 3 - distribution and waste water disposal systems of water users.

The linear programming method is a systematic procedure for trying various combinations of elements in such a way that the control variable comes nearer to each goal at each try, always keeping within the established limit when all the relationships are linear. Integer programming is used when the quantities involved are limited to integer values. Dynamic programming is the application of the theory of multi-stage decision processes. It leads to an optimal policy by steps, in ways that often correspond to methods by decisions are made.

Models afford a deep understanding of the behaviour of the real system, providing the possibility of introducing the necessary changes in the structure and operation of the system to produce higher benefits, decrease the relevant costs and reduce the relevant negative effects.

The model of a water resources system is a combination of rivers, canals,

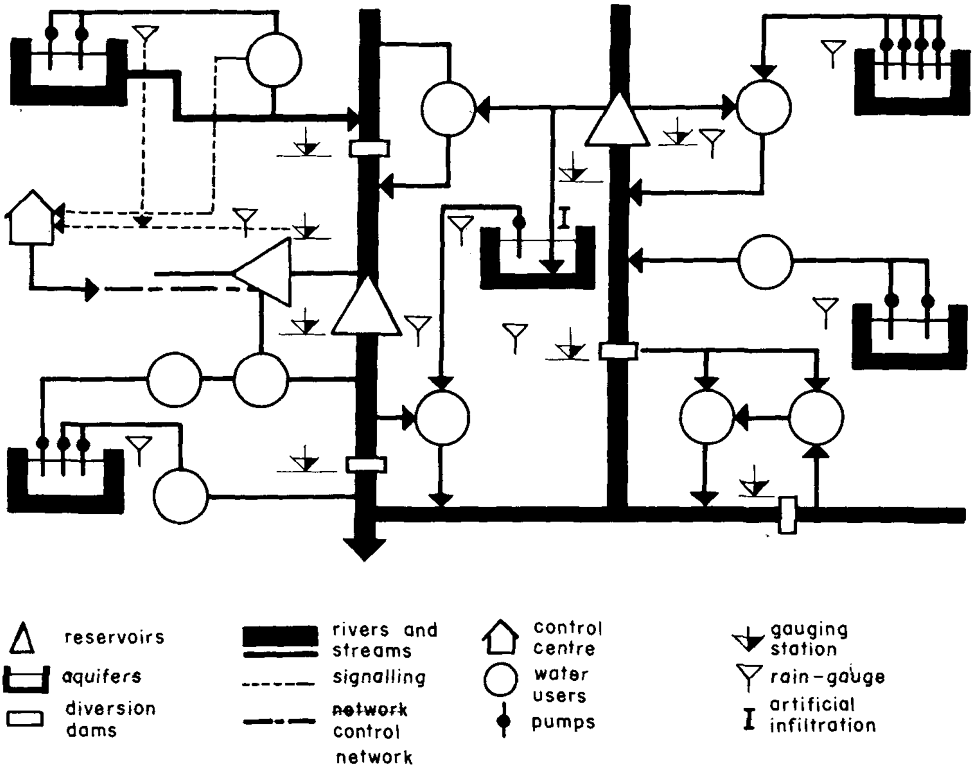


Fig. 3.11. Schematic representation of a system of surface and groundwater resources. The monitoring and control systems are depicted for two water resources and one of the water users only.

and pipelines, pumping, water purification and water treatment plants, hydropower stations (and their design heads) etc. Utilization variables concern the water supply for population and industry, areas under irrigation, power production etc. and are mainly expressed in cubic meters, kilowatt hours etc. per year. Constraints relate mainly to the volume of water available in reservoirs at the beginning of the operation season or at the beginning of each month, as well as to minimum flow, the monthly demand of energy etc. and to the nonnegativity of flow.

