12 THE FLOOD-CONTROL EFFECT OF RESERVOIRS

The function of flood-control release

$$f(O_{\mathrm{nd}}, V_{\mathrm{r}}, P) = O \qquad (12.1)$$

includes, similarly to the storage function, three variables

O_{nd} – non-damaging release from a reservoir during floods, constant or variable,
V_{r} – flood-control volume (need not be identical with the volume of the flood-control capacity).
P – reliability of flood control, usually expressed by the probable time of exceeding non-damaging discharges.

Three basic types of problems are related to these three variables, where two parameters are given and the third has to be determined; this is usually the size of the flood-control volume.

The necessary relationships can be constructed (according to what is given), by solving various alternatives, e.g.

$V_{\mathrm{r}} = f(P)$ for various O_{nd} values
$V_{\mathrm{r}} = f(O_{\mathrm{nd}})$ for various P values
$O_{\mathrm{nd}} = f(P)$ for various V_{r} values

12.1 ANALYSIS OF ISOLATED RESERVOIR FLOOD CONTROL EFFECT

For single-purpose flood-control reservoirs (which are today rather rare) it is sufficient to make a statistical estimation of the characteristics of the flood regime of a stream. Also for reservoirs with both a storage and a flood control function, when the flood-control effect of the storage capacity is either very small (e.g., for seasonal release control) or if hydrological data are not available for its determination, the flood-control function must be solved in isolation.

Method

In the curve of exceedance $W_{N,O_{\mathrm{nd}}} = f(P)$ giving the volumes of floods above the non-damaging discharge (Section 11.1.2) we can find the value $W_{N,O_{\mathrm{nd}}}$ corresponding to the selected (design) reliability of flood control; this is the sought size of the flood control volume of a reservoir V_{r} (Fig. 11.4).

The non-damaging release during floods need not be constant; however, uniform operating rules should be applied to all the floods in the sample of observations. If at various seasons of the year different sizes of non-damaging discharges are introduced, then it is expedient to divide the observed floods according to the date of their occurrence, to establish the respective samples of observations and to carry out the probability estimations separately. The flood-control storage capacity can vary during different seasons of the year.

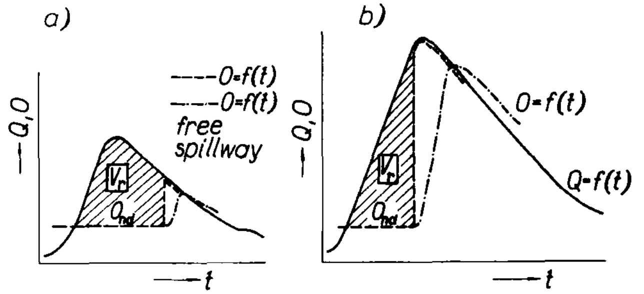

Fig. 12.1 Effect of the flood-control capacity of a reservoir on floods whose volume exceeds V_r

The flood-control volume V_r is not able to hinder the exceedance of a non-damaging discharge during floods, if their probability of exceedance (from the point of view of the volume) is smaller than the design rate of reliability; however, it is able to decrease the impact of the flood. Figure 12.1 shows the effect of V_r on floods with a volume $W_{N,O_{nd}} > V_r$. In the case in Fig. 12.1a the flood-control volume V_r was filled only after the maximum-peak discharge was reached, so that the flood-control measured not only decreased the volume of the flood wave, but also the maximum discharge. During the flood shown in Fig. 12.1b, the flood-control volume was filled already before the peak of the flood, so that the maximum release from the reservoir is identical with the maximum peak-flood discharge. However, even in this case the effect of the flood downstream of the reservoir is mitigated as at least part of the volume of the flood wave is held by the reservoir.

A sudden transition from the value O_{nd} to release equal to the inflow (Fig. 12.1) is possible only in reservoirs with a gated spillway. With an ungated spillway, the transformation effect of the uncontrolled volume (Section 11.2) appears after the filling of the flood-control volume, so that the release from the reservoir will be as shown by the dot-and-dash section.

