13 RULES FOR RELEASE CONTROL FROM RESERVOIRS IN DAY-TO-DAY OPERATION

The control of the outflow from a given reservoir at any water stage, at different flow rates, etc., is given by the operation rules, schedules and guides. These documents must be discussed and approved by the respective water-management bodies.

From the point of view of reservoir function, the most important part of the operation rules is that dealing with the effective use of water and the operation during floods.

It includes instructions for the use of water under normal conditions (within the given reliability range of the storage function), with steady storage, for emptying and filling, and for maintaining the proper water level; instructions for the operation during floods; and other principles, including provisions for cooperation with other reservoirs.

Besides these rules, which mainly concern the quantitative aspects of the proper use of water, the operation rules also include provisions which deal, e.g., with the water quality, with sediments, the flow in winter, cooperation with flood warning service and other exceptional events.

The design documentation consisting of the results of the calculations for a reservoir, of the respective economic aspect and the draft operation rules, form the input data for the operation rules and schedules. All these data have to be assessed and "brought up to date", as several years will have passed between the design stage and the elaboration of these rules.

Any operations of a reservoir should be based on a rule curve (table) which would clearly and explicitly determine the release. There can be several curves, each with a specific validity.

One of the basic obstacles for the optimum utilization of a reservoir is the lack of advance information about the future inflow (according to a reservoir cycle). In this respect the day-to-day operation of a reservoir essentially differs from the technical simulation. Flow forecasts can be used only to a limited extent (usually only for a few days ahead). Therefore, information about the flow time-behaviour is analysed and used to determine the rules for the discharge control which, regardless of forecasts makes it possible to make the best use of a reservoir. These rules can be presented in the form of curves or tables.

No rule curve is needed for very simple reservoir operation when, e.g., the storage capacity is not completely full and release from the reservoir = O_p (constant or variable in the course of the year); also with a full storage capacity $O = Q$ (as well as with a completely empty storage capacity, i.e., during a failure). Such operations coincide with the reservoir parameters; however, with the exception of very low-flow periods they do not make full use of the reservoir's possibilities to regulate the flow. Dispatching control of the discharge is therefore expedient for all reservoirs, in which it is useful from the point of view of the conservation and flood-control function or operational conditions (head, maintaning a higher or lower reservoir water level at certain times of the year etc.).

13.1 RULE CURVES AND THEIR CONSTRUCTION

Most frequently, a rule curve is constructed, based on the dependence of the required volumes of water (or water levels) on time during the year (Fig. 13.1a). In the simplest case, from the point of view of the storage function of the reservoir, this dependence limits the area in which only O_p must be released (or less during failures in water supply). Only if a reservoir has the storage volume $V > V_d$ it is possible to withdraw $O > O_p$. The rule curve does not determine to what extent the release can be increased. More advantageous therefore is the rule curve in Fig. 13.1b which, depending on the amount of water in a reservoir and on time, determines the amount that can be released.

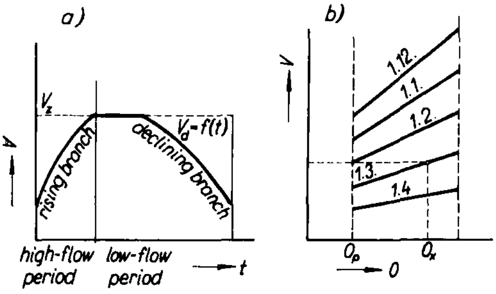

Fig. 13.1 Rule curves

A rule curve can be constructed if the inflows to the reservoir in years with very low-flow periods (close to the design interval) have an at least approximately identical time pattern. Of importance is the time of the high-flow and low-flow periods which should be identical in all the years. The existence of an annual flow cycle is a basic condition for the construction of a rule curve and therefore a dispatching control of the outflow is effective mainly for reservoirs where the filling and emptying cycle does not exceed the limit of one year (water-management year), regardless of whether it is a direct release, regulated flow of the river or a reservoir in a system. The possibilities are significantly smaller for over-year flow control; this is the result of the random character of the chronological sequencing of the mean annual flows.

The more regular the annual flow cycle, the more accurate the rule curve. For a simple hydrological regime the rule curve defines, besides the basic relation $V_d = f(t)$ which is often defined for the safe yield (Fig. 13.1a), different zones divided by further lines. From the point of view of the storage function, curves of reduced releases should be plotted and in the area of values higher than Q_d, an "anti-overflow" curve should be plotted (Fig. 13.2). Further details and principles concerning the construction of these curves are given, e.g., by Votruba and Broža (1966, p. 260) where further references can be found.

