E EFFECTIVENESS OF WATER RESERVOIRS AND THEIR FUNCTION IN SYSTEMS AND IN THE ENVIRONMENT

15 RESERVOIR FUNCTION IN WATER-MANAGEMENT SYSTEMS

Reservoirs are the basic elements of water-management systems. Their function is determined in cooperation with and in relation to other elements of the system (by diverting the flow from one catchment area to another, by river training, etc.). In a system, all basic functions of a reservoir can be made use of: storage, water conservation, flood control, water treatment, aquatic environment. Reservoir systems can be either single- or multi-purpose systems.

15.1 CHARACTERISTICS OF WATER-MANAGEMENT SYSTEMS WITH RESERVOIRS

A water-management system can be described as a set of water-management elements linked by mutual relations into one wholeness with the aim of utilizing and protecting the water resources. Water-management systems (the terms water-management systems and water resources systems are synonymously used in this chapter), of which storage and flood-control reservoirs form an important part, greatly change the natural flow regime of streams as well as the properties of the water. The extent of these changes is determined by the relative size and function of a reservoir, but also by the hydrological regime of the inflows, by the release conditions, by the geomorphological conditions of a reservoir, the quality of the inflow water, etc.

Water-management systems with reservoirs can be relatively simple if they have, e.g., one reservoir and several users, or compound if they have several reservoirs and many users, or if they have several purposes. Figure 15.1 shows some schematic representations of water-management systems with conservation reservoirs, flood-control reservoirs and reservoirs creating an aquatic environment.

Figure 15.1a illustrates a simple system with one conservation reservoir, two releases and a regulated flow downstream of the reservoir. The principles of the analysis of such a system optimize use of the water resource (reservoir) for three functions, $O_1 - O_3$.

Figure 15.1b illustrates a simple system with two conservation reservoirs and one water user. The analysis is based on the optimization of cooperation of two reservoirs to create the water supply for the single user.

Figure 15.1c illustrates a compound water management system with several (in this case two) conservation reservoirs and several users. The optimization as well as the behaviour (operation) of the system is complicated, as both sides of the water balance in the system are to be optimized mutually, i.e., utilization of the water resources and meeting the demand for water. The system becomes even more complicated if the water yield P_1 and P_2 does not cover the demands $O_1 - O_3$, and diverted water P_3 from the neighbouring catchment has to be included in the system (the dashed line in the figure).

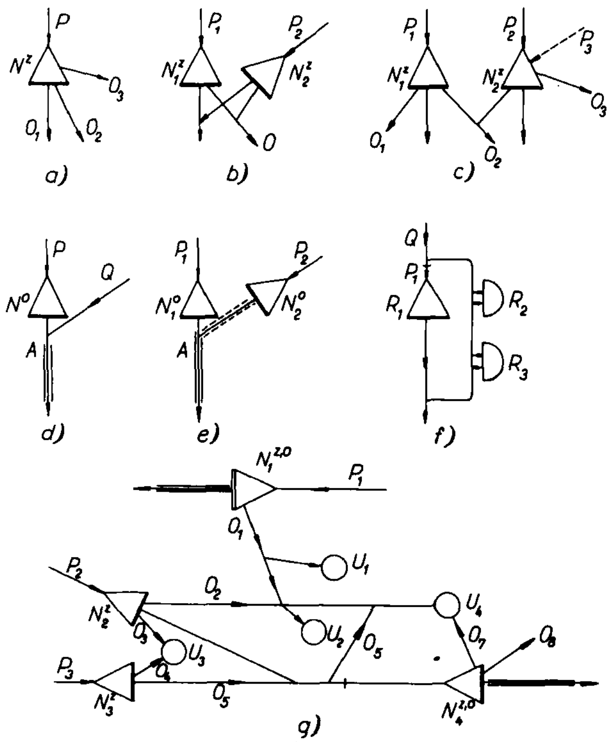

Fig. 15.1 Schematic representation of water-management systems with reservoirs

Figure 15.1d illustrates a simple water-management system with one flood-control reservoir, where the valley downstream of the confluence A with another non-regulated discharge Q is to be protected. In this case, the analysis is based on the optimization of the protection function of the reservoir with regard to the discharge Q. This is a certain type of river-flow regulation with regard to flood control.

Figure 15.1e illustrates a water-management system with several (in this case two) flood-control reservoirs, which are to protect the valley downstream of profile A, as well as the valley downstream of one of the reservoirs, from floods. The optimization of the control function of the system includes the calculation of the variants of co-ordinated operations of all reservoirs in any realistically possible flood situation in the system.

Figure 15.1f illustrates a system of several ponds through which water flows or does not flow and which has one common conduit. The aim of this system is mainly to establish an aquatic environment suitable for fish farming. As both the areas of the ponds and the discharge Q are rather small, the changes in the hydrological regime are insignificant. However, in the opposite case low discharges are significantly affected by evaporation from the water level and flood discharges by the storage capacity of the uncontrollable areas of the ponds.

Figure 15.1g illustrates a compound multi-purpose water-management system with several reservoirs on different rivers, with both conservation and flood-control functions. Besides optimizing the supply and flood control function of the reservoirs, the hydraulic link between the respective water users is also optimized so that they can obtain their water supply from various water resources (reservoirs). This co-operation is the more effective the more the hydrological regimes of the respective dam sites differ and the greater the difference between the relative reservoir volumes.

Further information about water-management systems can be found in books on this subject (Buras, 1972; Votruba, Nachâzel and Patera, 1974; Vitha and Doležal, 1975; Kos and Zeman, 1976; IIASA publications; Votruba *et al.*, 1979, 1988, with extensive bibliography, including explanations of general system terms). Here, the water-management systems are discussed only with regard to the reservoir function in these systems.

15.2 DEFINITION AND ANALYSIS OF WATER-MANAGEMENT SYSTEMS WITH RESERVOIRS

A systematic analysis of any system must include the optimization of its structure and behaviour. To facilitate the calculations, *simplified systems* are defined. For a correct simplification no element or link which is important for the correct result related to the investigated aim may be overlooked, but on the other hand every element or link which is not significant for the given aim should be eliminated. The defining of a system is one of the most responsible tasks of any water-management engineer.

Mathematical modelling and computer technology are indispensable aids in solving optimization problems. The construction of a model is a creative work requiring the ability to simplify and abstract. For compound systems a suitable method to use is *decomposition into sub-systems*, which are

- *spatial*, to decrease the scope of the system,
- *purpose*, to reduce the multipurpose character of the system,
- *time*, to decrease the dynamics of the system.

However, decomposition is only a methodological aid which should not completely change the concept of the system which is established by coordination. Therefore, the interpretation of the model's results to objective reality is just as significantly creative work as the construction of the model itself. The "interpreter" must therefore constantly compare the results gained from the model with practical experience, to verify the analogy of the behaviour of the model with reality, which is not general, but specifically typical for every given case.

A skilled "interpreter" avoids incorrect conclusions, while an unskilled one can even depreciate the results of a correct abstraction.

The interpreted result is implemented by a certain decision. Decisions concerning the use of water affect all people; these decisions have political consequences, because they influence people's behaviour and opinions. Proper consideration must be given as to whether the recommended solution can be implemented. The responsibility is very great as these measures usually have both economic and intangible impacts with long-term consequences.

Some examples of systems and an outline of how to analyse them are set out below.