The iterative computations with different combinations of components and different operating schedules make it possible to select the optimum solution. The capacity of computers as well as practical reasons of the natural regulation of flow in reservoirs and channels make it possible to use ten daily or monthly averages as entry data for the analysis of the water supply, power generation

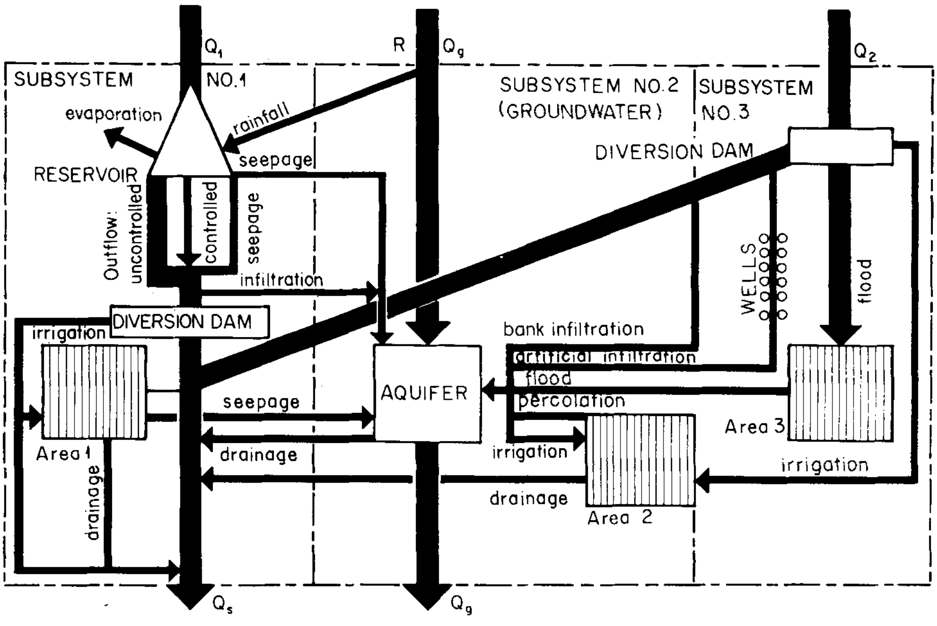


Fig. 3.12. Schematic representation of a surface and groundwater system for irrigation supply at the confluence of two rivers.

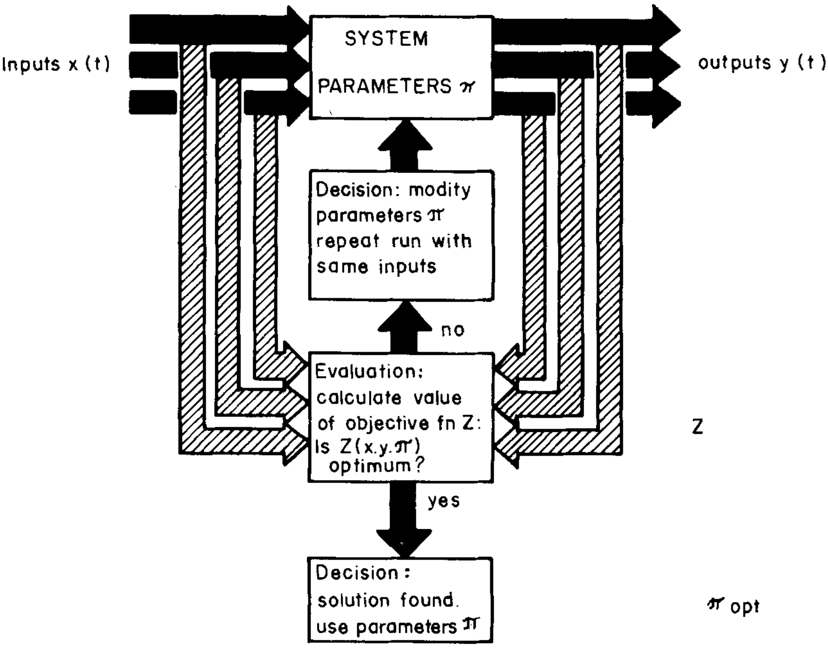


Fig. 3.13. Flow chart diagram for the selection of the optimum combination of project parameters according to Plate (1975).

etc. The break-up data for flood protection purposes should be in more detail, at least for six hour intervals, depending on the size of the catchment and the course of floods (Fig. 3.13).

