8 RIVER FLOW REGULATION

Let us consider a reservoir that is to ensure a given withdrawal at a given site downstream of the reservoir (Fig. 8.1); the natural discharge from the interbasin between the reservoir (dam site) and the withdrawal site is an important part of the water balance. Then the optimal reservoir operations will mean that they only supplement (compensate) the natural discharge from the interbasin, if it is unable to cover the required withdrawal at the withdrawal point. Release control from a reservoir by which the required withdrawal is ensured at the withdrawal point, together with the non-controlled discharge from the interbasin, is called *river flow regulation* (*compensation control*).

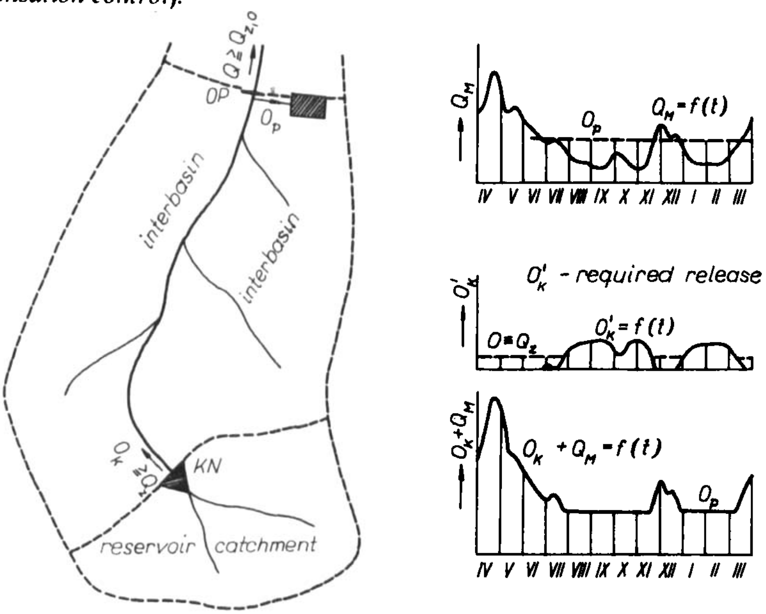

Fig. 8.1 Diagram of a reservoir with river flow regulation

Compensation in the broader sense of the word is, e.g., the case of drinking water supply from a reservoir, where withdrawal depends on the fluctuations of the groundwater yield, together with which it supplies water to the water mains; a reservoir compensates the differences between the total water demands and the capacity of the groundwater resource. However, in the more narrow sense, the essential trait is that a reservoir controls its own catchment, which is part of the catchment of the respective withdrawal point.

River flow regulation has often been used in reservoirs for irrigation, thermal-power plants and public water supply demands. In multi-purpose works it is frequently combined with direct withdrawal.

To explain the idea of river flow regulation let us consider the release control by the storage capacity placed either:

(a) at the withdrawal point with direct withdrawal from a reservoir,

(b) upstream of the withdrawal point with compensation operations,

(c) as in (b), however, with release control ensuring a constant safe yield (regardless of discharges from the interbasin).

Most efficient is (a), as the reservoir is in control of the whole catchment. If it is not possible to place a reservoir directly next to the withdrawal point, (b) is more expedient than (c), as it able to ensure a higher safe yield (withdrawal) at the withdrawal point. In case (c) the reliable discharge at the withdrawal point would only equal the sum of the yield at the reservoir site and the minimum natural discharge from the interbasin.

A reservoir with a compensation regime can "save" water during higher discharges from the interbasin and can therefore ensure a more balanced discharge at the withdrawal point than constant release would be able to achieve.

River flow regulation can be of an over-year or a seasonal type. It is not simple to estimate the reservoir cycle in advance, as in certain cases only insufficient discharges from the interbasin in short, closed low-flow seasons must be compensated, while over-year control must be used when the emptied volume is not refilled even in the high-flow seasons. The decision is only easy when over-year, low-flow periods have been observed at the withdrawal point.