12.2 HOW TO USE THE ACTIVE STORAGE CAPACITY FOR FLOOD CONTROL

A partly emptied storage capacity can either completely or partly catch the flood wave, thus taking part in the flood-control regime.

The storage capacity can be emptied partly, either automatically by the required withdrawals, or according to a plan with the aim of contributing to flood control as much as possible. However, the original function of the storage capacity must never be overlooked.

The cycle of emptying and filling of the storage capacity as well as the volume of emptying depends on the relative yield $\alpha = O_p/Q_a$ and therefore the automatic flood-control effect will also depend on this parameter.

When floods occur the following cases can arise:

(a) the flood wave flows into a full storage capacity (here and in the following text active storage capacity is often shortened to storage capacity); the maximum flood discharge is not decreased nor is any part of the flood volume held;

(b) the flood wave flows into a partly emptied storage capacity, which holds the wave:

– partly, however, before the maximum-peak discharge is reached, the storage capacity is again full so that the maximum discharge is not decreased,

– partly, however, the storage capacity is filled only after the maximum flood discharge is reached, which decreases the maximum of the flood,

– completely, so that the non-damaging discharge is not exceeded.

Quantitative calculations of the automatic flood-control effect of the active storage capacity were made by Brоža (1964). In a chronological discharge series (mean monthly discharges) for 1887–1940 at the Křivoklát site on the river Berounka, made more accurate at the time of floods by mean daily discharges (before and after the flood), and by detailed time recordings of the floods, the storage function was determined. At the time of the occurrence of floods it was taken into consideration how full the storage capacity was and the effect of the storage capacity on the maximum flood discharge and on the flood volume. Figure 12.2 shows a case in which the storage capacity holds an essential part of the volume ΔV_{pn} of the flood wave and the decreased maximum discharge Q'_{max}, the volume $W_{N,O_{nd}}$ that is not held exceeding the non-damaging release (hatched part). At the moment t_1 the partly emptied storage capacity was filled.

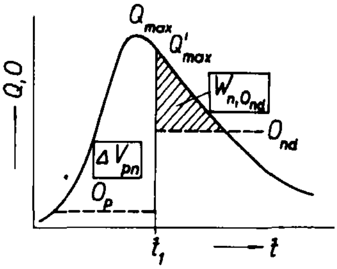

Fig. 12.2 Control effect of the storage capacity if a flood occurs immediately after a low-flow period (storage capacity not full)

The *flood-control effect of the active storage capacity* is the result of the combination of two phenomena of a random character: the occurrence of floods and the partial emptying of the storage capacity. The relationship of these two phenomena is in Central Europe a very loose one; a flood can occur, however full the storage capacity is. Therefore, the occurrence of floods and the rate at which these are held by the storage capacity can be considered as approximately independent. The solution is then simplified, as the probability of exceeding the flood characteristics (maximum-peak discharge, volume) influenced by the storage capacity P_z is given by the product

$$P_z = P(1 - p_z) \tag{12.2}$$

and the probable time of exceedance by the relationship

$$N_z = N \frac{1}{1 - p_z} \tag{12.3}$$

where P, N is the probability of exceedance, or the probable time of exceeding the characteristics of the original (uncontrolled) sample of floods,

p_z – probability of holding floods, i.e., the ratio of the number of floods held by the storage capacity and the total number of floods.

We can determine the number of floods which the storage capacity held completely during the period of observations. From the original curve of exceedance, e.g., volumes of floods, the curve of flood volume exceedance reduced by the control effect of the storage capacity is determined with the help of equations (12.2) or (12.3).

Figure 12.3 shows the exceedance curves of flood volumes above the value O_{nd} influenced by the active storage capacity determined at the Křivoklát site on the river Berounka for a 54-year period (1887–1940). The value of the non-damaging discharge was considered to be $O_{nd} = 350\,\mathrm{m^3\,s^{-1}}$, a constant yield was presumed; calculations were made for $\alpha = 0.3 - 0.95$.