An increase in the reliability of the results of optimization can be achieved by:

(a) a systematic selection and construction of alternatives, not by trial and error,

(b) formulating and programming operating schedules in such a way as to form the variable part of the model, or selecting the optimum operating schedule on the basis of a systems approach,

(c) generating a long-term series of synthetic hydrological data (e.g. for five hundred years), or probable characteristic hydrological situations which did not occur in the series observed, improving in this way the reliability of these entry data for future situations, especially in periods of minimum and maximum runoff,

(d) evaluating the benefits of relevant water resources systems on the basis of data whose stability and reliability or progressive increase or decrease can also be specified precisely enough in periods to come. These reliable data have to be derived from the population growth and development of living standards, based on the optimum needs of one individual,

(e) employing a sensitivity analysis, whose goal it is

- to define the dispersion interval of the entry data, safeguarding the generation of the output data in the sphere of the optimum solution,
- to identify the group of criteria which has the most important influence on the selection of the optimum solution and to analyse their interrelationship,
- to maximize the functional stability of the system by optimizing its structure, links and management.

Benefits and losses arising from the operation of different water resources systems can be characterized by the set of affected hydrological data, by a set of geographical and economic data, or by financial indicators. Benefits and losses, as well as the pay-off, are functions of the parameters of the system (Fig. 3.14).

$$B_i = F_i \ (X_1 , X_2 \ldots\ldots X_n) \qquad (3.48)$$

$B_1 , B_2 , \ldots, B_n$ - benefits and losses

$X_1 , X_2 , \ldots, X_n$ - parameters of the system

On the basis of the decision criteria for any combination of the entry data and elements of the analyzed system a set of outcomes may be determined, each outcome with a determined degree of probability.

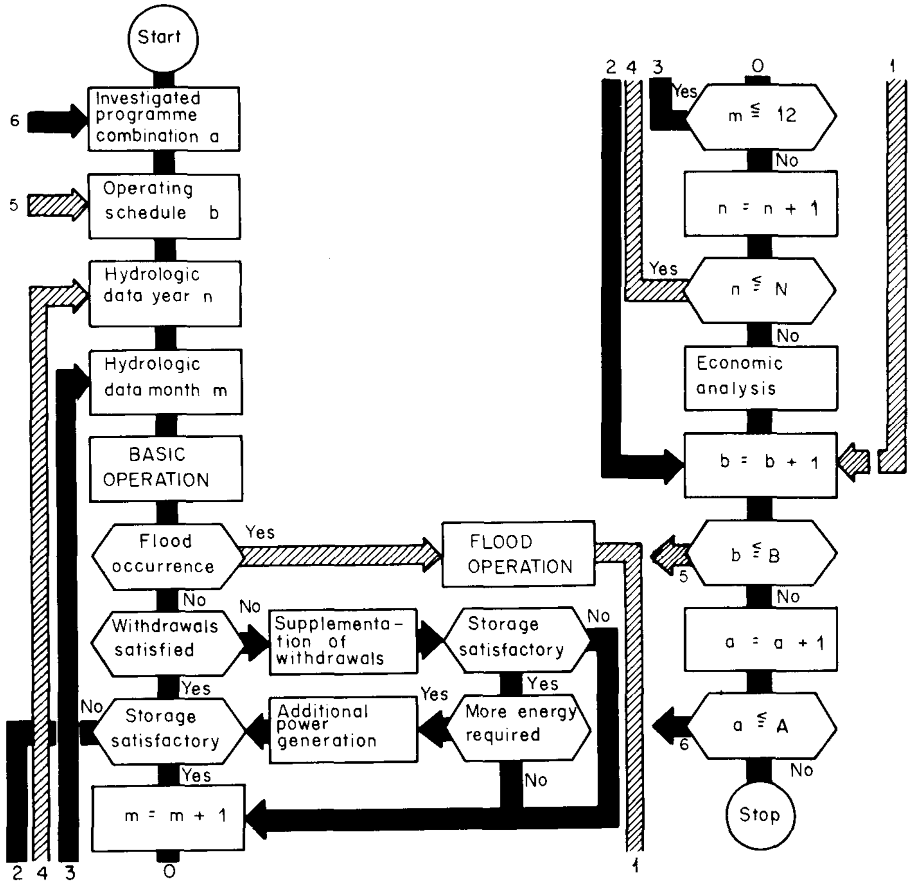


Fig. 3.14. Simplified flowchart diagram for modelling of a system of multipurpose reservoirs: A - number of investigated combinations a, B - number of investigated operating schedules b, C - number of analysed years n.