The basic rule for a reservoir with river flow regulation to ensure the required withdrawal $O_p(t)$ follows from the relationship

$$O_p(t) = Q_M(t) + O_K(t - \tau) \tag{8.1}$$

where $Q_M(t)$ is the uncontrolled inflow from the interbasin (part of the discharge at the withdrawal point at the moment t, coming from the interbasin between a reservoir and the withdrawal point),

$O_K(t - \tau)$ – release from a compensation reservoir, which must be let out into the stream at the moment $(t - \tau)$, so that in the discharge-travel time τ the discharge from the interbasin should be supplemented to the value $O_p(t)$.

Another condition is

$$O_K \geqq Q_z \tag{8.2}$$

where Q_z is the minimum yield in the stream downstream of the dam; at the most $Q_z = O$.

An indispensable condition for compensation operations is the *forecast of discharges from the interbasin in advance of a minimum time* τ. If there is no storage capacity near the withdrawal point, the forecast must be reliable, so as not to cause failures in water supply. Inflow from the interbasin is, however, frequently underestimated and a greater amount of water is released from the reservoir than necessary; water losses are then reflected in the capacity of the compensation reservoir. A *buffer storage reservoir* at the withdrawal point is able to balance the fluctuations of discharges. To construct an exact model of river flow regulation would be very complicated, as, e.g., the discharge-travel time τ is not constant; complicated hydrodynamic factors play their part in the stream channel, etc. Simplifications must therefore be introduced which must be taken into account when transferring the results to parameters of a project (Section 8.3).

Calculations are usually made in daily to monthly time intervals; it is therefore difficult to include the relatively short discharge-travel time τ (with the exception of daily discharge series) and the consequences of discharge forecasts.

Then all the quantities in equation (8.1) are in the same time interval and we can simply write

$$O_p = Q_M + O_K \qquad (O_K \geqq Q_z) \tag{8.3}$$

The discharge from the interbasin is given by the difference in discharges at the withdrawal site Q_O and the location of the reservoir Q_K, and therefore

$$O_p = Q_O + (O_K - Q_K) \tag{8.4}$$

or

$$O_p - Q_O = O_K - Q_K \tag{8.5}$$

Simulation of reservoirs with river flow regulation can be derived out in a chronological discharge series at the withdrawal site $Q_O = f(t)$; a discharge series at the reservoir site is indispensable for testing the conditions (8.2) during every step of the solution. If

$$O_K = (O_p - Q_O) + Q_K < Q_z \tag{8.6}$$

a supplementary release is added in the respective interval to the regulated discharge O_p

$$\Delta O = Q_z - [(O_p - Q_O) + Q_K] \tag{8.7}$$

and a balance step is made for $O'_p = O_p + \Delta O$ in the discharge series corresponding to the withdrawal site.

This ensures that any surplusses $(Q_M - O_p)$ from high discharges from the interbasin are not included in the calculation of the filling of the reservoir, as the discharge from the interbasin cannot be diverted to a reservoir without special measures; it is actually an idle outflow. The balance increments $(O_p - Q_O)\,\Delta t$, or $(O'_p - Q_O)\,\Delta t$

and the balance sums $\sum(O_p - Q_O)\,\Delta t$ can be determined successively in the chronological discharge series of the respective withdrawal site; this greatly simplifies the solution ($O_K < Q_z$ occurs only rarely in low-flow periods).