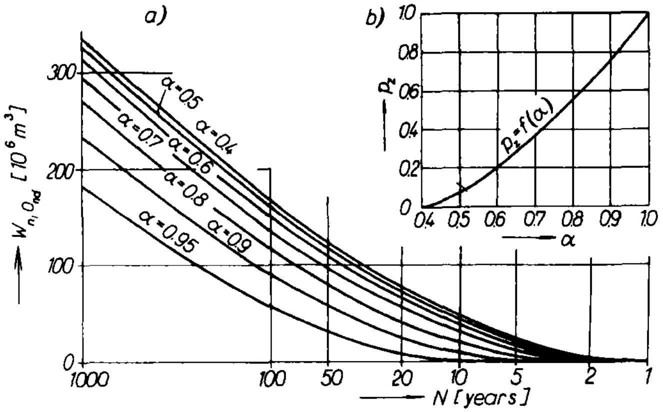

Fig. 12.3 Influence of the flood-control effect of the active storage capacity on the probable time of exceeding flood volumes $W_{N,O_{nd}}$ with a constant yield (α) (the river Berounka – Křivoklát)

With $\alpha \leqq 0.4$ the storage capacity did not show any flood-control effect. Only with very high relative yield ($\alpha \geqq 0.9$) did an automatic flood control with a roughly five-year reliability occur. With $\alpha = 1$ all floods should (theoretically) be held by the storage capacity.

Figure 12.3b shows the dependence of the probability of holding a flood in the active storage capacity P_z with a relative yield α.

The automatic control effect of the active storage capacity is relatively small. In reservoirs with an annual cycle it is practically nil; with over-year release control it is significant only for high values of α. However, it can still help the measures introduced to eliminate flood damages. For example, for Fig. 12.3 it is clear that with $\alpha = 0.8$ and the rate of flood control $N = 10$ years, bearing in mind the control effect of the storage capacity, the necessary size of the flood-control capacity (given by the value $W_{N,O_{nd}}$ – Fig. 12.2, 12.3) is smaller by 50% then the value V_r if the control function is solved independently.

The flood-control effect of the active storage capacity can be further increased by adequate operations of the reservoir. Rules for flood operation have to be determined in advance as part of the original design. To increase the flood-control effect of the storage capacity, operating rules (Chap. 13) and forecasts on the inflow to a reservoir should be available.

Partial drawdown of the active storage capacity according to operating schedules

The rule curve for the storage function of a reservoir usually determines the water volume in the storage capacity in relation to time; this is needed to ensure the planned withdrawal O_p with the required reliability. If the boundaries and durations of the low-flow periods differ greatly from year to year, then the rule curve is given by the upper envelope of the time behaviour of the necessary volumes in the storage capacity. If a rule curve is thus reliably constructed, the volume in a reservoir can drop below the prescribed value without causing a failure in water supply. However, if the rule curve allows it, the storage capacity can be partly emptied in certain periods, regardless of discharge conditions. The rule curve therefore determines the minimum values to which the storage capacity can be emptied during the year (difference between $V_z - V$) which can be used for flood control (Fig. 12.4). The size $(V_z - V)$ changes during the year and therefore the flood-control effect of the active storage capacity also changes. To what extent a rule curve can help flood control can be determined approximately by comparing the flood volumes $W_{r,O_{nd}}$ (considering the time of occurrence in a year), with the degree of the emptying of the storage capacity according to the rule curve (for the whole period of observation) and by determining the number of floods held by the storage capacity. For partly held floods, the volume that is not held and the maximum discharge must be determined. The effect of control according to a rule curve determined in this way is less favourable than in reality. A more accurate solution can be obtained by the simulation of release control in terms of the prescribed rule curve in a given discharge series (for the observation period).

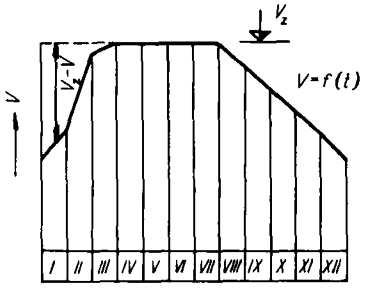

Fig. 12.4 Rule curve with within-year release control and how it can be applied to flood control

Reliability of flood control is determined as the mean time of exceeding O_{nd} by the relationship

$$N_{\mathrm{D}} = \frac{n'}{s}\,\frac{n}{n'} = \frac{n}{s} \tag{12.4}$$

where n' is the number of floods exceeding the harmless discharge during the observation period,

n – the duration of observation period (in years),

s – the number of floods, which are not held by the active storage capacity or only partly held.