15.2.1 Power and irrigation water-management systems

Water-management systems often combine power production and irrigation, although this usually requires a change in the regulation of the flow to serve one purpose or the other. For this reservoirs are needed. Figure 15.2 shows a section of a very complicated system, which will suffice to explain the principles of the method (the whole schematic representation of the system can be found in the AIRH Manual,

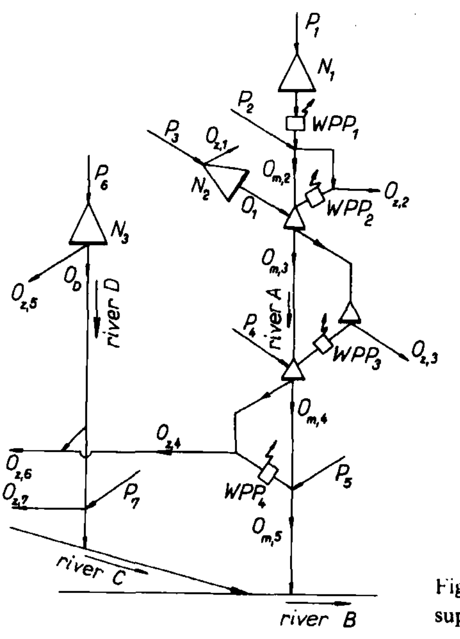

Fig. 15.2 Schematic representation of power supply and irrigation systems

1973, D1). The system consists of a cascade of hydro-power plants on the upper and middle reaches of river A and of numerous irrigation canals which divert water from the conduits of the hydro-power plant. Besides the main river A, the system includes other rivers (B, C and D), which, after meeting the demands of their "own" systems, supply the surplus of their discharges to the main system. The main system has three reservoirs, N_1, N_2 and N_3, of which reservoir N_1 is the first one on the stream, with a large volume and an enormous ability to regulate the flow.

The main task of an optimal operation schedule for a given water-management system is to make maximum use of the local discharge to cover part of the irrigation withdrawals from reservoir N_1. It is therefore necessary to determine how to cover the demands for irrigation water from the water resources of the system, from the discharges of the local rivers from the upper to the lower reaches, from the discharge of the main river in the same order, from the reservoirs, and finally from reservoir N_1. If the mathematical model is constructed according to the sequence of the releases for river flow regulation, release from N_1 can be minimized.

A compensation balance is used for the calculations in each control point, taking into consideration the excess flow Q (not used in the upper reaches), lateral tributaries P, minimum maintained flow Q_m in the main river and the water needed for irrigation O_z:

$$Q_{i-1} + P_i + O_{m,i-1} - O_{m,i} - O_{z,i} = Q_i \geqq 0 \tag{15.1}$$

The absolute value Q_i, if negative, equals the demand on withdrawals. The balance calculations must take into consideration the limits of storage volumes (V_{min}, V_{max}), the accumulation of the water inflow during the given period A_t, the amount of water in the reservoir at the end of the previous period V_{t-1}, the outflow volume O_t and evaporation and seepage losses E_t:

$$V_{min} \leqq V_{t-1} + A_t - O_t - E_t = V_t \leqq V_{max} \tag{15.2}$$

From these balance equations flow charts were elaborated for all the river control points and reservoirs, bearing in mind their mutual relationship. The flow charts consist of the following groups:

1. Input data
2. River flow regulation for the demand on water along the upper part of the system from river A
3. Design of reservoirs on river A
4. Design of reservoirs on river D
5. River flow regulation for the demand on water along the middle reaches of the system from river A and in the subsystem along river D
6. River flow regulation for the demand on water in the lower reaches of the system of river A (downstream of the cascade of WPP)

7. Calculation of outflow from river C and river A in their downstream reaches
8. Determination of total releases from N_1.

From the flow charts, which included the algorithms of solution, a computer program was prepared.

The model makes it possible to determine the reservoirs' operation schedules and release from N_1 with the aid of computer, discharge hydrograph (for a series of years) and a water-demand time pattern. The regular annual values of the water-management indices are determined from statistical assessments. The results of the calculations can be used to plan the future operations of the system, making more effective use of the flow of local rivers and the water in reservoir N_1. This solution is also used to construct a mathematical model for the operation schedules of the whole multi-purpose system.

The above mathematical model includes, despite its individual character, given by the aim and aspects of the problem to be solved, also general elements and procedures that can be used for the construction of other, similar models. It proves that mathematical modelling of water-management systems is a suitable method for solving the problems of multi-purpose water-management systems.

15.2.2 Irrigation water-management system

It is proposed to include in the power and irrigation system in the future (Fig. 15.2) new irrigation sub-systems to which water is pumped from rivers B and C. The function of this irrigation is illustrated in Fig. 15.3.

The calculation scheme of the system (model) includes, besides rivers B and C, three direct-supply reservoirs (N_1, N_2, N_3) with volumes V_1, V_2, V_3 (determined by the optimization method), three canals K_1, K_2, K_3 and six pumping stations, PI_1

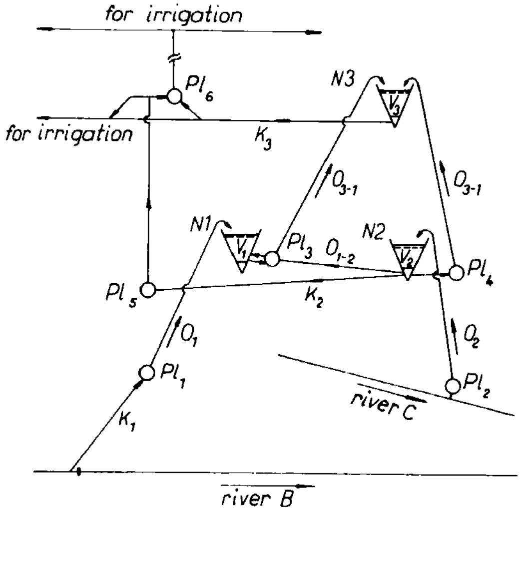

Fig. 15.3 Schematic representation of irrigation system

to PI_6. According to the scheme, reservoirs N_1 and N_2 are filled by pumps PI_1 and PI_2, reservoir N_3 by PI_3 and PI_4. Withdrawals from the reservoirs are used for the upper reaches using PI_5 and PI_6.

The aim of this economico-mathematical model of the system is to determine optimal relationships between the annual releases O_1 and O_2, supplied to the upper reaches from rivers B and C, and to determine the optimal reservoir volumes for flow regulation, with the possibility of flows from one reservoir to another (O_{1-2}, O_{3-1}, O_{3-2}) for some given total value O_0 of pumped water volume.

The following balance relationships were used as a basis for a mathematical model:

(a) relationships reflecting the flow regime conditions:

$$\begin{aligned} O_1 &= O_2 \geqq O_0 \\ V_1 &= \alpha_0 O_1 + O_{1-2} - O_{3-1} \\ V_2 &= \alpha_0 O_2 - O_{1-2} - O_{3-2} \\ V_3 &= O_{3-1} + O_{3-2} \end{aligned} \tag{15.3}$$

where $\alpha_0$is the accumulation pumping coefficient, $(1 - \alpha_0)$—the part of the flow used in transit.

(b) relationships reflecting the reservoir volume values

$$\begin{aligned} V_{1\,\mathrm{min}} &\leqq V_1 \leqq V_{1\,\mathrm{max}} \\ V_{2\,\mathrm{min}} &\leqq V_2 \leqq V_{2\,\mathrm{max}} \\ V_{3\,\mathrm{min}} &\leqq V_3 \leqq V_{3\,\mathrm{max}} \end{aligned} \tag{15.4}$$

An economic objective is the minimization of the total costs (capital investments I_i and annual costs C_i) of all n reservoirs during the standard life span T, therefore

$$\sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (I_i + TC_i) = \min \tag{15.5}$$

The balancing conditions (15.3) and (15.4) led to a system of linear equations

$$\begin{aligned} x_1 + x_2 - \xi_1 &= O_0 \\ \alpha_0 x_1 + x_3 - x_4 - \xi_2 &= V_{1\,\mathrm{min}} \\ x_4 + x_5 - \xi_6 &= V_{3\,\mathrm{min}} \\ x_4 + x_5 - \xi_7 &= V_{3\,\mathrm{max}} \\ \alpha_0 x_1 + x_3 - x_4 + \xi_3 &= V_{1\,\mathrm{max}} \\ \alpha_0 x_2 - x_3 - x_5 - \xi_4 &= V_{2\,\mathrm{min}} \\ \alpha_0 x_2 - x_3 - x_5 + \xi_5 &= V_{2\,\mathrm{max}} \end{aligned} \tag{15.6}$$

where x_j $(j = 1 \div 5)$ are basic variables; by comparison with equation (15.3) it follows that they correspond to the parameters $O_1 \to x_1$, $O_2 \to x_2$, $O_{1-2} \to x_3$, $O_{3-1} \to x_4$, $O_{3-2} \to x_5$, that are to be determined.

