9 RELEASE CONTROL IN A CASCADE OF RESERVOIRS (SEVERAL RESERVOIRS ON ONE STREAM)

The construction of a cascade of reservoirs, i.e., a *series of impounding reservoirs on one stream with a functional continuity*, was originally connected with hydro-power, production of which was a logical consequence of the efforts to make the best use of the natural power potential of a stream. However, during the water resources development the newly designed as well as the already constructed reservoirs have become a part of a system or cascade, even though they are no longer only used for power generation. A cascade can be an important part of a system of reservoirs.

In designing a reservoir in a cascade, the water-management function of the other reservoirs must be respected; the work of one reservoir is usually designed so as to meet the interests of the cascade as a whole.

Usually each reservoir in a cascade is partly used for water management and power production purposes while at the same time all reservoirs work together to ensure the total function. When a reservoir is to produce hydro-power and to supply water, the interests of the users are competitive: power production needs the greatest possible head for the peak-load power plants of the cascade to have a great output, while for water supply, full use is made of the reservoir storage capacities. This means that reservoirs in a cascade must be designed individually, case by case.

Using a cascade for water supply as an example, and excluding any influence of the downstream reservoirs on the function of the upstream reservoirs, we can formulate some basic principles for release control from reservoirs in a cascade that are generally valid.

As compared with river flow regulation, in this case one has to start with the *reservoir highest upstream*, which influences the work of the downstream reservoir, mainly by essentially changing its law of inflow, even if the original law of streamflow is not changed by withdrawals or losses. The work of the downstream reservoir is usually made easier by the upstream reservoir as, with the same storage capacity due to a better distributed inflow, a higher yield (withdrawal) can be obtained. The upstream reservoir is all the more efficient, the greater the relative yield (α) and the greater its catchment.

9.1 ANALYSIS OF CASCADES OF RESERVOIRS USING SYNTHETIC DISCHARGE SERIES

As with any water management problem, solutions of reservoirs in cascades in which, besides the balance of inflow, release and volume, other quantities have to be studied (e.g., the head), direct solutions in synthetic discharge series are most frequently used as they best enable a detailed study and evaluation of the respective quantity in every time step. Just as for river flow regulation, the series have to be modelled simultaneously at several sites; between the corresponding discharge values a relatively close correlation can be expected (as the discharge series concern the same stream). For practical reasons (Chap. 8) we shall consider synthetic mean monthly discharges.

In release control in a cascade of reservoirs the corresponding balance steps do not take place at the same time, but are shifted by discharge-travel time $\tau_{1,2}, \tau_{2,3}, \dots$ between the respective reservoirs. As we are trying to analyse the storage function of reservoirs in which the shortest cycle is a seasonal cycle and where the natural discharges from all parts of catchments and interbasins flow into one of the reservoirs, the time lag can usually be neglected without affecting the accuracy of the results.

In considering the time lags $\tau_{i,j}$, it would be necessary to prepare the initial hydrological data, i.e., the discharge series, in such a way that the respective time intervals (in our case months) would be shifted at the respective sites by the value $\tau_{1,2}, \tau_{2,3}, \dots$ Then the synchronous processes in reservoirs can be considered in the analysis.

The *upstream reservoir in a cascade* can be solved in the same way as an individual reservoir with direct withdrawal with an over-year or within-year cycle (Section 5.2). Besides determining the main parameters of release control (the size of the storage capacity $V_{z,1}$, yield $O_{p,1}$ and reliability P_1) the time pattern of the release from a reservoir $O_1 = f(t)$ must be calculated in the whole series.

As long as the emptying of a reservoir in any balance step V_k meets the condition that $0 < V_k < V_z$, release from the reservoir O_1 equals the yield O_p. If $V_k = 0$ (full storage capacity) with $Q_1 > O_p$ in the next step, or $V_k = V_z$ with $Q_1 < O_p$ in the next step (complete empying of the storage capacity + water supply deficit), the release from reservoir O_1 equals the inflow Q_1 ($O_1 = Q_1$).

Inflow P_2 to the *downstream reservoir* is given by the relationship

$$P_2 = O_1 - X_1 - Z_1 + Q_M(1, 2) \tag{9.1}$$

where X_1 is withdrawal from a reservoir or stream downstream of the upstream reservoir, which is not returned to the catchment of the lower reservoir; if at least part of the withdrawn water is returned to the stream, only the consumption is considered,

Z_1 – water losses from the upstream reservoir or from the stream downstream of the reservoir $[m^3 s^{-1}]$,

$Q_M(1, 2)$ – inflow from the interbasin between the upstream, and downstream reservoir, which is equal to the difference $(Q_2 - Q_1)$.

Note: Inflow to a reservoir influenced by an upstream reservoir is denoted P, the natural inflow from the catchment is denoted Q (e.g., Q_2 is the natural discharge at the site of the downstream reservoir).

After rearranging,

$$P_2 = (O_1 - Q_1) + Q_2 - X_1 - Z_1 \tag{9.2}$$

If $X_1 = 0$ (no withdrawal with consumption at the upstream reservoir of the cascade) and if the water losses are neglected $(Z_1 = 0)$, the relationship can be simplified to

$$P_2 = (O_1 - Q_1) + Q_2$$

If we are to study the inflow volume W_2 to a reservoir in individual time steps, we can write

$$W_{2,k} = \sum_{i=1}^{i=k} P_2 \Delta t_i = \sum_{i=1}^{i=k} Q_2 \Delta t_i + \sum_{i=1}^{i=k} (O_1 - Q_1) \Delta t_i \tag{9.3}$$

Equation (9.3) is an algebraic expression of the graphical solution of a cascade of reservoirs in mass curves, shown in Fig. 9.1. The mass curve of the inflow to the downstream reservoir is constructed by adding to the mass curve of natural discharges $\sum_{Q_2}$ the volumes augmented by the upstream reservoir, represented by the vertical distances between the mass curves $\sum_{O_1}$ and $\sum_{Q_1}$ which stand for the work of the upstream reservoir.