The control effect of the storage capacity, when using a rule curve, can be expressed by exceedance curves of the parts of the flood volumes not held (above O_{nd}) and by the maximum flood discharges influenced by the storage capacity.

As according to the rule curve the storage capacity is emptied to different degrees during the year, and for several months the storage capacity is full (Fig. 12.4), the mean flood-control reliability for the whole year does not reflect the flood-control effect to a sufficient extent. The rule curve, for example, requires that the storage capacity be full during the growing period so that floods are held by a reservoir mainly at a time when they cause the least damage to agricultural products.

The probability of the occurrence of floods differs at different times of the year. It can be presumed that there exists a certain relationship between the frequency of floods in the respective periods and the rule curve (concentrated occurrence of floods in a certain period ensures, e.g., that the inflow to a reservoir is sufficiently large to refill the partly emptied storage capacity, etc.). It can therefore be recommended to estimate the contribution of release according to a rule curve separately for certain periods of a year (one or two periods are sufficient). The reliability of flood control will be generally different in the respective periods of a year. Other measures can be introduced to increase the flood-control effect of a reservoir, which can be effective throughout the year or in certain periods of a year.

No rule curve for the storage function of an over-year reservoir has as yet been elaborated. However, from the point of view of the flood-control function a rule curve can be constructed for an annual cycle as the upper envelope of the required seasonal components of the volume in the storage capacity; this makes it possible to partly empty the reservoir during the year without endangering the reliability of water supply. The advantages of this release control for the flood-control function can be observed in wet and average periods. The estimation of the flood-control effect of a reservoir can again be made by a simulation of the release control in a discharge series for the observation period (with statistical estimations), where the safe yield requirements (decisive mainly in the over-year low-flow periods) and the rule curve are applied.

The advantages of the operating schedules need not be applied to flood-control release only (Chap. 13). The demands of the storage and flood-control functions are usually antagonistic. While for the augmentation of discharges the surplus water is divided evenly throughout the low-flow period, for flood control the surplus volume is quickly emptied from the storage capacity to make the whole volume determined by the rule curve available for any flood that might occur. Power-plant reservoirs require the biggest possible head, especially in winter, which is again contradictory to the flood-control requirements. Priority is given to the purpose that brings the greatest benefits or is divided between the storage and flood-control functions.

On the basis of the operating schedules, the flood-control effect of the storage capacity can be increased without any discharge forecasts, as compared with the automatic effect due to flow augmentation to the required withdrawal O_p. For example using the partly emptied storage, determined by the rule curve (Fig. 12.4), for the holding of floods, with a seasonal release control for a safe yield O_p ($\alpha \doteq 0.38$), a two-year flood control was ensured (Votruba and Broža, 1974).

It is expedient to combine the operating schedules and other means that help to increase the flood-control function of the storage capacity, including discharge forecasts.

Emptying of the active storage capacity on the basis of discharge forecasts

In this case, the storage capacity is partly emptied just before the flood occurs. This method of flood-control release must be based on forecasts of the inflow to a reservoir (runoff from a catchment); their accuracy and how well in advance the information is received, determines the effect of the active storage capacity for flood-control purposes.

Let us consider a work regime of the storage capacity of a reservoir during a flood, based on data obtained from forecasting services (Fig. 12.5). It is presumed that prior to the flood the storage capacity is full, i.e., that release equals inflow (whereby $Q > O_p$). In time t_1 information is received that in time Δt (i.e., in time $t_2 = t_1 + \Delta t$) inflow to a reservoir will increase to the value Q_2 which exceeds the non-damaging release O_{nd} from the reservoir. The forecast can also include the expected tendencies of the flood. Release from a reservoir can be increased to value O_{nd} (Fig. 12.5 shows a marginal case, with a maximum emptying of V_z; however, release from a reservoir can be increased gradually), which empties the storage capacity by the volume ΔV_{pn}. This volume can then be used to hold the flood wave volume above the discharge $Q_x = O_{\text{nd}}$. Figure 12.5 illustrates a case in which the storage capacity holds only part of the flood wave volume above O_{nd}, the rest can be held in the flood-control capacity with the given flood control reliability.