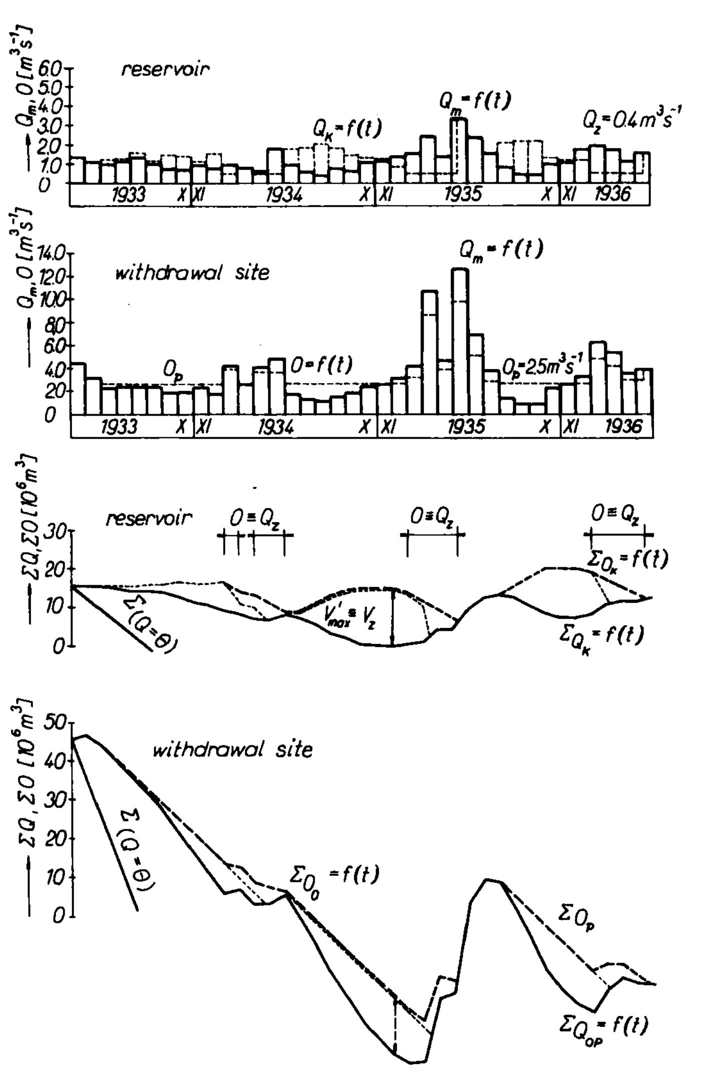

Fig. 8.2 Calculations of river flow regulation in mass curves

The graphical solution in mass discharge curves $\sum_{QK} = f(t)$ and $\sum_{QO} = f(t)$ (Fig. 8.2) concerns the same algorithm. The size of the storage capacity which is to ensure an augmented discharge O_p at the withdrawal point is to be determined; downstream of a reservoir there should be a minimum discharge Q_z.

The solution starts with a mass curve $\sum_{Q_O}$; a tangent is drawn parallel to the mass curve $\sum_{O_P}$. By transferring the vertical distances between curves $\sum_{Q_O}$ and $\sum_{O_P}$ to the mass curve $\sum_{Q_K}$, the as yet unverified mass release curve from the reservoir $\sum_{O_K}$ is determined. If $O_K < Q_z$ in any of the time intervals, we must correct the mass curve $\sum_{O_K}$ in that section in such a way as to make $O_K = Q_z$ (curve $\sum_{O_K}$ must be parallel to curve $\sum_{Q_z}$) and project the consequences of this correction to the further shape of curve $\sum_{O_K}$. In Fig. 8.2 the condition that $O_K \geqq Q_z$ was not met between two low-flow periods (1934), where the correction was reflected in the resultant size of the storage capacity V_z and during the filling of a reservoir (in the high-flow periods of 1935 and 1936).

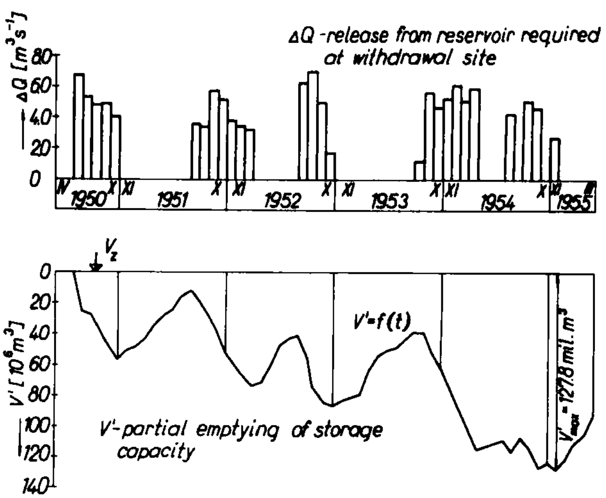

Fig. 8.3 Over-year regime of a reservoir with river flow regulation due to insufficient inflow in wet periods (with greatly different areas of the reservoir catchment and the withdrawal site)

If the area of the reservoir catchment is much smaller than the area of the inter-basin, over-year compensation release control must be introduced, as the inflow volume to a reservoir during a high-flow season is not large enough to refill the storage capacity emptied during the previous low-flow period (Fig. 8.3). If the mean release from a reservoir (given by the demands at the withdrawal site) were greater than the inflow, the required size of the storage capacity would increase with time.