The time series (inflow curve) $P_2 = f(t)$ is the basis for the direct solution of the downstream reservoir, the method being the same as for the upstream reservoir. The

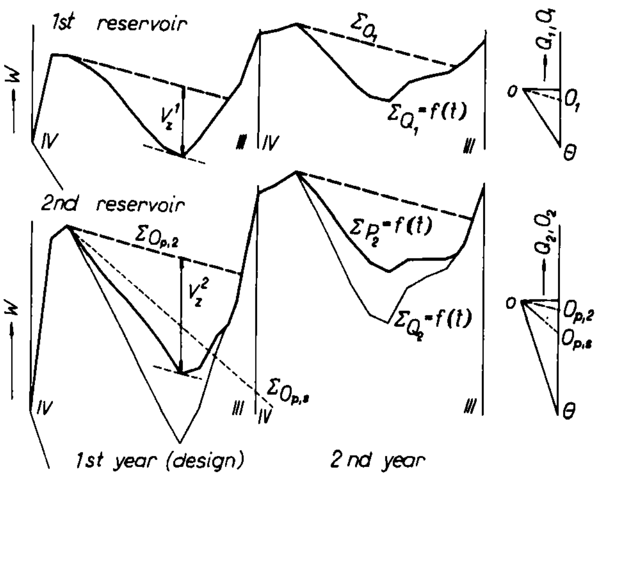

Fig. 9.1 Analysis of a cascade (series) of reservoirs in mass discharge curves

parameters of release control $V_{z,2}$, $O_{p,2}$, P_2 and the release time series $O_2 = f(t)$ are to be determined. In Fig. 9.1 we can also find the yield (withdrawal) $O_{p,s}$ in the mass curve $\sum_{Q2}$ which would make the storage capacity V_z^2 possible without the balancing effect of the upstream reservoir.

Then one can proceed to the third stage of the cascade, and so on, until the last downstream reservoir is reached.

In simple cases where cascades consist of two reservoirs (or under special conditions of more reservoirs) analytical methods can be used as for independent reservoirs. One condition, however, is a synchronous discharge regime from the upstream reservoir catchment as well as from the interbasin between the two reservoirs and the same reliability of water supply.

Let us presume that the relative volume $\beta_{z,1}$ of the upstream reservoir is greater than the relative volume of the downstream reservoir (for a greater number of reservoirs it holds that $\beta_{z,1} > \beta_{z,2} > \beta_{z,3}, \ldots,$ etc.). Then the downstream reservoir is always filled sooner than the upstream and cannot use the idle outflow from the upstream reservoir. The downstream reservoir can only control the discharges from the interbasin, regardless of the upstream reservoir function. This cascade can therefore be solved as two independent reservoirs, the inflow to the downstream reservoir being given by the discharge from the interbasin. The total reliable withdrawal from the cascade equals the sum of yields (withdrawals) of the two reservoirs:

$$O_p = O_{p,1} + O_{p,2} \tag{9.4}$$

However, if the relative storage capacity of the downstream reservoir is larger ($\beta_{z,2} > \beta_{z,1}$), it is upstream reservoir that is filled first in a wet period (following after a low-flow season, during which the reservoir empties). In this case, the surplus outflow is used by the downstream reservoir until its storage capacity is filled. The cycle duration is decided by the time needed to fill the downstream reservoir. The problem can therefore be simplified by considering that the storage capacities of the two reservoirs are at the site of the downstream reservoir ($V_z = V_{z,1} + V_{z,2}$). The characteristics of release control from a cascade (O_p, P) are then the same as the corresponding values determined for independent reservoirs, with a storage capacity of $V_z = V_{z,1} + V_{z,2}$ situated at the downstream reservoir site (hydrological data are discharge series $Q_2 = f(t)$).

This simple method does not give a detailed picture of the work regime of the respective reservoirs in a cascade; however, it helps to give a ready estimate of the regulating effect of release control of several reservoirs on the stream.

9.2 PRINCIPLES OF RELEASE CONTROL OF RESERVOIRS IN THE CASCADE FOR HYDROELECTRIC POWER PRODUCTION

In designing a cascade of reservoirs for hydroelectric power production, the role of the hydro-power plants in the power system, as well as the mutual relations between the electric power and water management demands, must be considered.

In Czechoslovakia, where most of the electrical power is supplied by thermal-power plants, hydro-power plants supply only about 25% of the total output. They supply electric power only to cover the peaks in the daily load diagram, to help regulate the frequency, etc. Reservoirs of hydro-power plants are usually a part of more extensive water schemes, including the supply of water for various users.

The basic requirement of hydroelectric power production is the optimization of the design and operations of a cascade from the point of view of the power output, with increased demands in the winter months. With a given design flow capacity of the turbines, optimization from the point of view of power output is transferred to a search for the choices which would ensure a maximum head of the hydro-power plants in a cascade. This state is stressed in those cases where the primary energy potential of a stream is enforced by pumping power plant.

Many books have been published on cascades of hydro-power plants, especially by Soviet authors (Kartvelishvili, 1961, 1967; Cvetkov, 1961; Reznikovski, 1964, 1969, 1974). Before computer technology was introduced, all the input quantities were usually given as deterministic quantities, contrary to the real conditions in the electric power systems, in which many data have probability characteristics (river runoff, including hydrological forecasts, energy demands for certain purposes, rated outputs of thermal and hydro-power plants, demands of other users from multi-purpose reservoirs, etc.).

Deterministic quantities can be included in the calculations only when disregard of the probability characteristics will not influence the accuracy of the solution. These, however, certainly do not include discharges in the rivers, load of the power system, rated outputs of power plants or water withdrawals for irrigation. In the calculations of the regime of hydroelectric power cascades, the changes in the input quantities with time must be considered as a probability process, which for the sake of simplicity is usually introduced with discrete time as a Markov chain, although it is actually a continuous process.

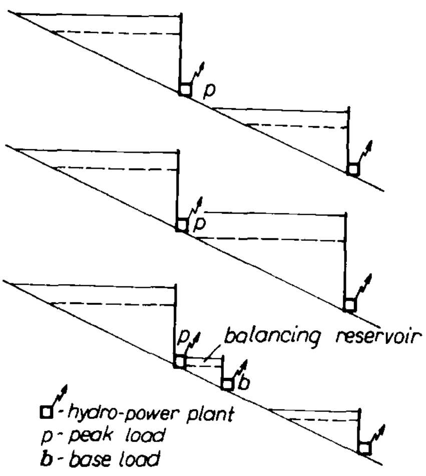

Fig. 9.2 Basic diagram of hydro-power reservoirs in a cascade

The probability concept is also reflected in the optimization, whatever its criterial function might be.

The influence of water management operations of a cascade of reservoirs on the head of hydro-power plants depends on the arrangement of the reservoirs. Figure 9.2

gives a basic scheme of the relationship of reservoirs in a cascade from the point of view of the power-plant head.