Any hesitation that the supply function of a reservoir might be threatened can be eliminated by forecasts on the further development of a flood or by further data supplied by the forecasting service (in Fig. 12.5 in time $t_{n,1}$ for the moment $t_{n,2} = t_{n,1} + \Delta t$). However, an experienced operator can estimate the risk caused by excessive emptying of the storage capacity without any forecasts. In Fig. 12.5 the hatched section shows the development of the flood, where the forecast discharge Q_2 turned into a maximum peak discharge. From the moment t_2 the water volume $V_d = \sum[Q'(t) - O_p]\,\Delta t$ can be used to supplement the storage volume; in terms of the mutual relationship of volumes ΔV_{pn} and ΔV_d, suitable rules to be applied during floods can be proposed.

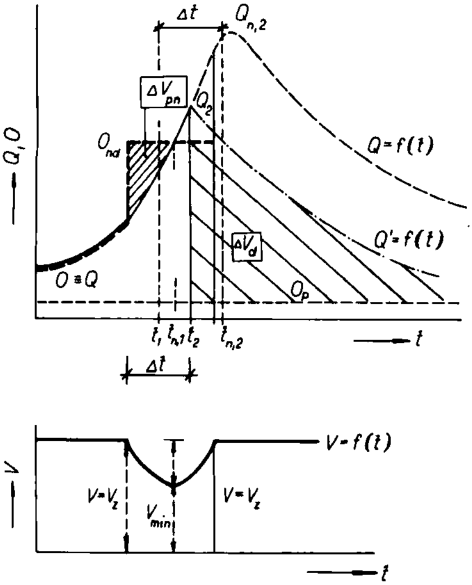

Fig. 12.5 Diagram of flood-control release using forecast data

To what extent the storage capacity can be emptied depends on how well in advance forecasts are received, on the increase of the discharge in time, on the size of the non-damaging release and other factors (e.g., the reliability of the forecast).

Forecasts should be received as far in advance as possible so that emptying can start at a time when the inflow to a reservoir has not yet greatly increased, making the emptying of the storage capacity more effective. The best available forecast is the forecast of discharges from precipitations in the catchment. As compared to discharge forecasts based on data from gauging sites upstream, where the time of the forecast is given by the discharge-travel time, precipitation forecasts include the time needed for the water particles of the catchment to reach the stream.

The operation rules often do not make it possible to introduce the complete value O_{nd} immediately. Time is needed to send the necessary information downstream. This time loss should, however, be as short as possible. Another possibility is to gradually increase the discharge; here too, however, the respective authorities have to be informed.

Operation rules must be chosen in accordance with the planned function of a multipurpose reservoir. The demand must be met that at the end of a flood the storage capacity be again filled to the level needed for its supply function. In the case in Fig. 12.6 the flood was overestimated and the volume $W_{O_{\mathrm{nd}}}$ was therefore not able to supplement the emptied part of the storage volume V_{pn}. However, this is still safe from the point of view of the storage function, as volume ΔV_{d} can be used to supplement the storage volume to the required level.

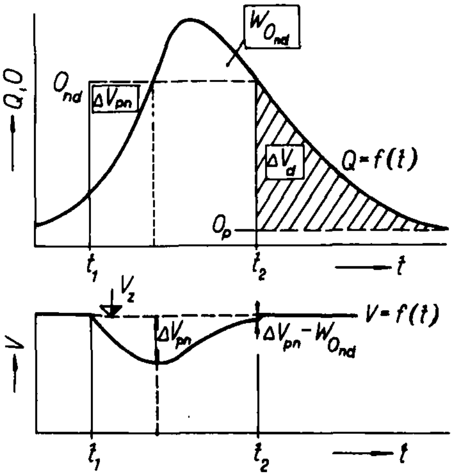

Fig. 12.6 Possibilities of filling up the storage volume when emptying of V_z is very high due to inaccurate forecast data