System analysis is a rational approach entailing any of the following steps (Fig. 3.15):

(a) Analysing the problem area, identifying its boundary and basic interconnections to other problems,

(b) Simplifying the problems to the point of analytical tractability, preserving all important aspects affected by various possible solutions, defining the system,

(c) Defining the hierarchy of objectives and goals,

(d) Identifying criteria for decision-making, employing feedback mechanism,

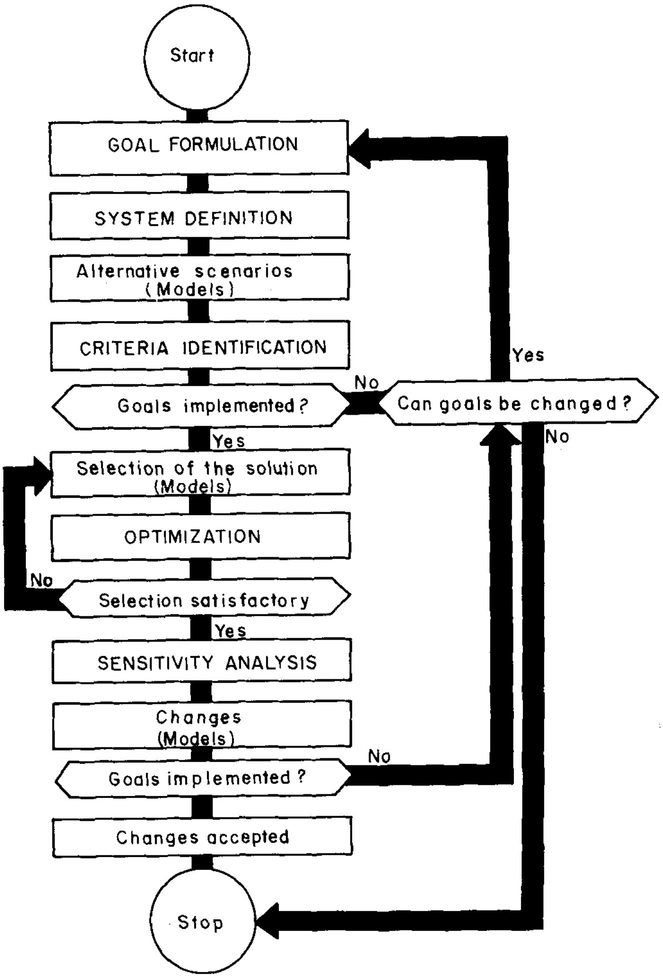


Fig. 3.15. Flowchart diagram for the selection and optimization of water resources systems.

(e) Modelling the system, examining appropriate alternatives, in order to optimize the structure of the system,

(f) Optimizing the function of the system, not omitting any dynamic interrelationships among the various components,

(g) Investigating the sensitivity of the results to the assumptions made, including the inclusion or exclusion of the problem components,

(h) Verifying that the selected solution satisfies the defined objectives and goals.

The hierarchy of decision criteria for development goals mainly includes

(a) political criteria, such as full employment, higher income and its better distribution, increased standards of life, promotion of industrial/agricultural development, electrification etc.,

(b) water management criteria, e.g.

- the increase of the rate of guarantee of water delivery for different categories of water users,
- the increase of the rate of guarantee of flood protection,
- economic utilization of resources available,

(c) economic criteria, e.g. fixed target at least cost, benefit maximization, cost-benefit optimization.

(d) environmental criteria etc.

The identification of these criteria determines the relevant political, water management, economic, environmental and other consequences: e.g. the minimization of relevant costs, expressed and realized as the minimization of present costs to achieve the requested goals, forms obstacles to future development trends.

Systems analysis with adequate entry data is to be used for solving problems of multipurpose projects and in conditions with a lack of data to identify problems. The possibility of a successful optimization is threatened by

(a) not including the really optimum solution among the selected alternatives,

(b) not identifying the really optimum function of the system,

(c) the possibility that the hydrological data are not sufficiently representative for the given task,

(d) the low reliability of the economic data for the future period of the functioning of the system,

(e) unexpected environmental consequences, especially those with a substantial economic impact.