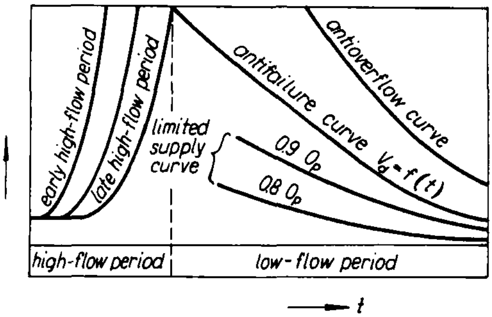

Fig. 13.2 Rule curve with a simple rate of discharge changes during the year

In the complicated hydrological conditions pertaining e.g. in Czechoslovakia, the construction of a safe rule curve is a very demanding task. It is especially difficult to determine the boundaries of the high-flow and low-flow periods. Studies of the latter showed, e.g., that their end can coincide roughly with the end of September until the middle of March, which is an almost six-month interval. Great differences can also be observed in the "spring" high-flow periods. However, in spite of this, the flow regime of the Czechoslovak rivers is cyclic to such an extent that it is still effective to use the dispatching control.

The complex time pattern required for storage volumes is the reason why the chronological flow series should be used for the construction of the rule curve. If we bear in mind that the real series are not even long enough to assess a reservoir's basic parameters (α, β_z, P) satisfactorily, then they will certainly not suffice to determine the filling and emptying of the storage volume. It is therefore essential to use sufficiently long synthetic flow series reflecting the flow variability during the course of the year. Only if absolutely unavoidable the real flow series can be used; however, the specific traits of the respective low-flow periods must be excluded, which can be done, e.g., by transferring the flows of significant low-flow periods to design conditions and including a certain margin up to the values of the required storage volumes V_d.

Method of constructing a rule curve from sufficiently long synthetic series: those years in which the demanded theoretical size of the storage volume is greater than the design value should be excluded. These years are failure-years as far as the design measure of release is concerned; these failures are planned and are therefore not taken into consideration in the construction of a rule curve.

Another point that must be considered is that at the end of every low-flow period the storage capacity should just have been depleted.

The "known" rate of inflow to a reservoir during the given simulated series of mean monthly flows and the demanded yield (release O_p) are used as a basis.

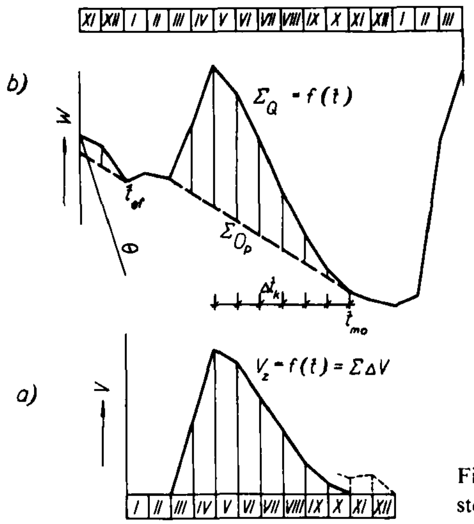

Fig. 13.3 Determination of the necessary storage volumes during the year

One should proceed from the end of the low-flow period (in time t_{lf}), when $Q < O_p$ (Fig. 13.3). In the last time interval Δt_k, the water volume which has to be supplemented from a reservoir to ensure a release O_p has to be calculated:

$$\Delta V_k = (O_{p,k} - Q_k)\,\Delta t_k \tag{13.1}$$

The storage volume must therefore be equal to ΔV_k in time $(t_{lf} - \Delta t_k)$. Similarly, in time $(t_{lf} - \Delta t_k - \Delta t_j)$ the storage volume must be $(\Delta V_j + \Delta V_k)$, where $\Delta V_j =$ $= (O_{p,j} - Q_j)\,\Delta t_j$, etc. Calculations continue until the moment when $\sum \Delta V \leqq 0$.

The method is shown in the form of a diagraph in Fig. 13.3a, where the storage volumes $\sum \Delta V$ needed to ensure the demanded O_p are plotted for one water-management year. Figure 13.3b shows numerical calculations (indispensable if synthetic series are used) with the help of inflow and release mass curves. The differences between ordinates $\sum Q$ and $\sum O_p$ give the $\sum \Delta V$ values.