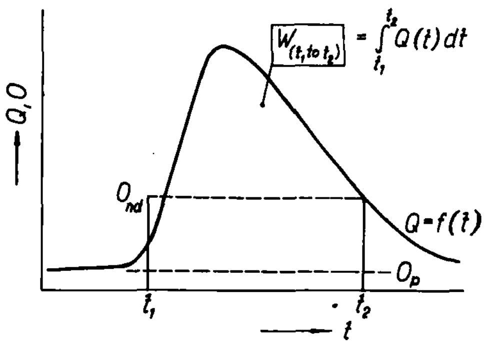

Fig. 12.7 Application of the forecast of flood inflow volume for flood-control release

Short-term forecasts of discharges can be based on data from water gauging stations in the catchment area if information is to be received a few days in advance.

Forecasts of the time behaviour of discharges based on a precipitation-runoff relationships have similar characteristics and are used mainly for reservoirs in smaller catchments.

If in the time interval (t_1, t_2) a flood volume $W_{(t_1 \div t_2)}$ is expected to flow into a reservoir, then the largest volume to be held by the reservoir is given approximately by the difference $W_{(t_1 \div t_2)} - O_{\mathrm{nd}}(t_2 - t_1)$, see Fig. 12.7. At the same time the greatest possible emptying of the storage capacity in interval (t_1, t_2) can be determined, given by the difference $W_{(t_1 \div t_2)} - O_{\mathrm{p}}(t_2 - t_1) - W_{\mathrm{b}}$, where W_{b} is the adequate safe reserve.

Seasonal forecasts can also be of use for flood-control release. In spring they are mainly forecasts of the runoff volume from snow supplies in the catchment, which make it possible to empty the storage capacity of a reservoir by the volume $W^{\mathrm{min}}_{(t_1 \div t_2)}$ −

$- O_p(t_2 - t_1)$ where $W^{\min}_{(t_1 \div t_2)}$ is the smallest expected inflow volume during the spring months. These forecasts are useful for catchments with large amounts of snow. In recent years, further methods of seasonal discharge forecasting, based on the analysis of historical discharge series considered as a stochastic process, have been developed (e.g., Anděl *et al.*, 1971; Buchtele, 1975). These forecasts could also be used to increase the flood-control effect of the storage capacity, especially in high-flow periods, when the discharge forecasts allow for the emptying of the storage capacity without any risk to its supply function.

To estimate the benefits of forecasts correctly a project should be elaborated, including all forecast relationships and other conditions. The effect of flood-control release is assessed for all catchments during the observation period in relation to the forecasts (simulation method). Statistical processing of the flood characteristics (volumes not held and a maximum release) gives a general idea about the contribution of forecasts to the increase of the flood-control effect of the storage capacity. Sometimes it is possible to determine only the number of floods, that are held by the storage capacity thanks to forecasts (O_{nd} is not exceeded); then the contribution of forecasts is characterized only by the probable time of exceeding the non-damaging discharge.

If various forecasting methods are used in one year, they should be estimated separately. To make the flood-control function of a reservoir as effective as possible we shall, as a rule, combine various measures enabling the use of the active storage capacity for this purpose: the automatic emptying of the storage capacity, operating

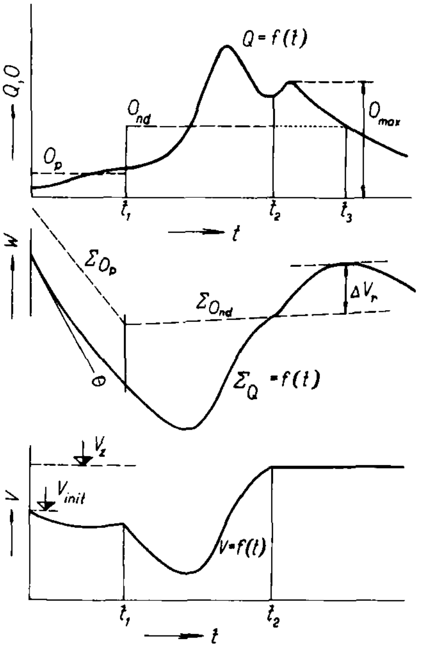

Fig. 12.8 Influence of active storage capacity on flood characteristics: determination of maximum release ($O_{\max}$) and uncontrolled parts of the flood volume (ΔV_r)

schedules and forecasts of all types. Any solution of such a complex case should include:

(a) the determination of the reliability of flood control,

(b) estimation of the probability of holding floods in the respective parts of a year,

(c) evaluation of the effect of the proposed measures on the floods which are not completely held by the storage capacity (O_{nd} is exceeded) (Fig. 12.8).