8.1 RIVER FLOW REGULATION USING SYNTHETIC DISCHARGE SERIES

As the cycle of a reservoir with a compensation regime cannot always be defined in advance, and as the "compensation" release is usually combined with direct withdrawal, the method used must be a general and adaptable one.

Most general, but also most time-consuming method is the analysis with synthetic discharge series, modelled simultaneously at the withdrawal site and the site of a reservoir, taking into account the cross-correlation relationships (See Chap. 3). Instead of the series $Q_O = f(t)$, it is possible to model the inflow series from the interbasin $Q_M = f(t)$. Sometimes discharges at another site between the withdrawal point and the reservoir have to be used which means that another synthetic series has to be constructed at this control site.

To create *synthetic discharge series in a system of river points*, the number of numerical characteristics needed to construct a mathematical model, which must be taken from real series, increases substantially; this, however, increases the risk that atypical influences might occur and makes any control very difficult. We shall therefore use monthly discharge series, though we are aware of the effect of this simplification on the results of the solution.

The algorithm of a direct solution in discharge series is described by equations (8.3) to (8.7), from which a computer program can be compiled. We have proved that by introducing supplementary releases ΔO (equation 8.7), if the condition that $O_K \geqq Q_z$ is not kept, the procedure is practically the same as for the solution with direct withdrawal; a hypothetical reservoir is considered to be at the withdrawal site.

With a selected size of storage capacity V_z' and with a given augmented discharge O_p at the withdrawal site, the reliability of water supply p is determined by calculations in synthetic series. The equation

$$V_k = \sum_{i=1}^{i=k} (O_p - Q_O)\,\Delta t_i \tag{8.8}$$

where the value O_p is replaced in the intervals Δt_i, in which $O_K < Q_z$, by the value $O_p' = O_p + \Delta O$, determines the number of failure years and the duration of failures to supply water as well as the volume of the deficit water.

If $V_k < 0$, the result of the balance step is $V_k = 0$; the inequality $V_k > V_z'$ signals the emptying of the storage capacity of the selected size and the beginning of water supply deficit. After evaluating the rate of water supply reliability p (most frequently occurrence based) one "point" of the relationship $V_z' = f(p)$ is determined. This procedure is repeated for further V_z' values and after constructing the relationship $V_z' = f(p)$, the theoretical size of the storage capacity $V_z(P)$ is found for the design reliability P.

If the theoretical size of the storage capacity is estimated at first, then direct calculations are made with a given volume V_z for various suitably chosen values of augmented discharge O_p (the minimum discharge Q_z downstream of a reservoir does not change). The results are the "points" $(O_p; p)$ of the relationship $O_p = f(p)$. Using this relationship, the required flow $O_p(P)$ for the design reliability is determined.

Similarly as for direct withdrawal, short synthetic series with a statistical evaluation of the results can be used for river flow regulation.

8.2 DETERMINATION OF THE SIZE OF THE STORAGE CAPACITY USING EXCEEDANCE PROBABILITY CURVES OF NECESSARY VOLUMES

This method, essentially the same as Andreianov's method (Section 6.1) for seasonal release control, can only be used for compensation reservoirs with an annual cycle.

In every water management year the value necessary to ensure the required augmented discharge O_p at the withdrawal site is determined by direct calculations, equations (8.3) to (8.7). At the same time, a test of the filling of this volume in the following high-flow period (i.e. the test of a reservoir's seasonal cycle) is carried out.

The set of necessary storage capacites determined for all the years of observations which are available (in real chronological discharge series) are arranged in ascending order of magnitude (whereby several members equal zero); the "empirical" points of probability paper are fitted by a smooth curve, i.e., the *probability curve of necessary volumes.* The size of the storage capacity $V_z(P)$ for the given reliability P is thus found.

8.3 OVER-YEAR RIVER FLOW REGULATION

In probability methods of over-year river flow regulation, the reservoir volume is divided into over-year and seasonal components (e.g., Ivanov, 1964; Orlova, 1956; Gildenblat and Korenistov, 1960; Klemeš, 1965). The approach is similar to the analytical solution of over-year release control (Section 5.1). We shall describe how the matrix method, based on Moran's methodological approach (Section 5.1), can be applied to river flow regulation, i.e., to determine the *over-year component* of the reservoir storage capacity.