ξ_k $(k = 1 \div 7)$ are complementary variables (supplementing further: $\xi_k = x_j$ $(j = 6 \div 12)$).

The economic condition (15.5) takes a linear form (objective function)

$$F_{\mathrm{opt}} = F_0 + f_{\mathrm{opt}} = F_0 + \sum_{j=1}^{5} \lambda_j x_j = \min \tag{15.7}$$

The calculation matrix of the problem model (matrix coefficients in Fig. 15.4) gives a clear picture of the system of equations (15.6) and the objective function (15.7).

This economico-mathematical problem can be solved by the simplex method of linear programming. The only difficult part is choosing the correct calculation procedure, to introduce the correct flow regime conditions and the corresponding economic characteristics and to consider non-linearity for the future.

$i \backslash j$	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	b_i
1	+1	+1	0	0	0	-1	0	0	0	0	0	0	O_0
2	α_0	0	+1	-1	0	0	-1	0	0	0	0	0	$V_{1,min}$
3	α_0	0	+1	-1	0	0	0	+1	0	0	0	0	$V_{1,max}$
4	0	α_0	-1	0	-1	0	0	0	-1	0	0	0	$V_{2,min}$
5	0	α_0	-1	0	-1	0	0	0	0	+1	0	0	$V_{2,max}$
6	0	0	0	+1	+1	0	0	0	0	0	-1	0	$V_{3,min}$
7	0	0	0	+1	+1	0	0	0	0	0	0	+1	$V_{3,max}$
f_{opt}	λ_1	λ_2	λ_3	λ_4	λ_5	0	0	0	0	0	0	0	minimum

Fig. 15.4 Calculation matrix of an irrigation system model

Flow regime conditions include: the regime of the resources (rivers B and C); dates and durations of withdrawals, storage and flows between the reservoirs; the relationship of the flows through the canals and pumping stations and the outflow volumes (i.e., the basic parameters of the model of the system); any limiting conditions of water management, etc.

The technical conditions that were considered are

- simplification of the scheme for modelling purposes,
- technical characteristics of reservoirs, canals and pumping stations,
- schemes of their mutual links, etc.

The economic characteristics were determined from the technical and water-management characteristics. Cost indices were used for canals, pumping stations and their pipelines. The economic characteristics of direct-supply reservoirs were derived from the hypothetical design of each one separately.

The calculated economic characteristics give the ratio of the total costs for a reservoir during T years vs. the elementary parameters of the model of the system. Generally these characteristics are not linear. However, from them the coefficients λ_j

were determined as linear from the alternatives, with regard to the intervals and the coordination between the parameters of the reservoirs and the system parameters that are to be optimized. Then the problem was solved by computer, using the simplex method of linear programming.

Irrigation systems are of great importance for the future development of water management and of agricultural production. Holý *et al.* (1976) published a survey of 46 important irrigation systems in Czechoslovakia, put into operation between 1961 and 1975. Their total area takes up 143 000 hectares, and the respective systems from 400 to 9131 hectares (Horný Žitný ostrov II). The question of optimization of complex irrigation systems was tackled by Korsuň (1972).

15.2.3 Water-management system for the supply of drinking water

An example is given below as to how the public water supply is being solved in Czechoslovakia:

The present resource is no longer sufficient (or will cease to be so in the near future), a new resource must be found and the possibilities investigated for extending the existing water mains to further users. This changes the former, essentially isolated, supply of water into a water-management system, usually a multi-purpose system, however, with a main aim being the supply of drinking water. The problem is to design a multi-purpose system, with the main purpose of water supply, and making the optimum use of the existing facilities. The problem has to be solved in several stages, by given dates.

The example was taken from the public water supply for a region in Bohemia—Liberec, Jablonec and Frýdlant (Kubíček, Technical University, 1972).

Description of the system (Fig. 15.5):

(a) local resources with a total yield of 170 l s^{-1}; to increase to 300 l s^{-1} in 1985,

(b) Souš, impounding reservoir on the river Černá Desná, the purpose and operation rules of which will change; the new resource is the Josefův Důl reservoir on the Kamenice.

In the future, Frýdlant region will not have a sufficient supply of water.

Regional water mains will be constructed in Jablonec–Liberec with a system of reservoirs and pumping stations.

With the main consumers and the respective water mains, we obtain the general description of the physical structure of the designed system. Some of its parameters are:

The Souš reservoir on the Černá Desná has a total storage capacity of $4.888 \cdot 10^6$ m^3 and a mean flow of 0.460 $m^3 s^{-1}$. To improve this condition it was suggested that water from the Bílá Desná be diverted through the old canal, which was originally built to divert flood waves. With the flow from the Bílá Desná the yield reached is $O_p = 0.290$ $m^3 s^{-1}$, while releasing $Q_{min} = 0.050$ $m^3 s^{-1}$ from the reservoir.

The Josefův Důl reservoir on the Kamenice has a storage capacity of $24.63 \cdot 10^6$ m^3 and a mean flow of 0.720 $m^3 s^{-1}$. After diverting water from the Jelení brook, the reservoir will have an O_p of 0.700 $m^3 s^{-1}$ including the released $Q_{min} = 0.125$ $m^3 s^{-1}$. Without the water diverted from the Jelení brook, the augmentation would be 10% less.

When comparing the effect of the two reservoirs in isolation with the demand for drinking water in the region (Table 15.1), the shortage of water in the year 2015 is calculated at 8.2 l s^{-1} and at 120 l s^{-1} in the year 2030.

When using the two reservoirs independently, the demand for drinking water in this region will be covered until roughly the year 2015, presuming that the conditions for the use of the water resources do not change.

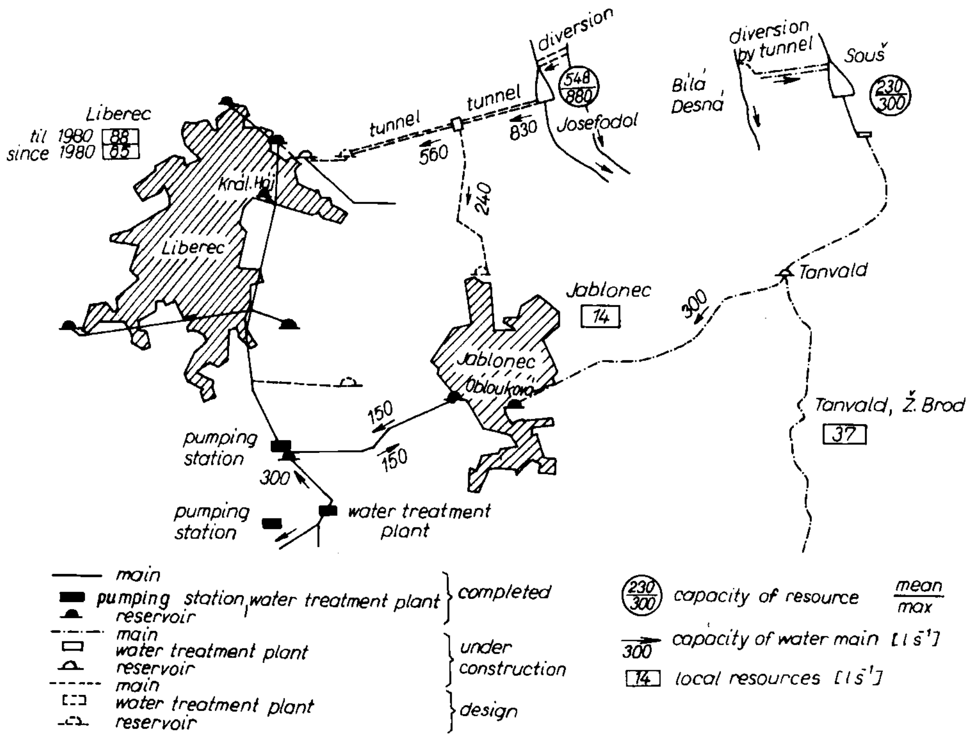

Fig. 15.5 Schematic representation of water-management system for public water supply to Liberec and Jablonec in the year 2015