If the effect of the storage capacity is not sufficient according to the required reliability, another auxiliary capacity should be included in the reservoir. However, this does not necessarily mean that the total capacity has to be increased, causing further costs. If a reservoir includes a surcharge capacity (which is often the case in those on small streams with ungated spillways) it can at least partly be used for a more reliable flood control.

12.3 UTILIZATION OF THE SURCHARGE CAPACITY

The size of the surcharge capacity (throughout the book surcharge capacity is used instead of the longer term flood surcharge storage capacity) depends on the arrangement of the spillway devices and on the conditions for transferring the so-called design flood, which ensure the dam against overflow, regardless of the operations of the reservoir. A surcharge capacity can also be found in a reservoir with a controlled spillway, if the height of the spillway gate is smaller than the overflow height corresponding to the design flood (the capacity between the upper crest of the gate and the maximum water level of the reservoir).

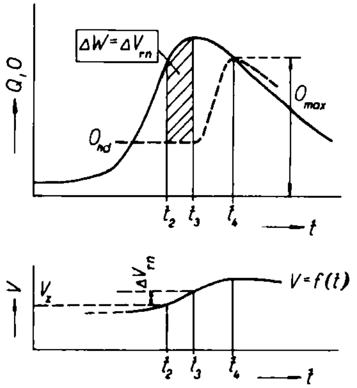

Fig. 12.9 Effect of surcharge reservoir capacity (with suitable operation) on the time pattern of the flood (release from the reservoir)

Part of the surcharge capacity can serve as flood-control capacity, as it can ensure a release of $O \leqq O_{nd}$. It is given by the discharge-rating curve that determines the spillway height h_{nd} which allows for the overflow of non-damaging release O_{nd} (Fig. 11.10). Up to that level it can be ensured that O_{nd} is not exceeded, by regulating the release through the outlets. To solve this problem the number of floods held by the capacity ΔV_{rn} during the observation period must be determined and the effect of the remaining part of the surcharge capacity on the floods that were not completely held must be estimated (Fig. 12.9). Time pattern of the floods influenced by the effect of the storage capacity is used as basic data. The volumes of inflow and release with a given Q and O must be "balanced" with the reservoir storage volume and the transformation of the time pattern of release, that is dependent on the water level of the reservoir, must be calculated (Section 11.2) (flood routing).

If the storage capacity and the respective part of the surcharge capacity ΔV_{rn} are not able to ensure the required rate of reliability, another capacity has to be designed (Fig. 12.10).

If the reservoir has a gated spillway, it is possible to make use of a part ΔV_r of the surcharge capacity to decrease the height of the gate (Fig. 12.11). This, however, does not increase the total volume of a reservoir.

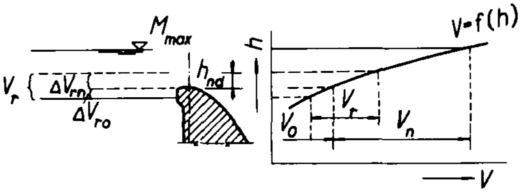

Fig. 12.10 Flood-control capacity and the surcharge reservoir capacity (design with a free spillway)

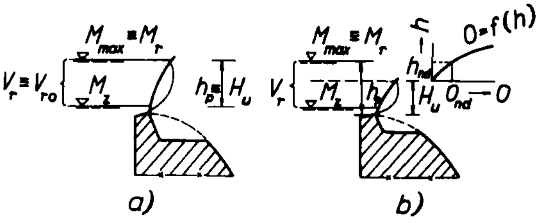

Fig. 12.11 Location on the flood-control capacity in the reservoir with a gated spillway and the possibility of lowering the height of the gate