Real chronological discharge series are used as a basis. The volume of release from a reservoir, that is indispensable to ensure the required augmented discharge O_p (and also the minimum discharge downstream of a reservoir Q_z), is determined by direct calculations at the withdrawal site for every year, using equations (8.3) to (8.7).

From the set of release volumes from a reservoir an exceedance curve of release volumes is constructed, then the correlation coefficient between the inflow volumes to the reservoir in one year and the release volumes are determined. As the replenishment of the inflows from the interbasin is the greater the smaller the water yield in the low-flow period is, the correlation coefficient will be negative.

In view of the dependence of the annual inflow volumes and outflow volumes conditional exceedance curves of the release volumes (ω) must be constructed for the selected inflow volumes (π). The exceedance curve of inflow volumes $\pi = f(p)$ must be divided into a sufficiently large number of intervals, in which the mean values $\bar{\pi}_i$ are determined. The statistical characteristics of conditional exceedance curves of release volumes $\omega_i = f(p)$ of the corresponding values $\bar{\pi}_i$ are determined, presuming a linear correlation, from the relationships for the conditional mean

$$\bar{\omega}_i = \bar{\omega} + r_{\pi,\omega} \frac{\sigma_\omega}{\sigma_\pi} (\bar{\pi}_i - \bar{\pi}) \tag{8.9}$$

and for the conditional standard deviation

$$\sigma_{\omega(\pi)} = \sigma_\omega \sqrt{1 - r_{\pi,\omega}^2} \tag{8.10}$$

The conditional coefficient of skewness is usually the same as C_s of the original exceedance curve of $\omega = f(p)$.

However, it is also possible to transform the skew distribution $\omega = f(p)$ into a normal distribution (with $C_s = 0$) and after constructing the transformed conditional exceedance curves it is possible, by reversing the transformation, to obtain the resultant exceedance curves of $\omega_i = f(p)$.

We divide the selected size of the over-year component of the storage capacity $V_z^{v'}$ into $(n - 2)$ parts (they should be of the same size) and determine the mean V_k values in the respective intervals; the total number n is made up by $V_k = 0$ and $V_k = V_z^{v'}$.

Then for all possible combinations of inflow volumes π_i, initial filling of a reservoir $V_{k,\text{init.}}$ and final filling $V_{k,\text{end}}$ the probability of exceeding the release volume from a reservoir $\omega = \pi_i + V_{k,\text{init.}} - V_{k,\text{end}}$, can be read from the conditional exceedance curves of $\omega_i = f(p)$. After multiplying these probabilities by the corresponding width of intervals Δp_i of the respective mean values π_i, and after adding the obtained values for all pairs $V_{k,\text{init.}}$, $V_{k,\text{end}}$, the conditional probabilities of exceeding the volumes of water stored in the storage capacity at the turn of two years are obtained, i.e., the coefficients of the matrix of transition $\mathbf{A}$, see equation (5.14).

The following steps are the same as for direct withdrawal from a reservoir. The result is the exceedance curve of the water volumes in a reservoir, which for $V_k = 0$ give the reliability of water supply.

By repeating the calculations for several $V_z^{v'}$ values, the relationship $V_z^{v'} = f(p)$ is reached, from which it is possible to determine, for the design reliability, the resultant value V_z^v. In calculating the seasonal component, the principles are the same as for direct withdrawal from a reservoir (Section 5.1.2); however, the non-uniform release from a reservoir in the course of a year and the variability of annual release volumes must be taken into account.

The method described above is rather time-consuming and requires a computer (with the exception of some stages).

For preliminary studies it is not always possible to use these complicated methods. It is more expedient to make use of the similarity of river flow regulation and release control for an augmented withdrawal O_p from a hypothetical reservoir with an over-year cycle, placed at the withdrawal point. With a given O_p, the storage capacity of the compensation reservoir (river flow regulation) as well as the storage capacity of the hypothetical reservoir (direct withdrawal O_p from a reservoir—usually for complete reliability in the given observation period), are determined in real time series. Then the over-year component of the storage capacity of a hypothetical reservoir is determined for the design reliability P from graphs, using the known statistical characteristics and correlation function as well as the over-year component V_z^v in real time series. The size of the storage capacity of a reservoir with a compensating regime is then corrected according to the ratio of both over-year components of the hypothetical reservoir.