The most common errors leading to the failure of systems analysis include

- selecting the wrong models,
- neglecting important components, links and feedbacks
- constructing models which are too detailed and exhaustive, making it difficult to select the optimum solution,
- using the process too rigidly or using the wrong criteria, i.e. those which do not lead to the requested decision,
- analysing relationships in the selected solutions which will be altered in the real situation or if a problem solution is obvious.

3.10 ECONOMIC OPTIMIZATION AND FINANCIAL ANALYSIS

Economic evaluation/optimization is a method of selecting the optimum solution for a useful utilization of limited resources such as capital, labour, land, water and other natural resources for different uses in the interests of human society. It consists in the selection of such a combination of structural variables as to minimize losses and maximize benefits. Its replacement by a minimization of investment costs is not adequate. Investment costs should be used as one of the criterion functions (Tab. 3.11).

TABLE 3.11

	Economic evaluation	Financial analysis
Goal	Growth of national income Better income distribution	Financement Money profit
Objective	Select the project, enabling maximum efficiency in using capital and natural resources available	Assessment of financial viability of economically optimum project
Viewpoint	(National) economy	Capital available to the project-undertaking entity
Input	1. Costs and benefits to the economy 1.1 directly to the project-undertaking entity 1.2 affecting other entities and individuals 2. secondary effects (transfer payments, sunk costs and inflation excluded)	Expenditures and revenues to the entity, external and secondary effects excluded. Transfer payments, taxes, custom duties, subsidies and depreciation, interest and amortization, sunk costs and general inflation excluded.
Prices	Shadow prices used, if market prices do not reflect the true values of projects effects	Market prices used.
Result	Net present worth (NPW): Discounted costs and benefits, subtracted former from the latter. Economic rate of return (ERR): The discount rate equalizing the present worth of benefits and costs.	Estimation of total capital requirements, split up into - local currency, - foreign exchange. Income statement, statement of financial sources, cash flow, balance sheet. Financial rate of return (FRR). Financial ratios: - return of fixed assets, - debt service coverage by internal cash generation, - debt/equity ratio.

Characteristics of economic evaluation/optimization and financial analysis.

Financial analysis is a method of assessing whether or not the relevant entity or entities intending to undertake the project is capable of financing its construction and operation.

The investment costs of a multipurpose project financed by several participants are generally expected to be less than the total of the costs of the single-purpose project that would produce equivalent outputs. In multipurpose projects there are

(a) separable costs which can be clearly separated and allocated to one of the participants $S_1, S_2 \ldots . S_n$

(b) common costs which are also to be shared equitably by these parties $0_1, 0_2 \ldots 0$

The total cost of a multipurpose project is, therefore

$$T = \sum_{k=1}^{n} (S_k + 0_k) + I \qquad (3.49)$$

I - irrecoverable subsidies.

TABLE 3.12

Activities	Input or output	Methods and tools	Other effects and criteria
Identification of benefits and costs	1. Direct costs and benefits - of the project-undertaking entities, - of other entities and persons 2. Transfer payments (taxes, subsidies and custom duties, interest and amortization, - inflation and depreciation excluded) 3. Secondary effects	Comparison of situation with and without project (no status quo since even without the project development is likely)	Secondary effects stemming from - project inputs (during construction) - project outputs (after completion) expressed - explicitly by multiplicators applied to prices, - implicitly by using shadow prices
Measurement of benefits and costs	Shadow prices based on opportunity cost principle OCC (if marked prices are distorted) - efficiency shadow prices - to achieve income growth and its improved distribution between consumption and investment, - social shadow prices - to distinguish between costs and benefits accrued to poor and rich to achieve improved income distribution		
Comparison of benefits and costs	Net present worth (NPW) = difference between present worth of benefits and that of costs using discounting technique. Economic rate of return (ERR) = discount rate at which NPW = 0 Discount rate = opportunity cost of capital (OCC) defined by Authority.	Criterion of economic viability: Absolute merit (single project) NPW at OCC ≧ 0, ERR ≧ OCC Relative merit (several projects) Max NPW at OCC NPW ≧ 0 low tariff leading to waste High NPW - impedes economic growth	Sensitivity analysis to deal with uncertainties affecting input data. Risk analysis using probability distributions for important projects. Qualitative assessment of intangible aspects.