In Fig. 9.2a, the fluctuation of the head is given only by changes of the water level in the upstream reservoir. The diagram in Fig. 9.2b shows a state in which the size of the head is influnced by the position of the water level in the upstream and downstream reservoirs. Finally, Fig. 9.2c shows an arrangement with a balancing reservoir by a peak-load power plant, which is usually used if distance between the end of the backwater of the downstream reservoir and the peak-load power plant of the upstream reservoir is great.

In low-flow periods, the demands of power production are at competition with the demands of water supply; this requires a planned emptying of the storage capacities of the cascade reservoirs. In the period that corresponds to the design conditions, all storage capacities of all reservoirs are emptied (if we do not limit the withdrawal) so that the minimum guaranteed output of the power plants in the cascade (with a given rate of reliability) is a design constant. However, at the time of emptying and filling of the reservoirs, the order of usage of the respective storage capacities, as well as the respective layers of the storage capacities of the reservoirs, can be changed in such a way that, while meeting the demands of the users, the greatest probability of exceeding the rated outputs of the cascade should be reached.

10 RELEASE CONTROL IN A SYSTEM OF RESERVOIRS

A system of reservoirs is a set of reservoirs on various streams, which cooperate in release control. These reservoirs can be on a main stream and its tributaries in one catchment, where the upstream reservoirs can influnce the inflow to the downstream reservoirs (Fig. 10.1a), or they can be in different catchments and can cooperate to cover the withdrawal demands (Fig. 10.1b). Most important is the relationship of their functions.

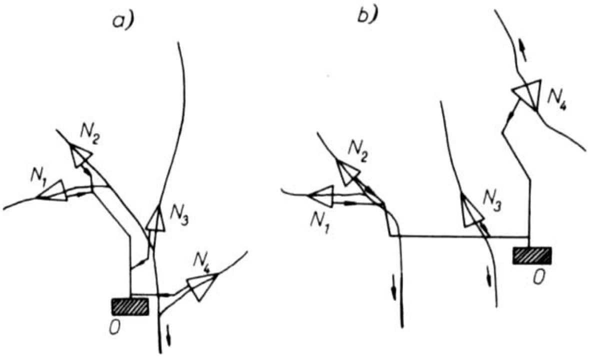

Fig. 10.1 Schematic representation of a system of reservoirs

The design of release control in a system of reservoirs is one of the most complicated problems in water management. A system of reservoirs serves many purposes, the priority of which can only be estimated objectively from the economic point of view. However, usually there are no available data that reflect the actual impact of the respective functions on the national economy, but there are also intangible aspects, e.g., the relationship of the reservoirs to the environment, social factors, etc.

Another reason for this problem being complicated is that it takes a long time to build such a system. Even if a proper concept were used from the beginning of the construction of the system, demands on the respective functions would certainly change during the long period of construction and the development would deviate from the original prognosis. More frequently, however, a system consists of individual reservoirs that were built according to the demands of the given period. When water demand increases or flood control measures must be introduced, which require the construction of further reservoirs, does a system that works as a functional entirety become more expedient. The necessary technological measures must be taken that enable the cooperation of reservoirs in the system. Further necessary assumption is the development of the methodology of the water resources systems with reservoirs analysis. The parameters of the existing reservoirs will be far from optimum with regard to their qualitatively new function in a system.

Several books on comprehensive analysis of water resources systems with reservoirs have been published, e.g., Buras (1972), Votruba, Nacházel and Patera (1974), Votruba *et al.* (1979, 1988). Characteristics of this relatively new branch can be found in Chap. 15.

Even though the methods of operation research as applied to the solution of water resources systems are not currently used in operation (with the exception of technical simulation), it is possible to determine quantitatively the contribution brought about by the cooperation of reservoirs in systems by much simpler methods. If a system of reservoirs is able to meet all demands completely and there is no need to determine the order of importance of the respective demands, it is sufficient to use only technical parameters. This concerns mainly single-purpose systems (e.g., supply of drinking water), or systems with one dominant purpose.

10.1 TECHNICAL PARAMETERS OF RELEASE CONTROL IN A SYSTEM OF RESERVOIRS FOR PUBLIC WATER SUPPLY

Reservoirs that are to cover water demands effectively—which means that with a given storage capacity they should ensure a maximum yield or with a given withdrawal should have the smallest possible storage capacity—should cooperate in a system; this is especially advantageous if

(a) the discharge regime of the streams with reservoirs working in a system is asynchronous,

(b) the discharge regulation through the respective reservoirs differs greatly.

In spite of the differences in the discharge time series in the streams of Czechoslovakia, the hydrological regime can be considered to be essentially synchronous (with the exception of the Danube). High-flow and low-flow periods occur in the same periods of the year, with differences in time, resulting only from the different altitudes (beginning of the winter period, spring thawing); over-year low-flow periods are also mostly identical. From the point of view of the water yield of these periods, using a five-point classification (very high-flow, high-flow, average, low-flow, exceptionally low-flow) the difference is never greater than one point. However, even these small differences in time can be put to good use, especially if the area of the system is large, and on the rivers with a different yield where even an insignificant asynchronous pattern on a stream with a large mean discharge can represent a great contribution to the whole system (as compared with other reservoirs on smaller streams).

A great difference in the regulation of the discharges (relative yield) in a system makes it possible to use the excess releases from reservoirs with a lower relative yield (the probability of occurrence is relatively high) and thus save the water in the storage capacities with an over-year cycle. The water volume gained by increased withdrawals from seasonal reservoirs at the time of a lack of water makes it possible either to decrease the storage capacity of the newly designed reservoir in the system, or to increase the overall reliability of withdrawal.

An important condition, however, is that corresponding technical measures should be introduced, namely that withdrawal structures and canals of a sufficiently large capacity be built.

A system of reservoirs should be analysed, similarly to other complicated methods of release control, in synthetic discharge series modelled simultaneously in a system of river sites. As it is presumed that all the reservoirs of a system have at least a seasonal cycle (with the exception of reservoirs with special functions, buffer-storage reservoirs, balancing reservoirs, etc.) monthly discharge series usually give a correct solution (analysis can then help to correct any errors).

The method we have derived (Bečvář, Votruba and Broža, 1968; Nacházel, 1970) is similar to river flow regulation. This is given by the regime of the reservoirs with high relative yield that augment the discharge to the required withdrawal at low-flow periods (withdrawal from seasonal reservoirs is identical to withdrawal from individual reservoirs with isolated function); however, in wet periods they only supplement the withdrawals from the seasonal reservoirs to meet the withdrawal demand in the whole system. The withdrawals from the seasonal reservoirs vary from the safe yield corresponding to their isolated function to the capacity of the withdrawal facilities which can be determined by a technical-economic analysis; if the augmented release (withdrawal) flows through the stream channel downstream of a reservoir, the upper withdrawal limit need not be considered in the calculations.