This approximate procedure is more reliable than calculations in real discharge series.

8.4 REAL OPERATION FOR RIVER FLOW REGULATION AND ITS CONSEQUENCES

For river flow regulation operations, short-term discharge forecasts at the withdrawal site, i.e., inflow from the interbasin (introductory part of Chap. 8), must be applied.

The significance of real manipulations with river flow regulation increases with the distance of the withdrawal site from a reservoir and thus with the increasing size of the interbasin and the ratio of the mean discharges from the interbasin and the reservoir catchment. The discharge-travel time τ from a reservoir is given by the distance of the withdrawal site. If the distance is great, water losses caused by incorrect flow regulation can play an important role in the total balance.

As one case differs from another, it is rather difficult to give any general instructions as to how to include operation losses in the design of the storage capacity. However, the general method based on the analysis of the most important facts described below can also be used in other cases, especially if the withdrawal site is at a great distance from the reservoir.

A basic condition of short-term discharge forecasts from an interbasin, in terms of which the release from a reservoir O_K is determined, is that the forecast values must be reliable. When water is withdrawn from a stream, an augmented discharge must be ensured at the withdrawal site $Q'_O \geqq O_p$ (within the range of the design water supply reliability). It is therefore essential for discharge forecasts from an interbasin that forecast values Q_M should be smaller than (or equal to) real values. The forecast of relatively low discharges from an interbasin is important; for higher discharges ($Q_M > O_p$) it will be sufficient to forecast their occurrence, regardless of their size.

An absolute forecast reliability would lead to disproportionate increase of unused release and therefore to a large storage capacity. It can be presumed that users will be able to handle short-term fluctuations in water supply. Another reserve can be a minimum guaranteed discharge downstream of the withdrawal site.

For buffer-storage reservoirs at the withdrawal site, the forecast rules can be less strict, as an overestimation of the inflow from an interbasin does not increase the danger of water supply failure.

Time factor of forecast is given by the discharge-travel time τ and depends on the initial forecast information, on the time necessary to evaluate this information and on the adaptability of operation. The main source of information will be data on the discharge at the discharge-gauging sites in the catchment. The inflow to a reservoir and the discharge at the withdrawal site will be studied (or the inflow to a buffer-storage reservoir). Information about precipitations, temperature, etc., can supplement the basic information, especially when assessing the development of the discharges.

One of the simplest methods is the forecast of the discharge from an interbasin Q_M in time t, in terms of the inflow to a reservoir Q_K in time $(t - \tau)$. This method is suitable for not too great a distance of the withdrawal site and a close relationship of $Q_M(t) = f[Q_K(t - \tau)]$.

When the withdrawal site is at a great distance, this type of forecast is unreliable (as the conditions differ in the reservoir catchment and the interbasin). In this case forecasts based on the inflow from the interbasin should be used. Value O_M is obtained as the difference between the flow at the withdrawal site and the release from a reservoir at time preceded by the discharge-travel time τ.

On the basis of information from the two main gauging sites, a combined forecast method can be used.

Deficits of water and losses caused by operation are further given by the time during which release from the reservoir stays unchanged. This could require forecasts and operation changes within the shortest possible time intervals. If the distance between a reservoir and a withdrawal site is very great this kind of operation is unsuitable, not only because it causes practical difficulties, but because it can violate the "regulation stability" due to hydrodynamic factors in the stream channel.

The risk of failure can be made smaller by changing the forecast technology to the benefit of reliability, however, at the cost of greater water losses.

The greater the relative yield, the smaller the relative size of operation losses. The influence of the higher relative yield is reflected in the duration of the emptying period and in the days when the forecast value O_M is greater than the difference $(O_p - Q_z)$, which is rather rare.

It is rather difficult to evaluate *short-term failures of water supply caused by operation.* From the balance point of view they are not actually failures, as the unavailable water volume remains in the reservoir and, after determining a water supply shortage, can be utilized at any time. As compared to these failures, operation losses mean a real loss of water from a reservoir, for which the size of the storage capacity must be increased. As these losses can be extensive, they should, for economic reasons, be estimated most reliably. If the river flow regulation is to be calculated in mean monthly discharge series, the relationship between the values of mean monthly discharges and the respective mean monthly operation losses must be taken into account.