Identification, measurement and comparison of benefits and costs.

There are a number of cost sharing methods, but the practical cost sharing is a result of negotiations. Participants in multipurpose projects are prepared to pay their separable costs and their share of common costs provided that their sum does not exceed the cost J_m of an equivalent single-purpose project $(S_m + O_m < J_m)$ and provided their benefits exceed or equal the costs

$$(B_m \geqq S_m + O_m). \qquad (3.50)$$

In many countries tariffs are not well related to costs of production and investment is often subsidized. Under such circumstances the expected net benefits of the relevant undertaking cannot therefore be used as a scale for sharing the common costs.

The participants should, therefore, share the common costs in proportion to their saving, resulting from the joint project, i.e. in proportion to the equivalent single-purpose costs less their separable costs in the multipurpose project. The range within which it is reasonable to negotiate the share of common costs is therefore

$$O_m = \sum_{k=1}^{n} O_k \frac{(J_m - S_m)}{(J_m - S_m) + \sum\limits_{k=1}^{n} (J_k - S_k)} \qquad (3.51)$$

$J_1, J_2, \ldots, J_n$ - costs of equivalent single-purpose projects

Costs and benefits must reflect the true value of project inputs, outputs and other effects on the economy as a whole. When the tariffs do not refer to the actual costs of resources used or saved by consumer decisions, they are based on sunk costs and the backward-looking pricing approach of calculating accounting costs is used. Price system distortions, namely

- price control imposed by the government,
- under- and overvalued currencies,
- protectionist measures by import quota and customs duties,
- taxes and subsidies hidden in prices,
- monopoly or government control over certain markets,
- interest rates distorted by inflation etc.

may lead to the failure of the law of supply and demand to operate freely. The valuation of resources requires a forward-looking pricing approach for calculating future marginal costs, reconciling the tariff and cost structure (Tab. 3.12).

3.11 PLANNING MODELS BASED ON PHYSICAL PARAMETERS

Physical parameters can already be adopted as a criterion in the planning stage. A simple planning model in which surface water and groundwater interactions are explicitly included in the project screening and sequencing process consists of a set of run-of-river diversions, reservoirs, well fields, water treatment plants and water conveyance projects (Fig. 3.16). The area may be divided into N planning districts. Water balances are to be analyzed in T years.

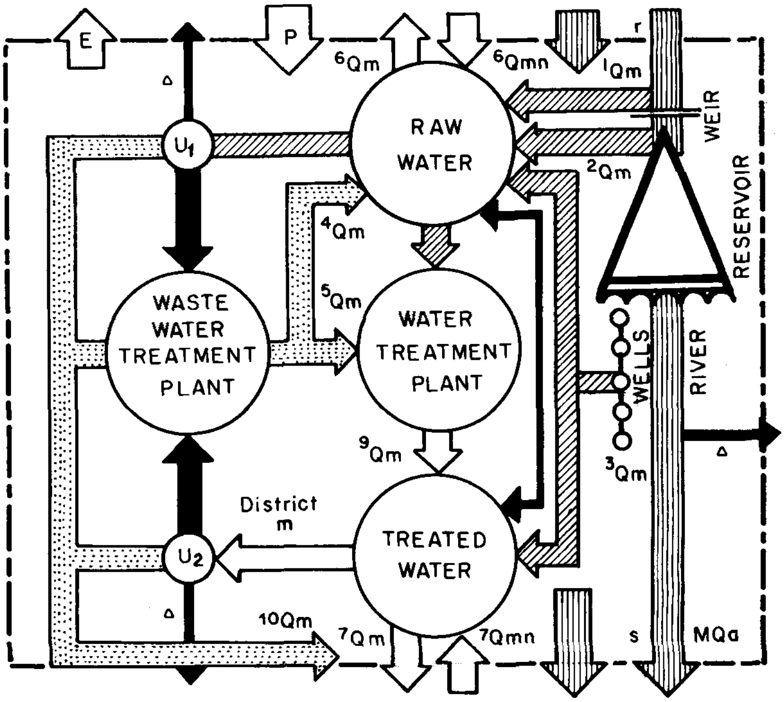


Fig. 3.16. Schematic representation of the m-th region in the planning model according to Maddock and Moody (1973); completed:
^{1}Q - withdrawal of uncontrolled discharges, ^{2}Q - withdrawal of controlled discharges, ^{3}Q - groundwater withdrawal, ^{4}Q, ^{5}Q - water re-use, ^{6}Q, ^{7}Q - conveyed water, ^{8}Q - groundwater inflow, ^{9}Q - treated water, ^{10}Q - waste water, water losses, U - water users, E - evaporation, P - precipitation.