Table 15.1 Comparison of the effect of the Josefův Důl and Souš reservoirs

Time level – year		1985	2000	2015	2030
Total demand on drinking water in the area Liberec – Jablonec – Frýdlant ($l\,s^{-1}$)		931.6	1196.0	1288.7	1400.5
Total yield of present resources (local) ($l\,s^{-1}$)		475.5	475.5	475.5	475.5
Effect of the considered reservoirs	Souš			230.0	230.0
when used separately ($l\,s^{-1}$)	Josefův Důl			575.0	575.0
Deficit of drinking water ($l\,s^{-1}$)				8.2	120.0

Effects of system solution

This multi-purpose system was identified by highlighting its main purpose, i.e., the public supply of water; the system will not only be extended, but new relationships will be established between all the elements.

The two reservoirs become more efficient when they cooperate with other facilities, such as those for the diversion and treatment of water, than when the respective resources function independently.

As the two reservoirs are relatively near each other, it was presumed that the hydrological regimes would be synchronous, which is unfavourable for their mutual cooperation. On the other hand, a favourable fact is the different flow regulation rate in the two reservoirs. The first one at Souš has, together with the diverted water from the river Bílá Desná, a relative yield $\alpha = 0.48$ and the reservoir at Josefův Důl has an $\alpha = 0.87$, including the water diverted from the Jelení brook. It is therefore a combination of a seasonal and an over-year reservoir.

Another condition for efficient cooperation of reservoirs is the capacity of the water-diverting facilities, the capacity of the water-treatment plants and the pipelines; this condition is frequently a constraint.

Cooperation was ensured by a rule curve, which eliminates the disadvantages of other methods. A rule curve was therefore prepared for the seasonal reservoir at Souš, whereby the volume of water in the reservoir must correspond to the planned safe yield. If at any time the storage volume of the reservoir at Souš is greater than that given by the rule curve, more water will be released, which is the principle of cooperation with the over-year reservoir at Josefův Důl.

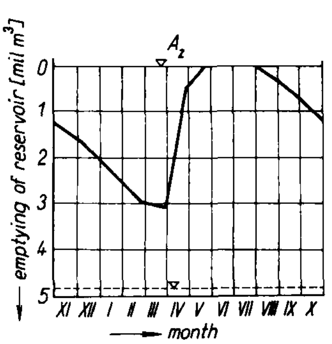

Fig. 15.6 Rule curve of a seasonal reservoir Souš

Calculations according to the rule curve of the reservoir at Souš (Fig. 15.6) were based on the chronological series for 1931 to 1960. Even though the cooperation was solved according to synchronous series, the effect was not negligible.

With the total withdrawal of the system of reservoirs at Josefův Důl and Souš of 935 $\mathrm{l\,s^{-1}}$, the result of the cooperation came to 120 $\mathrm{l\,s^{-1}}$. If the water volume in the reservoir at Souš reaches above the rule curve, 460 $\mathrm{l\,s^{-1}}$ is released; if it is below that curve the minimum release is 240 $\mathrm{l\,s^{-1}}$. In the same periods

$475\ l\,s^{-1}$ and $695\ l\,s^{-1}$ are released from the reservoir at Josefův Důl. The improved performance of the Souš treatment plant of $460\ l\,s^{-1}$ is made full use of in 76.5% of the given period. The maximum emptying of the Josefův Důl reservoir comes to $16.113 \cdot 10^6\ m^3$, which is less than when it was not functioning in cooperation. The emptying and release of the two reservoirs, functioning separately and in cooperation, in 1936 and 1937, is shown in Fig. 15.7.

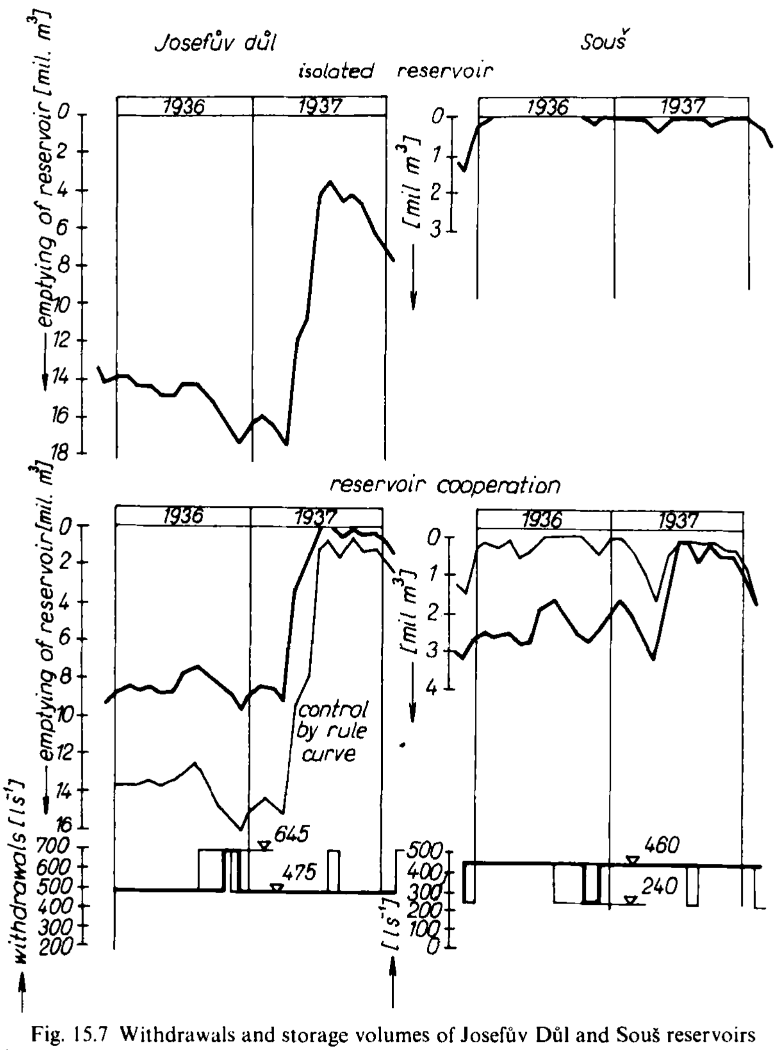

Fig. 15.7 Withdrawals and storage volumes of Josefův Důl and Souš reservoirs

15.2.4 Optimal cooperation of a system of reservoirs for public water supply

The given problem is to make optimum use of water resources with the already-existing reservoirs and one designed reservoir. Even though the formulation of the problem is similar to that in paragraph 15.2.3, a method is used here that consistently respects the stochastic elements of the system. The system approach was adequate to the task as the problem concerned the cooperation of seven reservoirs in northern Bohemia of great economic and political importance (Fig. 10.3). The problem was solved at the Technical University in Prague (1969). The results help in decision-making about constructions and operation of the water resources in northern Bohemia.

The problem was divided as follows:

(a) water-management authorities formulated the problem,

(b) the designer constructed the model, including the analysis, solution and implementation,

(c) the water-management authorities, which need not be identical with the ones mentioned in (a), decide on the method to be used for the application of the results.

As the problem could not be solved by previous methods of discharge regulation, the Monte Carlo method was used to simulate the operations of all the reservoirs. Natural flow series of 1931 to 1960 served as basic data. Synthetic monthly series were modelled for 500 years by computer, using the orthogonal transformation (principal components) method.