When increased withdrawals are made from reservoirs with a shorter cycle, discharge forecasts are used (as for compensation regimes), from which the size of withdrawals from reservoirs with a longer cycle are determined. Water losses can occur due to incorrect forecasts and operation, which theoretically lessen the effect of the cooperation of reservoirs. It is therefore necessary, at the end of the calculations, to correct the theoretical values of the release control characteristics or propose measures to eliminate operation losses in the system.

A simple case of two reservoirs, where the first (N_1) has an over-year cycle and the second (N_2) a within-year cycle, can serve as an example (Fig. 10.2).

Reservoir N_2, when working independently, has a release (withdrawal) $O_{p,2}$ with the reliability P. Operation is based on a simple central rule curve (see Section 13.1), which is given by a so-called "anti-failure curve" of the storage capacity targets $V_D = f(t)$ during the year (Fig. 10.2b). If the water volume in a reservoir is, on a given date, smaller than or equal to the value given by the rule curve, withdrawal from the reservoir equals $O_{p,2}$; if the storage volume is larger, the surplus volume is used to increase the withdrawal. With a full storage capacity, withdrawal equals the inflow (up to the value given by the capacity of the withdrawal facility and the water supply to the consumer).

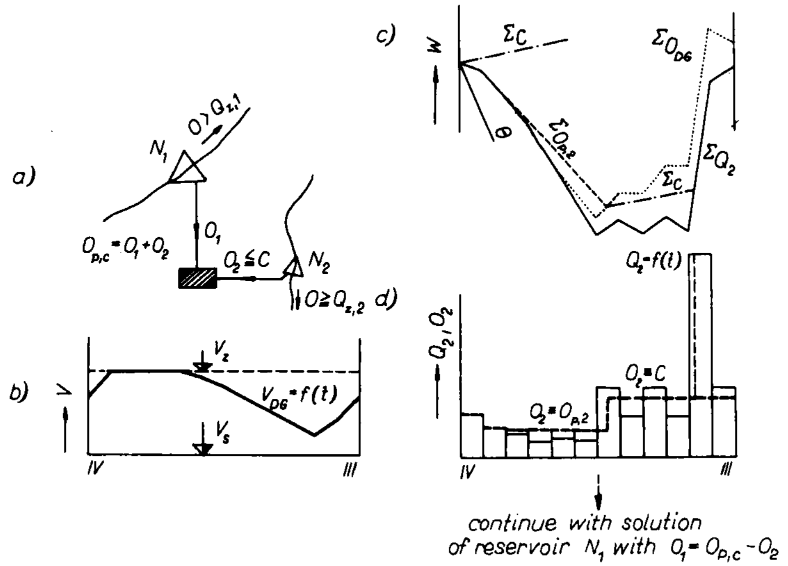

Fig. 10.2 Schematic representation of the cooperation of an over-year and seasonal reservoir, based on the utilization of excess outflow from the seasonal reservoir

If the time needed to transport withdrawal O_2 from reservoir N_2 to the user is shorter than from reservoir N_1, discharge forecasts should be used for the operation. This forecast need not be as accurate as for river flow regulation without a buffer-storage reservoir; deviations should, however, be balanced or be slightly more reliable as to excess discharges (i.e., over-estimations in the forecasts). However, operation need not be based on forecasts, when the volume of reservoir N_2 is used.

The basic relationship reflecting the cooperation of reservoirs to cover the withdrawal demand $O_{p,c}$ in a system is

$$O_{p,c} = O_1 + O_2 \qquad (10.1)$$

Release O_2 from the reservoir with a shorter cycle (Fig. 10.2c, d) is,

$O_2 = O_{p,2}$ when the reservoir storage volume is $V \leqq V_D$,

$O_2 = Q_2$ when the storage capacity is full, if

$Q_2 \leqq C$ (C – capacity of withdrawal facility) or, on the contrary, when the storage capacity is empty and with inflow going to reservoir N_2, for which it is

$Q_2 < O_{p,2}$ (failure in water supply, predicted within the framework of the given reliability rate P),

$O_2 = C$ with a full storage capacity and $Q_2 > C$,

$O_2 = O_{p,2} + \Delta O_2$ when $V > V_D$; for radical use of the water surplus in the storage volume $O_2 = C$ can be withdrawals as long as the volume stored in the storage capacity is not identical with the rule curve volume V_D, which ensures the greatest utilization of water surplusses.

With a given theoretical size of storage capacity $V_{z,2}$, which when functioning in isolation ensures a withdrawal of $O_{p,2}$ with a reliability P, direct calculations are carried out in a synthetic series of mean montly discharges, bearing in mind the principles for a better utilization of reservoir N_2. The result is a time release (withdrawal) series O_2 (Fig. 10.2d), from which the time series of required withdrawals O_1 from reservoir N_1 (with over-year release control) can be determined.

With a known course of withdrawal O_1 throughout the synthetic discharge series, direct calculations (simulation) bring us to the design size of the storage capacity of reservoir N_1, with the corresponding required reliability P (see Section 5.2).

If an already constructed reservoir N_1 were to be supplemented by a newly designed reservoir N_2, the problem could be solved by successive approximations for several values of $V_{z,2}$.

When already constructed reservoirs are to cooperate, a new reliable withdrawal from the system O_p (with a design reliability P) must be determined. The procedure can be the same as for the cooperating reservoir N_1. The result gives the size of the storage capacity $V'_{z,1}$, which is smaller than the constructed volume $V_{z,1}$ (theoretical size). The difference $\Delta V_1 = V_{z,1} - V'_{z,1}$ is used for a uniform (or proportional) increase of withdrawal O'_1 throughout the time of emptying of the reservoir, corresponding to the design conditions. For computer processing several values of the withdrawal increment ΔO_1 are selected and for these the respective reliabilities P are determined. The resultant effect of the cooperation, ΔO, corresponding to the design reliability P, is then determined by interpolation.