The upper envelope of all $\sum \Delta V = f(t)$ curves corresponding to the respective water-management years of the synthetic series is the limit, above which it is possible to pass on to greater releases from a reservoir with $Q_d > O_p$ without the risk of an unplanned failure. On the other hand, if the water volume in the storage capacity is smaller on the given date than is determined by the envelope, only O_p can be released. In view of the complicated hydrological conditions, no failure in water supply usually occurs even in this case. The upper envelope of the $\sum \Delta V$ curves can be defined as the basic rule curve $V_d = f(t)$ which divides the zone of increased supply; this zone must be defined for increased releases from a reservoir during high-flow periods.

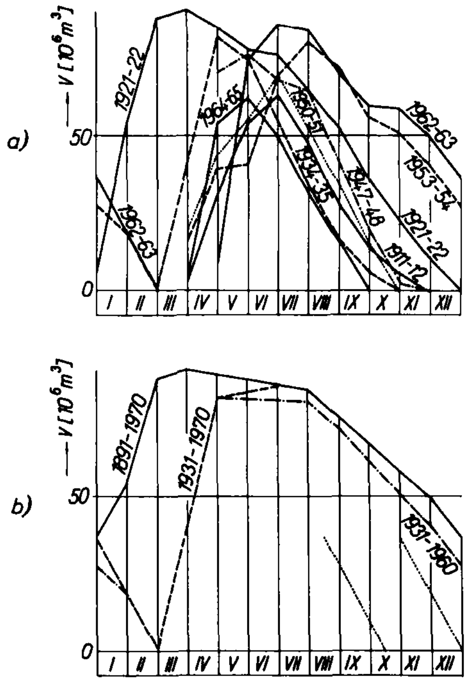

Fig. 13.4 Construction of base rule curve in complicated discharge conditions

This method was used for the construction of the basic rule curve in Fig. 13.4b. The basis for this curve was a flow series of 80 years (Berounka – Křivoklát, 1891–1970), which can be conceived as a certain section of a random series. Figure 13.4a shows the time pattern of the necessary storage volume in the respective low-flow periods, which differ greatly in time as to the commencement and termination of the low-flow and high-flow periods. The upper envelope of the determined necessary storage volumes (Fig. 13.4b) is the rule curve sought bearing in mind, however, the limited length of the flow series.

From Fig. 13.4b it is possible to notice the danger of constructing the rule curve directly from real flow series that have only a limited duration of observations. If a curve were constructed from the period 1931–1970, or 1931–1960, the upper envelope (dash or dot-and-dash) would allow for an extensive emptying of the storage capacity at the end of February. In a very low-flow period (1921–1922) the consequences of regulating releases according to such a rule curve would be very unfavourable. The low flow in the spring months would not be sufficient even partly to supplement the water supply in a reservoir (on April 1st, the volume would be only $4.5 \cdot 10^6$ m^3) and a failure to supply water would last from the beginning of May until the end of the year; the extent of the failure would also be significant. Even though the flow distribution of that year is not typical, it must be taken into consideration for the impact of its consequences.

The above example proves the significance of the variability in time of the occurrence of high-flow periods in the construction of rule curve. It has to be taken into account particularly if the yield approaches the fuzzy boundary between the within- and over-year release control. This example also explains the reason why synthetic series should be used that give a broader choice of the flow behaviour in time than the observed series.

For the construction of a rule curve the theoretical size of the storage capacity is usually considered, which generally differs from the design value. The theoretical ordinates of the curve should therefore be corrected in such a way that the maximum storage volume would be identical to the real volume of the storage capacity. The simplest way to do this is by a proportional increase of the theoretical values by the coefficient

$$\xi = \frac{V_z(\text{des.})}{V_z(\text{theor.})}.$$

Operation governed by this rule curve, compiled in this way, depends on the purpose or the method of utilization.