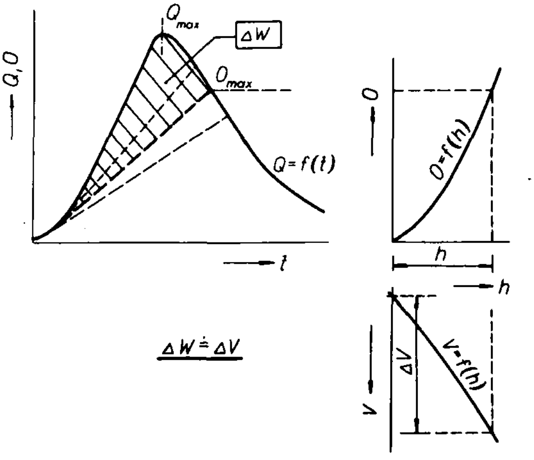

Fig. 12.12 An estimate of the transformation effect of the surcharge reservoir capacity

The surcharge capacity automatically decreases the maximum peak discharges of all floods. Figure 12.12 gives a comparison of the volume ΔW that has to be held in the surcharge capacity with a given release and of the volume ΔV, corresponding to the overflow height for a maximum release ($O_{\max}$). The two volumes should be approximately even ($\Delta W \doteq \Delta V$).

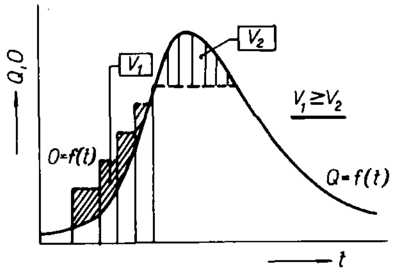

Fig. 12.13 Possibility of decreasing the maximum release by gradual closing of the bottom outlets (with ungated spillway)

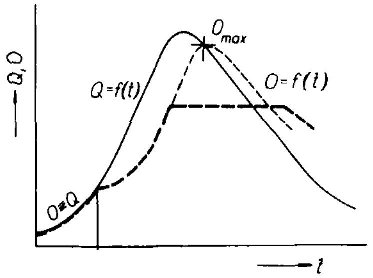

Fig. 12.14 Pre-emptying based on forecast data (with gated spillway) to catch the flood peak

With the help of discharge forecasts it is possible to increase the effect of the surcharge capacity on the maximum peak discharges. The simplest measure is step-by-step closing the lower outlets at the time when the maximum peak release from a reservoir is expected (Fig. 12.13).

Forecasts can be made better use of in reservoirs with a gated spillway, where a partial emptying of the storage capacity makes it possible to catch the "peak" of the flood wave and thus greatly decrease the maximum peak discharge (Fig. 12.14).

12.4 FLOOD ROUTING IN THE STREAM CHANNEL

For flood control the unsteady flow downstream from a reservoir must also be taken into consideration. Flood waves with a small probability of exceedance that are held only partly by a reservoir come into a stream as transformed discharge waves combined with the flood from interbasin. The conditions for the flood routing are different from those in the original (natural) streams.

Unsteady flow is one of the most complicated hydraulic phenomena. This problem was studied by mathematical models with the help of modern computer technology and verifications "*in situ*" e.g., by Gabriel (1975) and others.

12.5 FLOOD CONTROL AT THE TIME OF RESERVOIR CONSTRUCTION

When building a reservoir on a stream, the water (discharge) has to be diverted from the building site. For this purpose it is best to divide the construction period into stages and design the water-diversion facilities according to these stages.

As the dam grows, a storage capacity is created that can hold flood waves; this, however, represents a certain risk to the environment of the stream downstream of the dam.

The project for the diversion of water from the construction site must include, besides the protection of the construction itself, also the consequences caused by backwater during floods. Damage can also be caused in the inundation areas, but the greatest damages occur downstream of the dam. Measures and operation schedules therefore have to be implemented to control release from a reservoir under construction, bearing in mind that discharges can be greater than the design capacity of water-diversion conduits.