In 1969 the department of hydrotechnics of the Technical University in Prague studied the possibilities of cooperation between two reservoirs with an over-year

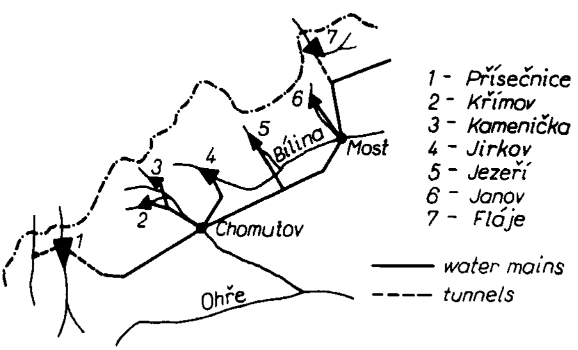

Fig. 10.3 Public water-supply reservoirs in the North-Bohemian industrial region

cycle and several seasonal reservoirs in the north Bohemian industrial region (Fig. 10.3). The total theoretical effect of the cooperation, 0.33 $m^3 s^{-1}$, is 16% of the sum of isolated withdrawals and as compared to the already constructed reservoirs. This greatly exceeds the reliable withdrawal from any of the seasonal reservoirs in the system (Nacházel *et al.*, 1969; Nacházel, 1970). It follows from an analysis of the real conditions of the cooperation of reservoirs in the framework of a system supplying drinking water that the present concept, in which the treatment plants are joined to the public water supply reservoirs (the treatment plant capacity corresponds to the safe yield of a reservoir), will not be able to meet future requirements. To distribute water-treatment plants according to the needs of a region supplied by a system of public water supply reservoirs (in the optimal way from the aspect of raw water supply as well as treated water distribution) is an important precondition for the full exploitation of the effect of the cooperation of reservoirs without having to double their capacity.

10.2 SYSTEM WITH WATER DIVERSION

Diversion of water is frequently used in systems as it helps to intensify the natural hydrological potential of a reservoir catchment. As systems with water diversion are always greatly influnced by local conditions, the variability of designs is extensive. Figure 10.4 shows schematic representation of some water diversion systems designed in Czechoslovakia. The most usual case (Fig. 10.4a) is to increase the inflow to a reservoir on stream *1* by diversion from the neighbouring catchment *2* (by canal or pumping); this is especially suitable if a relatively large storage capacity can be constructed on stream *1*. Frequently, the water is brounght to a reservoir from the upstream catchment joining the recipient downstream of the dam site (Fig. 10.4b).

Other, more complicated systems have lateral reservoirs. The diagram in Fig. 10.4c illustrates a case where conditions in the upstream catchment of stream *1* are not suitable for building the main reservoir; therefore, a suitable site for a dam was chosen on tributary *2*, to which water is diverted from the main stream. In Fig. 10.4d the arrangement is similar: but here water is also diverted from neighbouring catchment *3*. In the case shown in Fig. 10.4e the diversion to a lateral reservoir holds only part of the upstream catchment of the main stream *1* and, therefore, besides direct withdrawal from the reservoir, water is also withdrawn from the stream (if hydrological conditions are suitable). In Fig. 10.4f water is diverted from stream *1* and the surplus water is diverted to catchment *4*, which is a passive catchment from the water-management point of view. The lateral reservoir, which is filled by pumping, smoothes the pattern of diverted discharges. In the diagram in Fig. 10.4g, stream *2* flows in the opposite direction from the natural flow (the water from recipient *1* is pumped to a reservoir from a cascade of low stages). The diagram in Fig. 10.4h reflects specific local conditions: Dam P_1, built on stream *1* just downstream of the confluence with stream *2*, creates a reservoir for the supply of drinking water. This reservoir may not be used as a recreation facility, which is a pity, as it is close to a town. In the catchment of stream *2* farming is going to become more intensive, which will necessarily influence the quality of the water. It was therefore decided to divide part of the reservoir in the valley of stream *2* by a dam P_2; the water is taken to the stream downstream of dam P_1 by a tunnel O_z. Reservoir N_2 ensures the required discharge in stream *1* downstream of the dam and serves a recreational function, while reservoir N_1 supplies mainly drinking water.

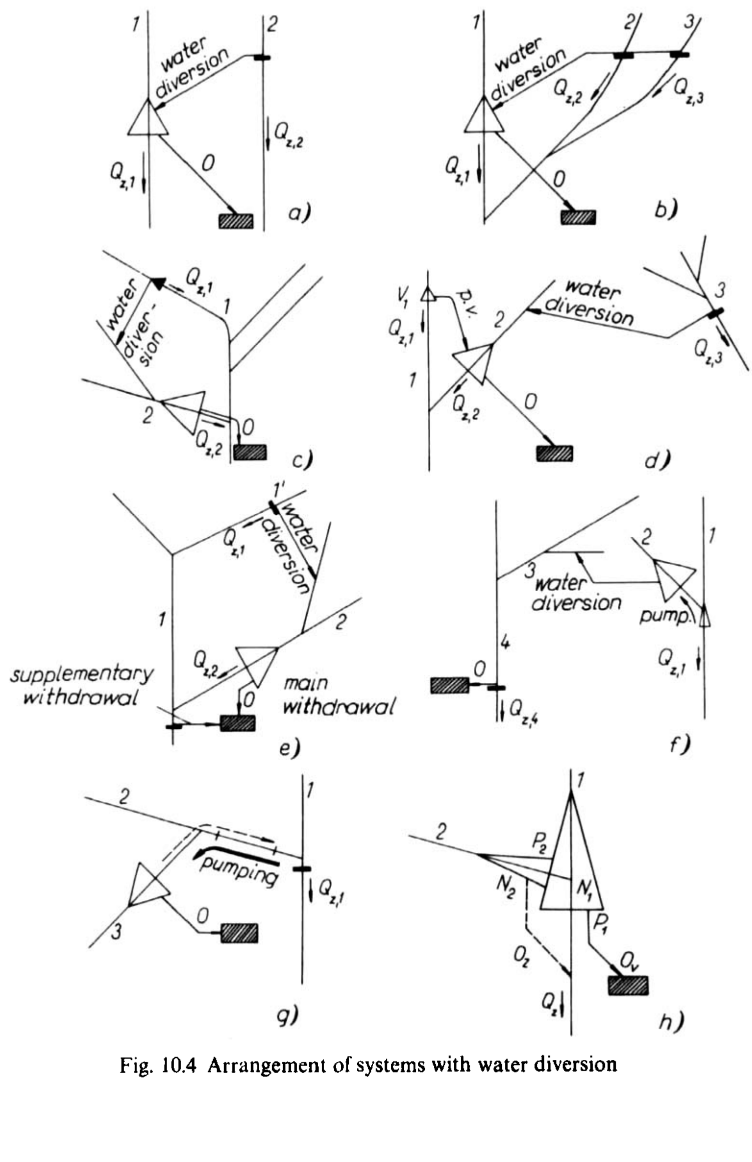

Fig. 10.4 Arrangement of systems with water diversion

A universal method for the solution of such systems is the method based on simulation with synthetic discharge series. Ideal input data, i.e., discharge series observed simultaneously in a system of river sites, will be available only in very rare cases as the water is frequently diverted to the reservoir catchment from small streams without any hydrological observation. Generally, it is presumed that the discharges at the river sites are synchronous and that the corresponding values are proportionate to the long-term mean discharges.