In view of the capacity of the computer, the synthetic series were modelled in fours selected according to the resources that fed the respective water mains; the groups Přísečnice, Křímov, Kamenička, Jirkov and the groups Fláje, Jirkov, Kamenička. The reliability of the modelled series was tested by statistical and water-management tests, which were in good agreement with the real series.

The simulation model of the optimal cooperation of reservoirs was controlled step by step from the simplest couple of reservoirs to the final four reservoirs and to the whole system. The aim of the simulation model was to ensure effective operation with reservoirs: if one reservoir has a surplus supply of water or if there is an overflow, release from this reservoir can be increased, while, on the other hand, the release decreased from the cooperating reservoir and better use can be made of the water supply in the next low-flow period.

This method can be applied to a whole system of reservoirs; however, this requires basic changes in the operation of the respective reservoirs. If, for example, in specific conditions reservoirs are exploited for a uniform yield, then cooperation requires a transition to nonuniform control of release, which further—in the case of a demand to uniform release in the area of water consumption—requires river flow regulation of all reservoirs. Release from the respective reservoirs corresponds to the hydrological situation; however, as all reservoirs cooperate, the final release is a uniform one. The claim for a final uniform release in the area of the demand for water is not a limiting condition, however; generally, the cooperation between reservoirs can be based on any arbitrary release curve; the objective function that must be adhered to is the best possible exploitation of the whole system.

While adhering to the required reliability ($P_0 = 99\%$), rule curves were prepared from synthetic series for all the seasonal reservoirs involved in the cooperation. No rule curves were prepared for over-year reservoirs and their regimes in the cooperation with other reservoirs were controlled only as far as their reliability were concerned.

An example of the cooperation of the two reservoirs at Přísečnice and Křímov is shown in Fig. 15.8. Cooperation can ensure an increased release of up to $64\ \mathrm{l\,s^{-1}}$. In the whole region it is possible to gain an extra $330\ \mathrm{l\,s^{-1}}$, which is 16% of the sum of the isolated releases, $2.006\ \mathrm{m^3\,s^{-1}}$. Analyses of the mutual relationships in the storage volumes in synthetic series showed that any compensation of deficits of water would be hydrologically risky. Cooperation in breakdown situations should be considered as a kind of reserve in the distribution plan, depending on the actual situation.

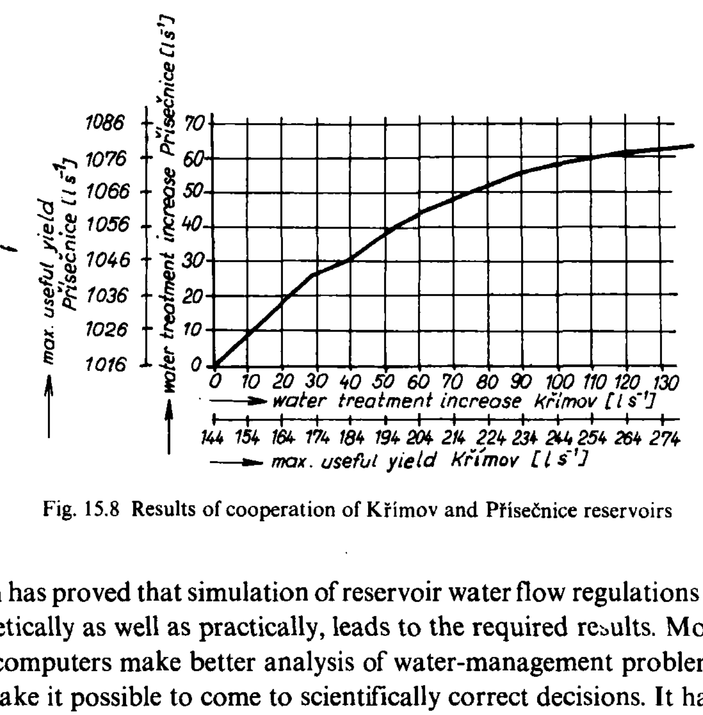

Fig. 15.8 Results of cooperation of Křímov and Přísečnice reservoirs

Research has proved that simulation of reservoir water flow regulations is a method that, theoretically as well as practically, leads to the required results. Modelling and the use of computers make better analysis of water-management problems possible, and also make it possible to come to scientifically correct decisions. It has also been proved that methods of operations research can successfully resolve the question of cooperation between reservoirs in various watersheds with given capacities of release facilities. The described method can be applied to any case which has similar technical and hydrological conditions.

15.2.5 Optimization of multi-purpose systems with river flow regulation

The problem concerns a system with three reservoirs N_1, N_2, N_3 and with three water withdrawals S_1, S_2, S_3 for industry, irrigation and drinking water—all with full consumption (Fig. 15.9). The operations of the whole system are to be optimized. The method of simulation modelling was used both for the design and operation of the system. The model was a simplified statistical and deterministic one.

The state of the system was assessed in constant time intervals, given by the state at the beginning of the interval and the changes during the interval. Optimization is ensured by the economic assessment of the alternatives. A criterion, for example, can be the ratio between the benefits and the costs during the presumed life span.

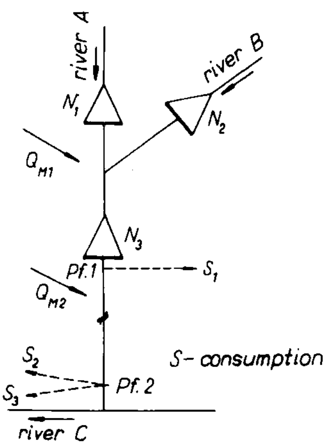

Fig. 15.9 Multi-purpose water-management systems with river flow regulation

Data and resolution

Hydrological data consist of chronological series of mean monthly natural or modelled flows in the reservoir sites and at the point of withdrawals; this also determines the inflows from the inter-catchments $Q_{M,1}$ and $Q_{M,2}$.

Storage capacities are important parameters if the solution is only to be a quantitative one, regardless of the properties of the water. The capacities can be given in fixed or variant values. Water losses can be introduced in the first considerations by a decrease of the storage capacities (e.g., to 90%).

The water demands S_1 and S_3 for industry and households are given by mean values in $m^3 s^{-1}$. The water demand S_2 for irrigation is given by a curve for the vegetation periods; it must be considered for the largest possible area to be irrigated and in the case of a lack of water for alternatives of smaller irrigated areas.

The maintained minimum flow Q_{min} downstream of a reservoir and in the control points is determined by special calculations or, e.g., Q_{355d} can be introduced for preliminary solutions.

As this is a case of river flow regulation, the water demand will be met mainly by the outflow from the inter-catchments and if the need arises it will be supplemented by water from a reservoir. For a point 2 equation:

$$Q_2 - \sum_{i=1}^{3} S - Q_{min} = Q_{d,2} \qquad (15.8)$$

where Q_2 is the flow in point 2,
$\sum S$ – the sum of withdrawals,
Q_{min} – the maintained minimum flow downstream of point 2,
$Q_{d,2}$ – the surplus (+) or lack (−) of flow, stored in a reservoir or released from it.

Various orders of emptying and filling of a reservoir are studied. A comparison of the variants helps determine the optimum operation. If, in this case, the result is an impermissible shortage of water supply, the amount of the irrigation water is decreased to the amount of economically optimal utilization of the water resource.

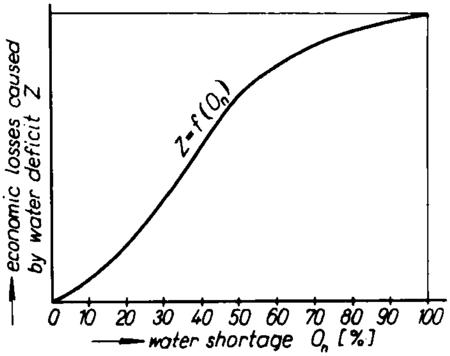

Fig. 15.10 Relationship of economic losses and water deficits

Important for the economic assessment of the supply of water for industry and irrigation is the relationship between the deficits in supply of water O_n and the respective economic losses Z (Fig. 15.10) which, as a rule, is non-linear. Presuming that the release for drinking water will not be reduced and that maintained minimum outflow will continue, the objective function can be written as

$$Z = O_{n.ir}C_{ir} + O_{n.in}C_{in} \overset{!}{=} \min \tag{15.9}$$

where $O_{n.ir}$ ($O_{n.in}$) are the deficits in supply of water for irrigation (industry),
C_{ir} (C_{in}) – economic losses caused by the deficits in supply of water for irrigation (industry).