The planning process can be modelled by a mixed-integer programme whose objective functions minimize

- the volume and distance of water conveyed,
- the volume and lift of water pumped (or maximize the head and volume used for power generation).

The first objective function may be written

$$\sum_{t=1}^{T} \sum_{m=1}^{N} \sum_{a=1}^{A_c} \left[\sum_{c=1}^{C} Q_{ctma} \cdot d_{mac} + \sum_{n=1}^{N} Q_{ctman} \cdot d_{cman} \right] \rightarrow \min \qquad (3.55)$$

c - category of the resource

a, A_c - index and total number of projects in the category

t,T - index and total number of planning periods

m,n, N - indices and total number of planning districts

Q_{ctma} - volume of water supplied by project c during the period t in district from resource a

d_{mac} - distance of water conveyance by project c from the resource a in district m

Q_{ctman} - volume of water conveyed from (+) the resource a district n to district m by project c during the period t

The second objective function differs only in the variables T representing head

$$\sum_{t=1}^{T} \sum_{m=1}^{N} \sum_{a=1}^{A_c} \left[\sum_{c=1}^{C} Q_{ctma} \cdot H_{mac} + \sum_{n=1}^{N} Q_{ctman} \cdot H_{cman} \right] \rightarrow \min \qquad (3.56)$$

Adopting the minimum cost as a criterion, the objective function minimizes the present value of the capital costs and operating costs over the planning period. According to Moody and Maddock (1972) the objective function may be adopted

$$\sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{a=1}^{A_c} \left[\sum_{c=1}^{5} Q_{ctma} \cdot 0_{ctma} + \sum_{c=1}^{5} I_{ctma} \cdot K_{ctma} + \sum_{n=1}^{N} Q_{ctman} \cdot 0_{ctman} + \sum_{m=1}^{N} I_{ctman} \cdot K_{ctman} \right] \rightarrow \min \qquad (3.57)$$

0_{ctma} - operating, maintenance and replacement costs per unit of water supplied by project number a of the resource c in planning district m per planning period t

0_{ctman} - ditto from planning district n

I_{cma} - the present value of construction costs of project number a of the resource c in planning district m

I_{cman} - ditto in planning district n

K_{cma} - integer column variable - if K = 1, the construction of project number a of the resource c in planning district m is completed at the beginning of the planning period t. Otherwise, K = 0.

This objective function is subject to the following constraints:

(a) Total water demand constraints: Total volume of water supplied and the imports minus the exports must be greater or equal to the total water demands in planning region m during the planning period t.

$$\sum_{a=1}^{A_c} \left[\sum_{c=1}^{5} Q_{ctma} + \sum_{c=6}^{7} \sum_{n=m}^{N} (Q_{ctman} - Q_{ctman}) \right] \geqq D_{tm} + MQ_{at}$$

D_{tm} - water needs in planning district m during the period t

MQ_{at} - volume of the minimum runoff of the resource c during the period t

(b) Project initiation constraint: No water may be supplied from project a of the resource c in planning region m until the project has been completed. Once constructed, it cannot provide more water than its yield.

(c) Processing constraints: The volume of treated water produced by well fields and water treatment plants and the volume of treated water imports must be greater or equal to the treated water demands.

(d) Flow requirement constraint: The sum of unregulated upland stream flows in planning district m which discharge to a stream segment rs, minus the withdrawals by diversions and reservoirs upstream of this segment and the volume of water lost from the stream to the underlying aquifer due to groundwater pumping, must be greater or equal to the required flows downstream of the segment rs.

The values in the flow requirement constraint imply certain seasonal patterns of surface water flows and downstream flow requirements, i.e. a set of operating rules which may be used to alter the timing of surface water withdrawals due to groundwater pumping.