In real series of mean daily discharges, direct calculations are made, bearing in mind the proposed forecast method, which make it possible to determine the mean operation losses in each month. It is then possible, presuming an indirect linear correlation relationship between the mean monthly inflow to a reservoir Q_K and mean monthly operation losses, to construct conditional exceedance curves of these losses (valid for any month of a year or for selected periods) and, simultaneously with the modelling of synthetic series of mean monthly discharges, to model a parallel time series of mean operation losses. In the final solution, the thus determined water losses from a reservoir, are considered as part of the release.

It can be expected that during reservoir operations these losses will be smaller than presumed by the original project, mainly as a result of experience, better forecasting methods, etc. The increased augmented discharge O_p will cover water demands for a longer period of time than presumed by the project.

A very effective means of limiting water losses or failures to supply water due to operation is a *buffer-storage reservoir at the withdrawal site* (Chap. 7).

Let us consider a buffer-storage reservoir with a working volume V_n, in which part ΔV_p is to cover operation failures and part ΔV_z to limit operation water losses ($V_n = \Delta V_p + \Delta V_z$). The basic working stage of such a reservoir is the filled volume ΔV_p and the empty volume ΔV_z. During operations the discharge forecasts from the interbasin are taken into consideration, as well as the volume in the buffer-storage reservoir. The supplementary inflow ΔQ, determined from the filling of volume $\Delta V_z(+)$ at the forecast moment (presuming an equal distribution throughout the period between the respective operation intervals), or from the emptying of volume $\Delta V_p(-)$, is added algebraically to the forecast value Q_M. The corrected values $(Q_M + \Delta Q)$ are then used to determine the release from a reservoir O_K ($\geqq Q_z$). If we were to design the working volume of a buffer-storage reservoir $V_n = \Delta V_p + \Delta V_z$ as equal to the sum of the greatest determined plus and minus deviations of the forecast discharges Q_M from reality (in the sphere where the forecast of values Q_M influences the release from a reservoir O_K), we would eliminate water supply failures and operation losses. Such demands on the buffer-storage reservoir as far as water losses are concerned would, however, be too strict. It would be better to choose several values of V_n, to carry out calculations in discharge series and derive from them the relationships between the size of volume V_n, or its parts ΔV_p and ΔV_z, and the frequency and depth of water supply deficits or the volume of operation water losses. The size of the buffer-storage reservoir can then be determined by an economic analysis.

This method was used in the Water Resources Development and Construction Institute in Prague (Votruba Jr., 1975). Data on various sizes of main and buffer-storage reservoirs were fed into a computer. The basis was a two-day advance discharge forecast from an interbasin. After assessing the real operations of the system, a simulation solution in real series of mean daily discharges for 1931 to 1970 was used.

An analysis of river flow regulation showed that water-management operations can have a great impact on the reservoir design parameters, because of operation water losses, which are extensive especially if the distance between the reservoir and the withdrawal site is great. For great distances, a buffer-storage reservoir at the withdrawal site (or in the system of the user) is indispensible, as such a reservoir can remedy the consequences of imperfect operation (caused by inaccurate discharge forecasts) much more effectively than supplementary capacity in the main reservoir.

There are, however, further reasons for a buffer-storage reservoir such as variability of discharge-travel time, hydrodynamic phenomena in the stream channel, random concentration of increased small withdrawals on the route between a reservoir and the withdrawal site, operation of weirs, etc.

The theoretical size of the storage capacity of the main reservoir must be increased by the volume necessary to cover further water losses from it (mainly by evaporation from the water level) or to eliminate any errors resulting from mean monthly discharge series (if they are not already included in the estimate of operation losses). The procedure is analogous to that for direct withdrawal from a reservoir with an over-year or within year release control (Chaps. 5 and 6).

In river-flow regulation, operation losses are only an additional factor which can make the solution less accurate. The danger of any distortions due to the initial real discharge series or any other factor is the same as that which can arise in over-year or within-year discharge control with direct withdrawal (Sections 5.3, 6.4).