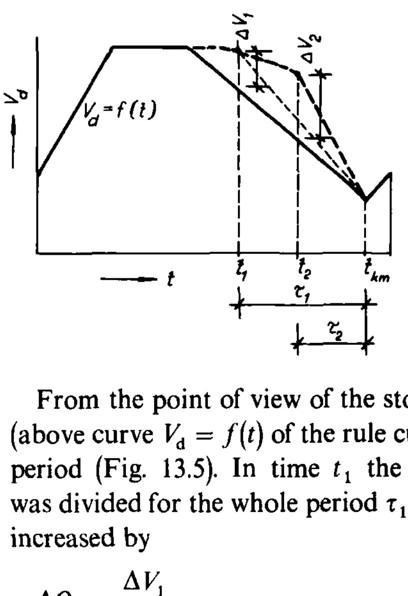

Fig. 13.5 Operation based on the rule curve when the storage volumes given by this curve are exceeded

From the point of view of the storage function, the water surplus in the reservoir (above curve $V_d = f(t)$ of the rule curve) is used evenly up to the end of the low-flow period (Fig. 13.5). In time t_1 the surplus volume was $\Delta V_1 = V_{re,1} - V_{d,1}$, which was divided for the whole period $\tau_1 = t_{km} - t_1$ so that the release from the reservoir increased by

$$\Delta O_1 = \frac{\Delta V_1}{\tau_1} \tag{13.2}$$

and reached the value $O(\tau_1) = O_p + \Delta O_1$. At moment t_2 the surplus was $\Delta V_2 = V_{re,2} - V_{d,2}$ and after calculations for the rest of the low-flow period $\tau_2 = t_{km} - t_2$, the release could be changed to $O(\tau_2) = O_p + \Delta O_2$, etc.

If there is no special need for these more detailed operations, it is possible to release the largest useful (usable) amount O_o from the real storage volume ($V_{re} > V_d$);

as soon as the surplus value is used up ($V_{re} = V_d$), the release is changed to O_p (two-stage release control).

In complicated hydrological conditions the storage volume frequently drops below the values prescribed by the rule curve. This drawdown, however, need not cause a failure in water supply and it is possible to continue to release O_p with only a small risk. As the design reliability is always less than 100% (for a within-year flow control usually up to 97%; occurrence-based), a failure to supply water might occur. It is most important to become aware of such a danger in time, but this is rather difficult for reasons of the complicated flow regime in some rivers.

Of certain help can be an analysis of the time pattern of emptying of the reservoir at the end of the low-flow period and the determining of the storage volume which signals the danger of a failure in the water supply. The example in Fig. 13.4 can serve as an illustration. Let us presume that with an irregular flow rate there is only a short period in which preventive measures can be introduced to control any failures in water supply; this period might be, e.g., two months. From the pattern of outflow from the reservoir at the end of the low-flow period (Fig. 13.4a), it is clear that the greatest demand on the storage volume of the reservoir two months prior to complete emptying is $37 \cdot 10^6\ m^3$ (this happens to be the same as the minimum given by rule curve). This value can be accepted regardless of whether the low-flow period comes early or late (it need, however, not be the same). As soon as, roughly from the middle of July to the beginning of January, the storage volume drops below this value, operation prescribed for this case must be introduced. The further depletion of the reservoir must be systematically assessed with the help of the control curve—which is the dotted curve in Fig. 13.4b—reflecting the most intensive possible emptying of the reservoir at the end of the low-flow period. This curve is independent of time within the interval in which it is real.

The basic measure to abate the consequences of a failure to supply water is to reduce the releases from a reservoir in time; this means that although the period of failure is prolonged (if as a failure we consider any withdrawal below the value O_p), a complete breakdown of supply, i.e., when the storage area is completely empty and release equals inflow, can be avoided. In the case studied, water-saving measures can be started two months in advance. If the water in the storage volume decreases below $37 \cdot 10^6\ m^3$ with a withdrawal $O = O_p$, the whole deficit ΔV_1 is divided over the whole two-month period (τ_1) so that release from the reservoir O_{r1} will equal

$$O_{r1} = O_p - \frac{\Delta V_1}{\tau_1} \tag{13.3}$$

At a later stage (e.g., after 2 weeks) the deficit ΔV_2 (Fig. 13.6) is distributed over the remaining time τ_2 of the presumed low-flow period and therefore

$$O_{r2} = O_p - \frac{\Delta V_2}{\tau_2} \tag{13.4}$$

In applying this method, the storage volume can exceed the value of the control curve (in Fig. 13.6 by the value ΔV_3 in time t_3). For reservoir operations this is a sign of a certain improvement of the critical situation; however, care should continue to be taken. In this case it is better to permit a safe yield of O_p and to presume that further emptying of the reservoir will continue according to the control curve transferred in time by the interval Δt which is given by the storage volume in time t_3.