In the first stage, the total discharge Q_c to a reservoir at each time step of simulation has to be determined:

$$Q_c = Q_v + (R - Q_z - U) \tag{10.2}$$

where Q_v is the inflow from the catchment of the reservoir,
- R is the discharge in the adjacent stream from which water is diverted to the reservoir,
- Q_z is the minimum guaranteed discharge in the adjacent stream downstream of the withdrawal site,
- U is the wasted discharge of the diverted stream due to the limited capacity of the water diversion facility.

In using series of mean monthly discharges, a method must be elaborated to determine indirectly the wasted discharges U (mean monthly values U_m).

Let us presume that the minimum diversion capacity equals the value K. This is given, e.g., by the capacity of the inflow structure of the diversion (tunnel, canal, pipeline) or by the capacity of the pumping station. If there is no reservoir capacity at the withdrawal site or if the reservoir has only a daily storage cycle (e.g., when

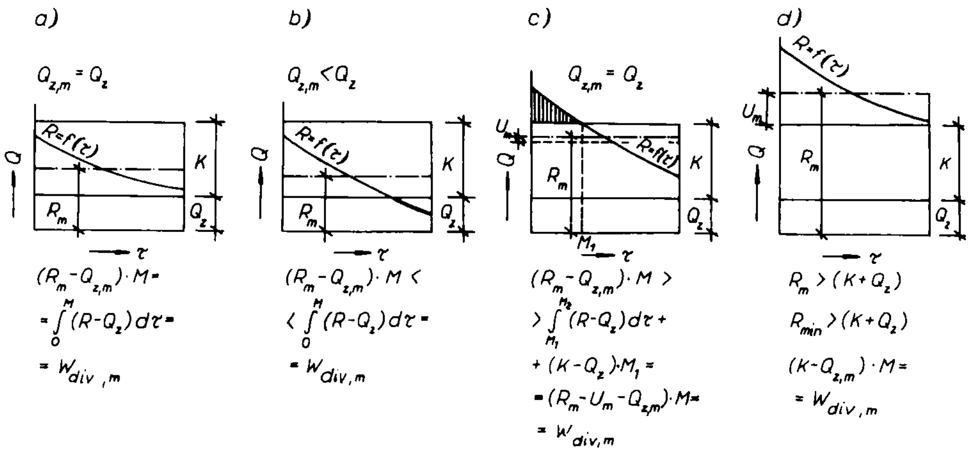

Fig. 10.5 Relationship between the mean annual discharges, water diversion and wasted discharges and accurate values gained in exceedance curves of discharges in one month

water is pumped only at night), an analysis of discharge exceedance curves in the respective months in real series should be used to calculate the mean discharge losses U_m.

Figure 10.5 shows the exceedance curves of mean daily discharges $R = f(\tau)$ in months with different mean discharges R_m (M – duration of the month), showing the various relationships between the respective discharge components R when water is being diverted. In the cases shown in Fig. 10.5a, b the wasted discharge U equals zero, which can be expected in low-flow months. The diagram in Fig. 10.5a shows a case in which the discharge fluctuations within a month do not influence the mean monthly values R and Q_z, so that the difference $(R_m - Q_{z,m})$ is the accurate balance value. From Fig. 10.5b it follows that if discharge R drops below the value Q_z within a month, the mean monthly value would be $Q_{z,m} < Q_z$. If this phenomenon is neglected, the solution is safer. If the discharge in a month is $R > (Q_z + K)$, discharge losses will occur. Figure 10.5c gives the duration of this state M_1; the hatched area is the unused water volume; if this is transferred to a rectangle, where the base equals the "width" M of the time step (1 month), then its height determines the value U_m. If discharge R throughout the month is greater than $(Q_z + K)$, then the diverted part of the discharge (mean monthly value) equals the maximum diversion capacity (Fig. 10.5d).

An analysis of the above relationships in real series makes it possible to construct the dependence between the diverted discharge components $(R - Q_z - U)_m$ and the mean monthly discharges R_m. In certain cases this can be functional (e.g., with large values of R_m, when $(R - Q_z - U)_m = K$; or, on the contrary, with small values of R_m, when $(R - Q_z - U)_m = R_m - Q_z$, otherwise correlational. Then the corresponding series of the components diverted to the reservoir $(R - Q_z - U)_m$ can be related to the random synthetic series R_m and the diverted volume $W_{\text{div.},m}$ can be determined in each step.

This method is very time-consuming, but it can be simplified by using summation discharge curves in the respective months, which also gives sufficiently reliable results (Pilná and Votruba, 1971).

Often the complicated scheme of diversions and withdrawals can be essentially simplified. Figure 10.6 shows the approximate conformity of a solution of a system

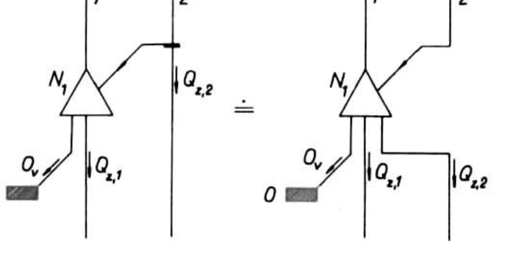

Fig. 10.6 An example of how a water-management solution of a system with water diversion can be simplified

with water diversion and a solution for an independent reservoir. One condition, however, is that the diversion capacity from stream *2* to the catchment of reservoir N_1 is large enough: for example, when water is diverted from a small stream ($Q_a \lesseqqgtr 0.50\ m^3\ s^{-1}$) by a tunnel with a free water level, then the smallest diameter of the tunnel (about 2 m) can divert all the water with the sole exception of flood peaks.