15.2.6 Water-management systems for flood control

Flood-control measures in a catchment (region) constitute a single-purpose complex system as these have all the signs of complexity: large scope, stochastic phenomena, a complex hydraulic regime, complex relations. The individual measures (flood-control reservoirs, flood-control volumes of multi-purpose reservoirs, flood control effect of active storage, training of rivers, influence of gated weirs, influence of the winter regime, etc.) cause changes which mutually interact. A flood-control system can also be abstracted from a multi-purpose system.

The system of reservoirs in a relatively small catchment in southern Bohemia serves as an example.

Description of the system

The valley of the Stropnice and the Svinenský brook can not be used intensively for farming, as the channel can only hold about 30 to 40% of a one-year flood. The problem is resolved by controlling the flood regime of the two streams with the help of a system of flood control reservoirs.

If the plots in this area are to be used for agricultural purposes, then a five-year flood control must be ensured. This control can be ensured by river training or a combination of river training with small flood-control reservoirs; one of the systems to include small flood-control reservoirs can be found in Fig. 15.11.

For flood control in the *Stropnice catchment*

(a) Humenice reservoir and Zevlův pond

(b) Humenice reservoir, Zevlův pond with water diverted from Humenice to the near-by Žárský pond, with an unused flood control capacity of $1 \cdot 10^6$ km^3, by a 3.5 km-long canal.

For flood control in the *Svinenský catchment*

(a) Kamenná and Žumberk reservoirs

(b) Kamenná reservoir with a 2.75 km long canal to Žárský pond and Žumberk reservoir

(c) the same as in (b) but with further reservoirs on the Keblanský and Dluhošť brooks (tributaries of the Svinenský brook).

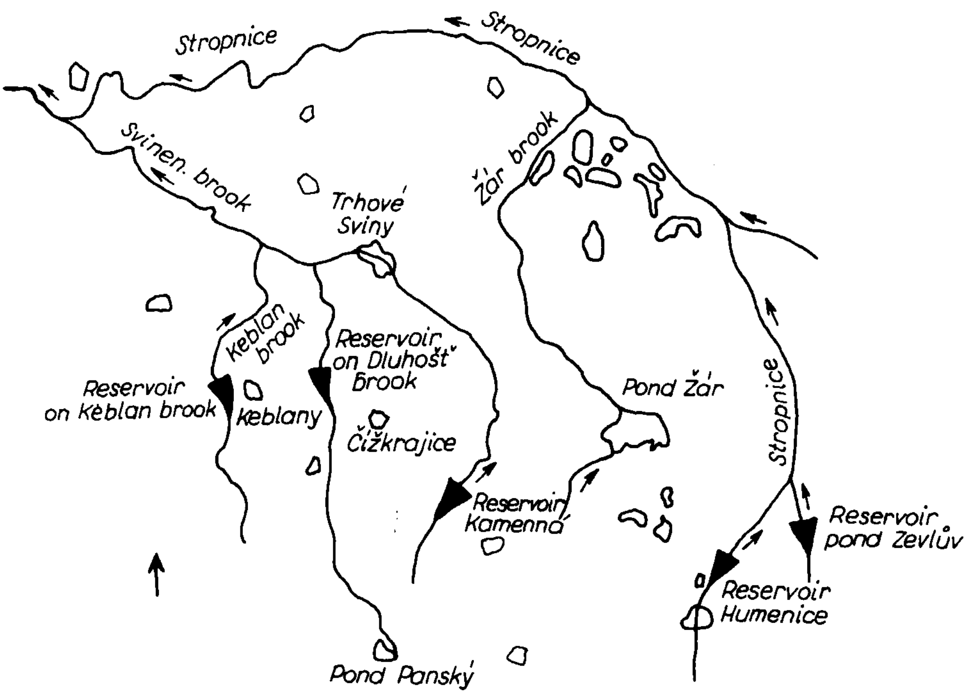

Fig. 15.11 Map of flood control measures in the catchment of the Stropnice and Svinenský Brook

Hydrological data consisted of data on the size of the floods and their form in some of the sites; however, there were no data on the routing of the flood waves in the streams in this region.

The problem was resolved in stages:

stage 1: assessment of the isolated flood control of the respective reservoirs;

stage 2: assessment of the control of the respective reservoirs when functioning in cooperation (system approach).

Flood control of individual reservoirs

The aim was to ensure flood control without any manpower and with the simplest possible devices, so as to decrease the value Q_5 as much as possible whilst making the maximum use of the reservoir's flood-control capacity, and not to impair the conditions downstream of the reservoir even when $Q_n > Q_5$. The reservoirs were designed as dry reservoirs with bottom outlets without gates. They filled as the capacity of the outlets was smaller than the inflow during floods. The profile of the outlets was designed so that with a flow Q_5 a reservoir would fill up to the crest of the spillway. Table 15.2 explains the transformation of three designed reservoirs with individual functions; these reservoirs are empty before the floods.

Table 15.2 Transformation effect of reservoirs considered independently

Reservoir	Q_1 [$m^3 s^{-1}$]	transform. [$m^3 s^{-1}$]	Q_5 [$m^3 s^{-1}$]	transform. [$m^3 s^{-1}$]	Q_{100} [$m^3 s^{-1}$]	transform. [$m^3 s^{-1}$]
Humenice	10.3	0.67	19.0	0.91	79.3	75.4
Pond Zevlův	7.4	0.32	13.5	0.36	56.5	49.2
Kamenná	8.6	1.66	15.8	2.14	66.0	66.0

The influence of the reservoirs on a decrease of the maximum peak discharges of selected n-year flood in a series of sites downstream of the reservoirs was also studied. Under the most favourable conditions, Q_1 decreases on eight profiles on the Stropnice river came to 18.7 – 49.4% of the original value and Q_5 to 16.0 – 49.0% of the original value; on Svinenský brook Q_1 decreased to 31.1 – 65.7% and Q_5 to 24.2 to 64.6%. On the other hand, under the most unfavourable conditions, Q_1 decreased to 40.3 – 88.5% and Q_5 to 45.6 – 86.3% of the original value.

Flood control of reservoirs cooperating in a system

After considering the various alternatives, the optimal flood-control design was selected.

It was decided to construct the Humenice reservoir and the Zevlův pond without using the Žárský pond in the *Stropnice river catchment.* Together the two reservoirs control a catchment of 54.44 km^2 and this is practically sufficient to catch Q_5, which downstream of the Humenice reservoir decreases to 4.8%, and downstream of the Zevlův pond to 2.7% of the original value; 17.92 km of the stream is designed to be trained.

Kamenná reservoir on the *Svinenský brook* should cooperate with reservoirs on Keblanský and Dluhošťský brooks and 13.5 km of the stream should be trained. Žumberk reservoir, with its small storage volume and its special role in the protection of the environment, was not recommended in the final design.

It proved to be inexpedient to include the Žár pond in the system. Canals from the pond to the Humenice and Kamenná reservoirs would be very expensive. The inclusion of the Žár pond in the system would also endanger the very profitable fish farming in this pond.