Short-term flow forecasts, e.g., according to the recession curves (Buchtele and Hladký, 1976) can be of help in decision making in such cases and improve the operation.

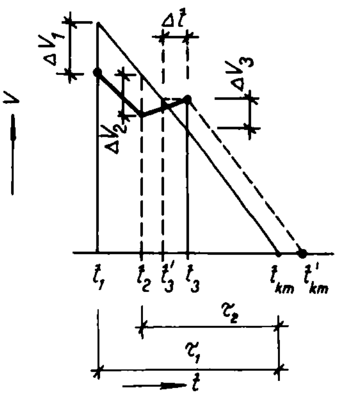

Fig. 13.6 Operation based on the control curve of the rule curve when there is a threat of a failure in the water supply

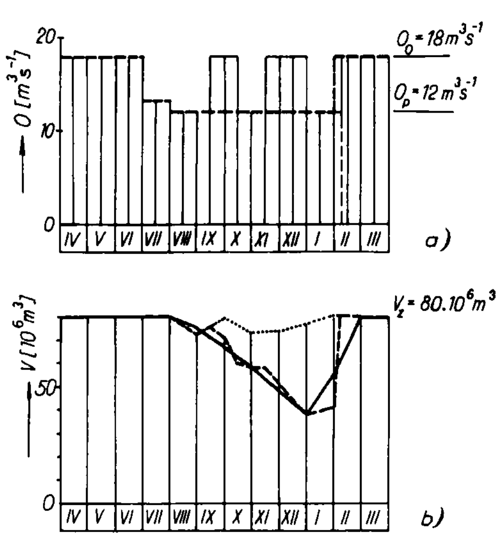

Fig. 13.7 Effect of operation rules with two-stage manipulations (........ control for O_p; ---- rule curve) ▶

When evaluating the contribution of the rule curve for the supply function according to the rule curve in complicated hydrological conditions it is necessary to bear in mind that the water supply benefit, as compared with the control of the safe yield, will not be very expressive.

In high-flow years, or periods, an increased release from a reservoir can be ensured without a rule curve; on the other hand, the fact that low-flow and high-flow periods can occur at different times greatly reduces the advantages of control according to the rule curve.

Figure 13.7a compares the release from a reservoir in an average year, presuming that the release can be 50% greater than O_p both for normal operations of release (constant throughout the year) and for two-stage operations according to the rule curve (Fig. 13.7b). As a result of the rule curve an increased release can be ensured for roughly two months longer than when applying a constant O_p. This is ensured by the better utilization of the reservoir storage capacity (compare the time behaviour of the storage volume shown by the dashed and the doted curves).

If increased release due to the rule curve cannot be utilized effectively, there is no point in constructing this curve. However, as this method of outflow control ensures that every year the reservoir storage volume is decreased slightly, it also helps to increase the reservoir flood control function (Chap. 12), which is always useful.

13.2 FAILURES IN WATER SUPPLY

If the designed water supply reliability is less than 100%, certain failures are admissible, i.e., the release can be less than planned. However, this reliability only applies to a reservoir (i.e., the water source), not to the whole system up to the place where the water is used. It does not include failures in the devices for water release and transport (pumping stations, pipelines, etc.), failures in the reserves, etc., which are of importance to the operator.

As the design reliability is a technico-economical issue (Section 4.4), standards frequently have to be used for lack of economic data. However, even with this lack of data any significant failures in water supply should be assessed and remedies introduced. The principle of a timely reduction of releases, thus controlling the extent of the failure in water supply mentioned in the previous section, can be applied in different ways by different users; in certain cases other measures can be more expedient.

Using synthetic flow series of sufficient length, a certain number of failure periods are also obtained and these can be applied to operation principles in those periods in which a water supply failure might occur. These principles should be elaborated with the participation of the water users (consumers), as this is the only way to minimize the consequences of failures (economic, political, sanitary, etc.). As it is difficult to assess the duration and extent of the failures in advance, the principles should be of a general type and measures should be introduced successively (reduction of water supply, use of reserves, etc.). Only recently has research begun to tackle these problems.

13.3 RESERVOIR OPERATION DURING FLOODS

Operation methods to control floods must include floods with any probability of exceedance and all real operational stages of a reservoir, including any breakdowns of water-diverting devices.

The most important task is to ensure the planned flood-protection function of a reservoir. The complex concept of controlled outflow during floods (Chaps. 11 and

12) should include calculations for the protective function of a reservoir, including floods which exceed the design reliability.