The diversion capacity must always be considered in relation to the reservoir regime. For seasonal cycles results need not be distorted even if the diversion capacity is relatively limited. In low-flow periods, which are important for release control parameters, even a small diversion capacity can ensure that the discharge from the neighbouring stream (*2*) will be used without any losses, so that the alternative scheme, which considers that stream *2* flows into reservoir N_1 and the required minimum discharge $Q_{z,2}$ as part of the yield (withdrawal) from the reservoir, practically corresponds to reality. As it is not considered that discharges in stream *2* would drop below the value $Q_{z,2}$, which is not the case with a real operation, the results of the alternative solution are slightly biased so as to be on the safe side. In the following wet period, when the reservoir capacity is full, the alternative scheme is rather too optimistic compared with reality, because due to the limited diversion capacity, excess releases occur at the withdrawal site on stream *2* and the reservoir is therefore filled more slowly. However, if the reservoir cycle is no longer than one year, this inaccuracy does not affect the design size of the storage capacity, the augmented withdrawal (O_v; $Q_{z,1}$; $Q_{z,2}$), nor the reliability.

With over-year release control, wet periods of over-year low-flow seasons can, if the whole problem is simplified, lead to an over-estimation of the release-control characteristics and the results must therefore be adjusted.

The above simple methods show how the problem of the cooperation of reservoirs can be solved at a time when the more general methods are being studied. Including storage reservoirs in systems offers further advantages; e.g., respective resources can replace each other, breakdowns can be overcome more easily, etc.

10.3 SPECIAL CASES OF RELEASE CONTROL

Special cases of release control can concern reservoirs which work independently, in cascades or in systems.

10.3.1 Release control with various water supply reliabilities

Individual withdrawals from multi-purpose reservoirs can supply water at different rates of reliability. This problem has not yet been solved and the following should therefore only be considered as an attempt to find a solution to this problem.

Let us consider a reservoir that is to ensure a withdrawal O_{p1} with a reliability of P_1 and a withdrawal O_{p2} with a reliability of P_2, whereby $P_2 > P_1$. The size of the storage capacity V_z is to be determined. At the same time the minimum storage volume, which ensures only withdrawal O_{p2}, must be determined so that withdrawals requiring a different water supply reliability can be implemented.

Let us first consider a solution in synthetic series of mean monthly discharges. In the first step the size of volume V_z' for withdrawal $O_p = O_{p1} + O_{p2}$ and the lower withdrawal reliability (i.e., P_1) must be determined. By a gradual increase of the volume above the value V_z' volume V_z can be determined; this will ensure a greater reliability (P_2) of withdrawal O_{p2}. If the storage volume is $V \geqq V_z'$, both withdrawals are unlimited. When the water volume in the storage capacity decreases further, withdrawal O_{p1} is eliminated (which might cause problems).

This solution can be transferred to an equivalent scheme of two reservoirs on one stream with zero inflow from the interbasin between the dam sites (Fig. 10.7). Applying the method described in Section 9.1, the size $V_z(1)$ for the given withdrawal O_{p1} and reliability P_1 is determined in synthetic discharge series. As the same time, the time series $O_2 = f(t)$ of the release from reservoir N_1 must be calculated and considered equal to the inflow $P_2 = f(t)$ to reservoir N_2. In series $P_2 = f(t)$ the size $V_z(2)$ necessary to ensure withdrawal O_{p2} with a reliability P_2 must be determined. The design size of the storage capacity is $V_z = V_z(1) + V_z(2)$. In this case, too, volume V_z' must be determined to make real operations possible.

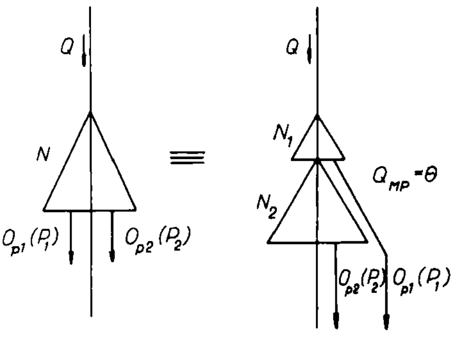

Fig. 10.7 Substitutional solution with various withdrawal reliabilities in a cascade (series) of reservoirs (calculations in synthetic series)

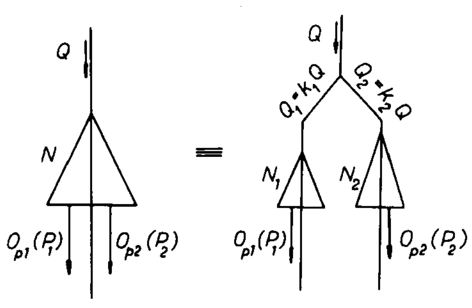

Fig. 10.8 Substitutional solution with various withdrawal reliabilities in a system of reservoirs with an optimal distribution of inflow

Discussions are frequently held to decide what the probability of exceeding the minimum maintained discharge in the stream downstream of a reservoir should be; it is believed that it could be smaller than the probability of exceeding withdrawals needed for households, industry, etc. This is then also a case where the storage capacity must be determined with a different reliability, with the only difference that should a failure of withdrawal O_{p1} ($P_1 < P_2$) occur, it may not drop to zero. This might also apply to other types of withdrawal.

In that case a certain minimum release $O_{1\,\text{min}}$ from reservoir N_1 (e.g., $Q_{364\text{d}}$) can be chosen, which together with withdrawal O_{p1} flows into reservoir N_2. This makes certain that even if reservoir N_2 fails, the chosen minimum outflow can be maintained in the stream or a limited withdrawal $O_{1\,\text{min}}$ can be ensured. Under these new conditions $V_z(1)$ must be larger and $V_z(2)$ smaller.

For statistical solutions based on real discharge series (regardless of whether release control has an over-year or a within-year cycle), an alternative scheme consisting of two reservoirs (Fig. 10.8) can be used. In this case reservoir N_1 ensures withdrawal O_{p1} with a reliability P_1 and reservoir N_2 a withdrawal O_{p2} with a reliability P_2, while discharge Q is divided into inflow $Q_1 = k_1 Q$ to reservoir N_1 and into inflow $Q_2 = k_2 Q$ to reservoir N_2 ($k_1 + k_2 = 1$, or $Q_1 + Q_2 = Q$). By trial and error, a division of discharges Q_1 and Q_2 must be found so as to lead to a minimum value of the sum $V_z(1) + V_z(2)$. This condition is derived from the logical presumption that one single volume $V_z = V_z(1) + V_z(2)$ enables an optimal "cooperation" between the storage volumes of reservoirs N_1 and N_2 and the volume can therefore be the smallest possible. For the design of the size of volumes $V_z(1)$, $V_z(2)$ and also V_z' (for $O_p = O_{p1} + O_{p2}$ and P_1) the same method as for the design of the storage capacity for direct withdrawal is used (see Chaps. 5 and 6).