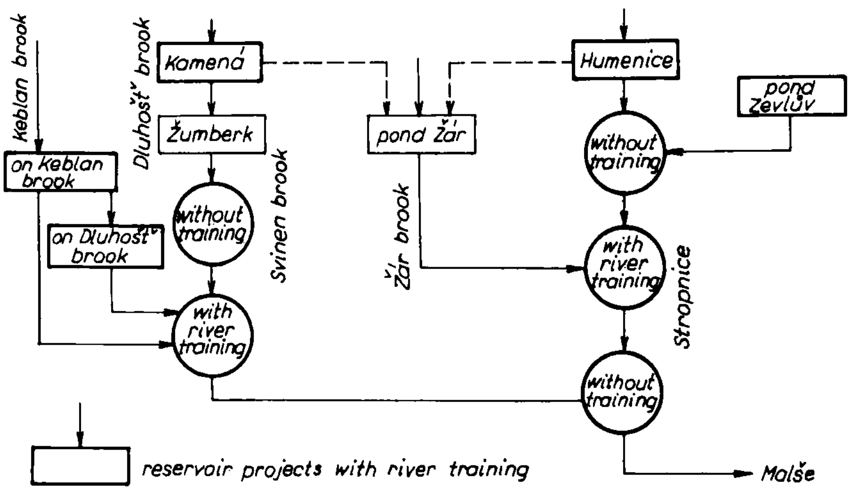

Fig. 15.12 Schematic representation of flood control system in the Stropnice and Svinenský Brook catchment

A schematic representation of the final design is in Fig. 15.12. The most efficient cooperation of the two sub-systems was recommended on the basis of a detailed analysis.

Other examples of the analysis of water-management systems can be found in Votruba *et al.* (1974, 1988).

Besides water-management systems which are concerned with the best utilization of water, there are also systems which are solved mainly in technical (not in economic) parameters. These are, for example:
- short-term flow regulation in a system of backwater of weirs (Gabriel, 1975),
- temperature regimes in a system of reservoirs,
- a complex watermain network (Šerek, 1968, 1972).

15.3 FUNCTION OF SMALL RESERVOIRS

The aim of small reservoirs is to ensure release and flood control on small streams, to create a supply of water for common use, to change the properties of the water or establish an aquatic environment for fish of duck farming and recreation.

Small reservoirs are usually shallow, with a mean depth up to 4 m (fish farming reservoirs are usually up to 1 m), with an inundated area of up to 100 hectares and a capacity of up to $3 \cdot 10^6$ m^3. The dams are usually up to 10 to 15 m in height and the catchment area is no more than 20 km^2 (Pavlica, 1964).

As there are many such small reservoirs, they are also of economic importance. They can be divided into ponds and small reservoirs (Cablík, 1960).

Ponds are mainly for fish farming and are therefore emptied every year when the fish are being fished out. They can greatly affect the discharge, if they are part of a system, in the upper part of the catchment or in regions with small streams.

Small reservoirs serve local needs and can again be classified into:
- industrial reservoirs: to supply industry with water;
- recirculation reservoirs: to balance the discrepancies in the demand for circulated water in industrial plants;
- fire-protection reservoirs, to ensure a sufficient supply of water for fire-fighting;
- irrigation reservoirs;
- drainage reservoirs: to collect water from the drained plots;
- retaining reservoirs: to catch gross sediments and impurities;
- recreational reservoirs.

Ponds and small reservoirs play an important role in the protection of the natural environment. They are also more suitable than streams for recreational purposes.

15.3.1 Conservation function of small reservoirs

Even though the principle of the conservation function of all reservoirs is essentially the same (to store surplus water for periods where there is a lack of water), small reservoirs have some specific characteristics. They can be filled by either *surface, ground* or *waste water.*

A pond fed by *rain or snow water* running down from the nearby ground is called a "*heavenly pond*". The inflow is not continuous and occurs only during the spring snow melt and strong precipitations. The inflow W_s [m³] can be calculated from

$$W_s = \varphi F H_s$$

where φ is the surface runoff coefficient,
F – the "catchment" area in [m²],
H_s – precipitation depth or water value of the snow cover at the start of melting in [m].

Value φ is very variable in the same catchment (from 0 to about 90%) and depends on the soil (permeability, humidity, vegetation) and on the size and duration of the precipitations. Area F is in the order of several km².

Drainage water consisting of a part of rain and snow water has a similar inflow regime. Annual inflow to the "heavenly" pond is very variable, as it depends not only on the annual precipitations, but on its distribution throughout the year and on the intensity and duration of the respective rainfalls. Significant water losses are caused by evaporation and seepage or infiltration.

Data on the annual inflow and total expected water losses are used to determine the volume of the pond. Water-management and economic calculations determine the probability of the filling of the pond in a water year. The lower limit of the volume is that which can be filled on average once every two years ($p = 50\%$). However, the value can be much larger, e.g., with a probability of filling $p = 10\%$ and even less (Cablík, 1960).

Ponds are more frequently filled by *surface water from streams.* Ponds can be either on, or near the streams in which case water is diverted to them by canals. Ponds without through-flow (lateral reservoirs) are more suitable as they have optimal conditions for fish farming and are not affected by floods and sediments.

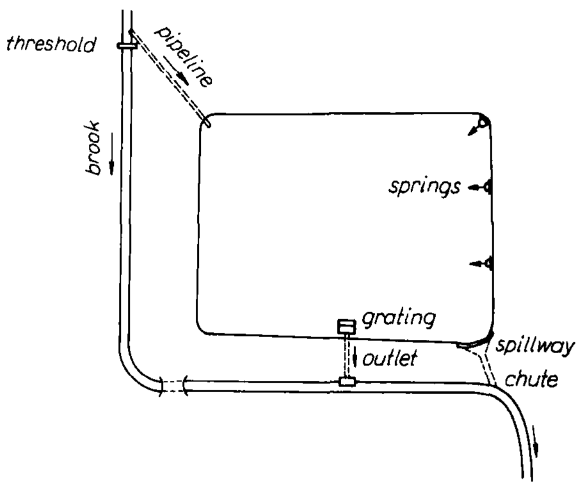

Fig. 15.13 Layout of village pond fed by a pipeline from a brook and from springs

The same hydrological data are used to design these small reservoirs as for the large impounding, or lateral, reservoirs. Finding the correct resolution is more difficult, however, as it concerns the hydrology of small catchments which frequently do not have direct water gauge measurements, therefore indirect methods, most frequently methods of analogy, must be used to determine the law of inflow.

Sometimes the pond is fed by *ground (spring) water*. Such an inflow is relatively constant, but rather small; this is why the spring is usually not the only source, but is supplemented by surface water (Fig. 15.13).

Waste water is rarely used to fill a pond, and then only to help treat it.

Only those small reservoirs which supply water to industry and for irrigation have any significant storage function. The storage capacity of such a reservoir is usually calculated from the given inflow and release laws by the simulation method. Reservoirs which establish an aquatic environment must preserve the optimal characteristics of the water and replenish evaporation and seepage losses.

Such handling of water can be contradictory to the demands of water management. The compensation of water losses in low-flow summer months can further decrease the low flow in the rivers. On the other hand, emptying of the ponds during autumn fishing can increase the autumn flows dangerously, especially if it takes place at the time of high autumn flows in the streams. On the other hand the refilling of the ponds can further decrease the winter flow. Therefore even fish-farming reservoirs should have operation schedules that adhere to the water management requirements.

Fire-control reservoirs are of small importance as far as storage is concerned. They are usually in villages or near buildings that are to be protected against fire danger. They can be filled by surface or ground water or even from the water mains. The only rule is that the water level should not drop below the necessary limit and that the water should be easy to pump. Fish-farming and other small reservoirs can also serve for fire protection purposes.

15.3.2 Flood-control function of small reservoirs

Small reservoirs and ponds usually do not have a special flood control capacity under the crest of the spillway. The floods are controlled simply by transforming the flood wave in the overflow space. The measure of decrease of the maximum peak discharge of a flood wave depends on its volume and shape, on the surface area of the ponds and on the length of the overflow crest.

The spillway is usually ungated and the width of the overflow jet is small so that Záruba's method (Section 11.2) for the transformation of a flood wave can be used. The design flow for the calculation of the spillway is the flood flow with a selected probability of exceedance, Q_N. The transformation function of a reservoir is reflected in the decrease of the maximum peak discharge only in fairly large reservoirs on relatively small streams.