The draft of operation determines when and where the respective reservoir devices should be used to control the flood flows. It must also be determined to whom the flood operation, the increasing flood danger, and other data should be reported. This is absolutely vital as every reservoir forms part of flood-control plans.

13.4 DAY-TO-DAY OPERATION AND OVER-YEAR RESERVOIR CYCLES

The essentially random character of the time sequence of the mean annual flows makes it impossible to use the whole volume of the storage capacity for the efficient use of water.

The operation rules can be applied only when the storage area is almost full, or at times when water supply failures might occur; but in spite of that, a rule curve is useful as it can be used for roughly one-third to one-half of a reservoir's operation time (depending on relative yield α (see Chap. 5)). We outline here the method that makes it possible to exploit the advantage of operating rules for over-year reservoirs.

In constructing the basic curve of the rule curve, using a verified synthetic flow series of sufficient length, the years with average flow $Q_r \geqq O_p$ apply in isolation, and the years with $Q_r < O_p$ as the initial years of the over-year low-flow period. For safety reasons, the maximum emptying according to the rule curve should not exceed the value given by the difference between the total storage capacity $V_z(P)$ and the over-year storage component $V_z^v(P)$ with the design reliability P, even though in real operations the two parts (that can be used only for theoretical calculations) are mutually exchangeable. In practice, it is possible to determine the value V_z^s given by calculations in the years with $Q_r \geqq O_p$ and then, using the method described in Section 13.1, the upper envelope of necessary storage volume can be established. It then must be decided whether or not the years with $Q_r < O_p$, considered as the initial years in the framework of the over-year design period, require a greater storage volume. If this is the case, then the upper envelope of the required storage volume must be corrected and the basic rule curve is obtained.

At times when the storage capacity is almost empty, control curves can be used, which—as is the case for the within-year flow control—can contribute to a timely discovery of the approaching water supply failures. As the reservoir has an over-year cycle, analyses of the emptying of the reservoirs should cover a longer period than for within-year flow control (e.g., 4 months or more).

The difficulties connected with a better exploitation of reservoirs with over-year flow control initiated studies to help to solve this problem, at least for special cases when operation is constrained by further conditions. An original answer to the problem of increased release from an over-year reservoir at the time of a balance deficit, before a further reservoir with an over-year cycle is put into operation, was presented by Kubát (1976), as shown in Fig. 13.8.

The continuous development of the water demand is covered by the construction of resources in stages. Figure 13.8a shows that the need in time $(t_1 - t_2)$ was not fully covered because construction of reservoir B was started too late. During this period, release from reservoir A would be increased (Fig. 13.8b). After reservoir B starts operation (in time t_2), release from reservoir A would be decreased, thus "compensating" the increased release in the interval $(t_1 - t_2)$ without any harm to the planned storage function, including the sufficient supply of water (theoretically release can be decreased from moment t_2 till moment t_4).

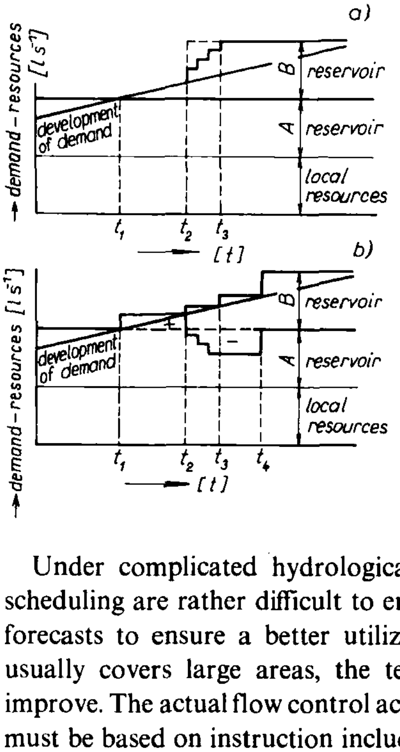

Fig. 13.8 Cooperation of over-year reservoirs operations to cover increasing demands

Under complicated hydrological conditions, the possibilities of the operating scheduling are rather difficult to ensure and attention is therefore also paid to flow forecasts to ensure a better utilization of a reservoir. As the water-management usually covers large areas, the technical facilities for forecasting also gradually improve. The actual flow control according to data supplied by the forecasting service must be based on instruction included in the operating rules and schedules.