If the design reliability of the individual withdrawals does not differ greatly, the method can be simplified. For example, it is possible to determine the size of the storage capacity for a design reliability P', which can be calculated as a weighted mean:

$$P' = \frac{O_{p1}P_1 + O_{p2}P_2}{O_{p1} + O_{p2}} \tag{10.3}$$

When compared with the real reliability of the results (random deviations in the size of the storage volume) inaccuracies due to the simplified introduction of different withdrawal reliabilities can be disregarded.

10.3.2 Release control in the period of the first filling of a reservoir

Reservoirs cannot meet all water demands as soon as their construction has been completed. Water-management calculations, however, presume that the storage capacity is full before a low-flow period starts; this corresponds to established operational conditions, but not to the state existing at the end of construction and the beginning of operation.

The first filling of a reservoir takes place under so-called *test operations*, during which operation is tested from the technical and safety points of view (limited changes in the water level of a reservoir, planned measurements, "flushing" of the reservoir with regard to the water characteristics, etc.). When there is an urgent need, reservoirs can be used, with certain limitations, during construction and test operations (supply of drinking water when the reservoir is only partly filled, checking of the installations, etc.). Sometimes the flow regulation operations should also be checked (e.g., work of a reservoir in a system, compensation operations, etc.). For this period a special program should be prepared.

Let us presume that when a reservoir is put into operation the storage capacity is empty. For *within-year release control* the development of the filling of the reservoir can be estimated even under complicated hydrological conditions, presuming the occurrence of a low-flow year in which the demands on the storage volume are close to the size of the design. At first, the consumers who receive their water from a new source are exposed to the "water management" risk that the supply might fail; however, the following year operations already correspond to the conditions as they were foreseen by the project.

If at the time that a reservoir with *over-year release control* is being put into operation a low-flow period lasting several years should occur, water supply might not be ensured without any failures for several years. To avoid this, special operation rules have to be introduced. A smaller reliable withdrawal is not as a rule contradictory to the demands on a reservoir, as at the beginning of operation the design capacity is not completely being exploited.

For quantitative calculations of the work of an over-year reservoir during initial filling, mean discharges for k-years with the probability of exceedance equal to the design water supply reliability P (Section 5.1) can be used.

The most unfavourable case of first-year operations is the occurrence of a low-flow year with a mean discharge of a probability of exceedance P. The maximum withdrawal in that year is equal to the mean discharge $Q_{1\mathrm{r}} \equiv Q_{\mathrm{I}}$ with the probability of exceedance P; whereby the amount of water in the storage capacity at the end of the year again equals zero.

The mean discharge in the first two years is considered to be equal to the theoretical discharge for the two year period $Q_{\mathrm{II}}(P)$ corresponding to the probability of exceedance P. As the first year was ascribed a mean discharge $Q_{1\mathrm{r}}$, the respective value $Q_{2\mathrm{r}}$ is determined from the relationship

$$Q_{2\mathrm{r}} = 2Q_{\mathrm{II}} - Q_{1\mathrm{r}} \tag{10.4}$$

Reliable release in the second year can at best equal the value $Q_{2\mathrm{r}}$; with $O = Q_{2\mathrm{r}}$ the storage capacity is again empty at the end of the year. The same result is reached with any other couple of mean annual discharges, the mean value of which is Q_{II} (in the first year it must be $Q_{\mathrm{r}} > Q_{\mathrm{I}}$).

From the theoretical mean discharge for a three-year period $Q_{\mathrm{III}}(P)$, we can calculate

$$Q_{3\mathrm{r}} = 3Q_{\mathrm{III}} - Q_{2\mathrm{r}} - Q_{1\mathrm{r}} \tag{10.5}$$

which equals the release from a reservoir in the third year, etc.

As soon as the value $Q_{i\mathrm{r}}$ exceeds the design value of withdrawal from a reservoir O_p, flow regulation operations envisaged by the project can start, even though it is only then that the storage capacity begins to be filled (in the sense of the long-term trend). If the actual demands on withdrawal are smaller than the calculated limit values, the reservoir is filled more quickly. High-flow years during the initial stages of permanent operations also speed up the filling of a reservoir.

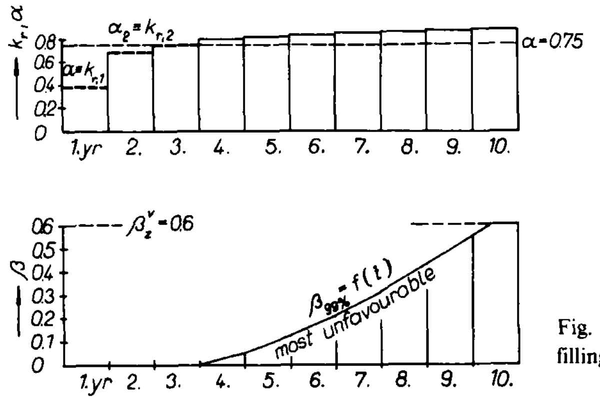

Fig. 10.9 Approximate solution of the first filling of a reservoir with an over-year cycle

Figure 10.9 gives the results of calculations for a yield by an over-year reservoir during the initial filling with release control parameters of $\alpha = 0.75$; $\beta_z^v = 0.6$; $P_o = 97\%$; $C_v = 0.40$; $C_s = 2C_v$; $r(\tau) = 0$. Withdrawal must be reduced only during the first two years of operations; however, the storage capacity is only filled after 9 to 10 years with discharge conditions corresponding to a 99% reliability, if an over-year low-flow period of a 99% exceedance probability occurs.

The solution of the storage function of a reservoir during the period of initial filling is essentially simple. Even though we have not discussed the consequences of various discharge situations in detail and have dealt only with the "over-year component" of release control, the results can be considered reliable for the determination of operating rules for this period. Decision-makers must not consider a planned contribution of the newly built reservoirs immediately after completion, but after test operations and after the period of the initial filling. The logical consequence of these considerations should be, especially for reservoirs with over-year release control, that construction should start well in advance of time. In the working schedule of construction and the programs of test operations the first operational filling and beginning of water supply should be chosen so as to meet real withdrawals that might be needed, i.e., before the beginning of the spring wet period.