A greater decrease of flood flows can be attained by the cooperation of small reservoirs in a cascade or system. The difference in the function of the cascades of large reservoirs (Chap. 9) and the control function in the cascade of small reservoirs is that in the latter the asynchrony of the phenomena in the reservoirs, i.e., a shift in time in the downstream direction, can be observed more clearly. The reason is the short-term character of the phenomena during the transformation of the flood wave in a small catchment.

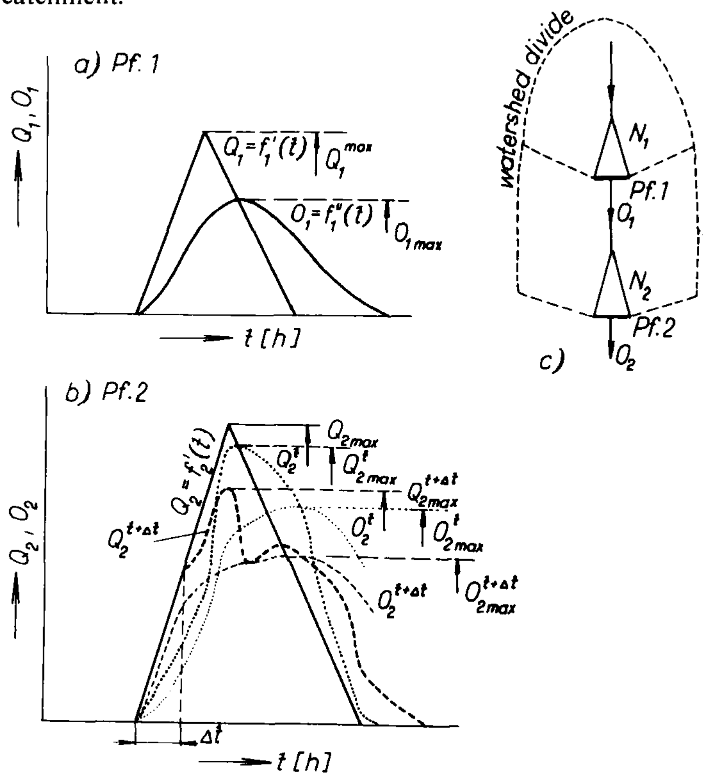

Fig. 15.14 Transformation of flood waves in a cascade (series) of small reservoirs with a synchronous and asynchronous function
(*a*) discharges in pf *1*; (*b*) discharges in pf *2*; (*c*) layout of the reservoirs

Figure 15.14 illustrates the transformation of a flood wave in a cascade of two small reservoirs N_1 and N_2 in points pf *1* and pf *2* on a small stream. Non-transformed floods are denoted by simple triangles ($Q_1 = f_1'(t)$ and $Q_2 = f_2'(t)$); it is assumed that a reservoir is full up to the crest and water only runs over the ungated spillway.

Figure 15.14a illustrates the course in time of a non-transformed flood wave Q_1 (inflow to the reservoir) and a transformed flood wave O_1 (outflow from a reservoir) in point pf *1*.

Figure 15.14b illustrates the course of a non-transformed flood wave Q_2 prior to the construction of reservoirs, two inflow curves Q_2^t and $Q_2^{t+\Delta t}$ into reservoir N_2, with the considered flood-control effect of reservoir N_1 and the respective outflow curves O_2^t and $O_2^{t+\Delta t}$.

Curves Q_2^t and O_2^t are constructed on the premise that the function of the two reservoirs N_1 and N_2 is synchronous, i.e., presuming that the difference $(Q_1 - O_1)$ at moment t manifests itself at the same moment by the same difference $(Q_2 - Q_2^t) = (Q_1 - O_1)$. Thus, a modified inflow Q_2^t to reservoir N_2 is obtained from which the transformation wave in reservoir N_2 can be calculated by the known method; the result is the course of outflow O_2^t from reservoir N_2.

Curves $Q_2^{t+\Delta t}$ and $O_2^{t+\Delta t}$ are constructed, presuming that the functions of the two reservoirs N_1 and N_2 are asynchronous, with a shift in time; i.e., that the difference $(Q_1 - O_1)$ at moment t manifests itself by the same difference $(Q_2 - Q_2^t) = (Q_1 - O_1)$ in reservoir N_2 at the moment $t + \Delta t$, i.e., with a time lag of Δt. Thus, the modified inflow $Q_2^{t+\Delta t}$ to reservoir N_2 is obtained and from this the transformation of the flood wave in N_2 is calculated; the result is the course of the outflow $O_2^{t+\Delta t}$ from reservoir N_2.

From Fig. 15.14b it is possible to see that the difference between the curves Q_2^t and $Q_2^{t+\Delta t}$ and between curves O_2^t and $O_2^{t+\Delta t}$ is significant. This is obvious from the course of the curves and their peak values: $Q_{2\max}^t$ and $Q_{2\max}^{t+\Delta t}$; $O_{2\max}^t$ and $O_{2\max}^{t+\Delta t}$. In our case, the time lag of the reservoir function, and its inclusion in the calculations, was reflected in a decrease of the maximum peak discharges. However, there are innumerable combinations of the final effects of the two reservoirs N_1 and N_2 and the results can differ greatly, depending on

- the volume and shape of the flood waves in the two points and on their mutual times,
- on the inundation area of the two reservoirs and the dimensions of the spillways,
- on the distance (time lag) between the two reservoirs.

The flood-control function of a cascade of such reservoirs therefore cannot quantitatively be assessed sufficiently accurately, and it must be calculated in great detail. If the final results are to be optimized, the optimization method, which is essentially very simple, must be applied to many alternative solutions.

The flood-control function of a system of small reservoirs can have a great impact on the river during the flood wave. The effect of the system of reservoirs must be determined by a systems approach (Section 15.2.6). Calculations with technical parameters are rather simple, but they become more complicated by the transition from a deterministic problem to a stochastic problem. Optimization of the structure and the behaviour of the system can be rather demanding if the system is a large one, as it requires many alternative solutions. Economic optimization is even more difficult as it is not easy to obtain all the necessary economic data for the calculations of costs and flood damages. Uncertainty increases in dynamic systems with different time horizons.

15.3.3 Function of the aquatic environment of small reservoirs

Small reservoirs are mainly used for fish or water fowl farming, recreation and aesthetic improvement of the environment. They are usually not important as far as water management is concerned.

Fish-farming reservoirs are demanding as to the physical and chemical characteristics of the water. *Warm-water pond cultivation* for carp breeding must have water with sufficient plant nutriments, with a summer temperature of 20 to 30 °C and with a neutral or slightly alkaline pH. The most suitable ponds are those rich in organic matter, but without mud.

Cold-water pond cultivation which mainly produce trout, grayling, huck must have water with a low organic-matter content, a high oxygen content and a low temperature (in summer a maximum of 16 to 20 °C).

Recreation reservoirs must have clean water and a constant water level. Inflow must be sufficient, especially in the summer low-flow period. Outlets should allow discharge at the top and the bottom so as to enable the regulation of the released water quality. The banks of the reservoir should be adjusted for sunbathing and games. Sanitary facilities and parking lots ensure the good quality of the water. Recreation reservoirs play an important part in the human environment.

Lateral reservoirs are best suited to ensure the good quality of the water. However, many large *impounding reservoirs* are also used for recreation, and some impounding reservoirs are even built purely for such purposes.

The *use of ponds for recreation* might seem contradictory. Thirty years ago, recreation could be included as one point in the general uses of water, but today it is a strong sociological phenomenon and recreation on the banks of ponds has become a special type of water use. The contradiction between fish farming and recreation lies in the demands on the quality of the water, but even large ponds can be fertilized in such a way as to meet the demands of holiday makers, who want clean water and a pleasant environment (Lavický, 1969).

Reservoirs can also form a part of architectonic layouts, parks, etc.; these are usually shallow, or formed by low dams on brooks.