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CONTROL STRATEGIES, EFFICIENCY AND DESIGN OF BYPASS FLOOD-CONTROL RETENTION BASINS IN GERMANY

Markus Fischer[1], Ronald Haselsteiner[2]
1. Institute of Hydraulic Engineering and Water Resources Management, Technische Universitaet Muenchen, Germany
2. Fichtner GmbH & Co. KG, Germany

ABSTRACT: Presented paper concentrates on the possibility to retain water in the middle reaches of rivers with bypass basins. At the large rivers in Germany Rhine, Danube, Elbe etc. some bypass flood-control retention basins were constructed and actually a lot more basins are in design or construction phase. First experiences of operation and efficiency were gained during recent flood incidents. Referring to the efficiency of bypass flood retention basins in the middle reach of German rivers results of an ongoing research project at the Institute of Hydraulic Engineering and Water Resources Management of the Technische Universitaet Muenchen are presented. Finally some geotechnical aspects of the embankments are considered as the dikes of flood-control retention basins are impounded only temporarily and therefore specific design criteria respected unsaturated and unsteady groundwater flow are permitted by the standards.

Key Words: retention, flood, basin.

1. INTRODUCTION

Recent flood events in the years 1993, 1999, 2002 and 2005 have revealed insufficiency of existing flood protection structures and management. Flood protection dikes were not able to withstand the hydraulic loads. The capacity of flood retention basins in the upper reaches of rivers was not sufficient for efficient retention. The results were damages that by far exceeded the theoretical costs to adjust or install adequate flood protection structures and management for damage prevention.

The efficiency of these retention structures strongly depends on the general operation strategy, e. g. basins with controlled intake structures or with uncontrolled weirs, and in case of using a controlled intake structure it depends on the quality of the supra-regional flood prediction. This topic is actually researched by a lot of scientific institutes and universities. Especially the interaction between the prediction of flood hydrographs and control strategy, especially shape and peak of the flood, determine the efficiency as well as the basin volume and the capacity of its control structures.

As the specific technical standards concerning dams and especially flood-control retention basins were revised and republished in the year 2004 these standards actually represent the technical state of the art concerning operation, design and maintenance. Therefore a short summary of the requirements for the design of embankments, spillways and outlet structures is given in order to present a possibility for comparison to other international standards referring to similar structures and basins. Two renewals among others of the new standard have to be accented. The first is the introduction of three design flood discharges for the design of the spillway, for the structure safety and for flood protection. The second refers to the ecological and environmental recommendations that mainly concern aquatic and terrestric migration devices as well as conservation and maintenance of alluvial forests that are located within the basin. Migration possibilities can be warranted by the adjustment of the outlet structures. Alluvial forests can be conserved be regular temporal flooding.

2. HYDROLOGICAL AND STRUCTURAL DESIGN

2.1 General

As shown in Figure 1, a bypass flood retention basin consists of an inlet and an outlet structure and of at least one embankment dam and in case several other structures and embankments. The inlet and outlet structures have to be designed for an effective control of the filling and emptying process of the basin. Due to safety aspects the (n-1)-rule shall be taken into account when defining the number of inlet and outlet devices.

Particularly in case of uncontrolled bypass retention basins an internal partitioning can improve the retention effectiveness. For controlled basins the water level within the basin is dependant on outlet and inlet strategies. Therefore it is only indirectly dependant on the flood discharge within the river section.

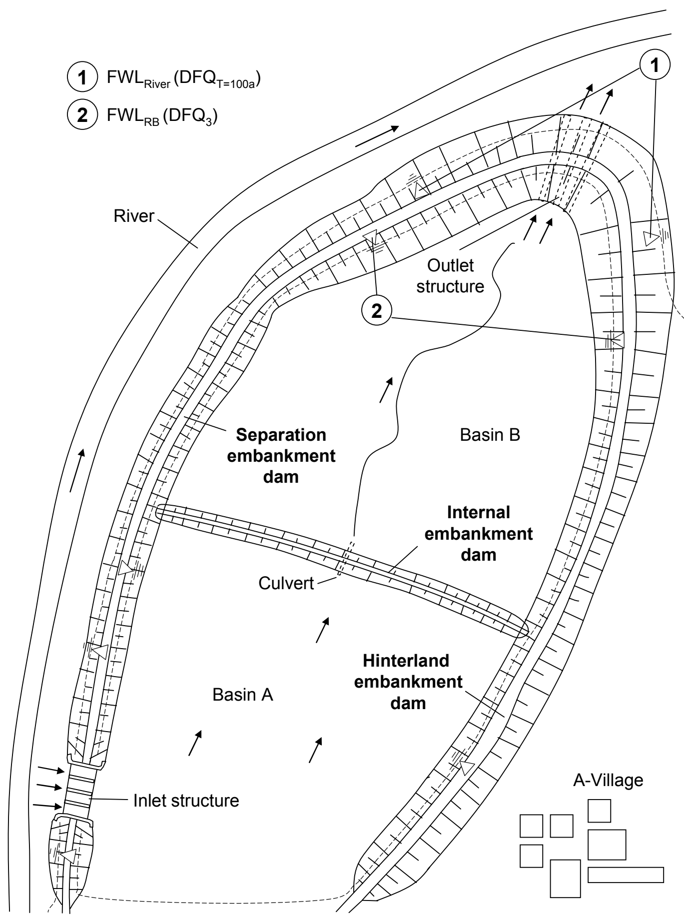


Figure 1: Typical bypass flood-control retention basin along rivers based on Haselsteiner (2007a)

2.2 Design floods

In Germany the complete design and therefore the design flood discharges (DFQ) and flood water levels (FWL) are depending on the classification of the basins in the four classes very small, small , medium and large basins. The classification according to DIN 19700-12/2004 takes into account the height of the dams and the reservoir volume. Due to significant safety aspects a change of classification is possible resulting in an up- or downgrade of the class. The classification for flood retention basins according to mentioned code is given in Figure 2.

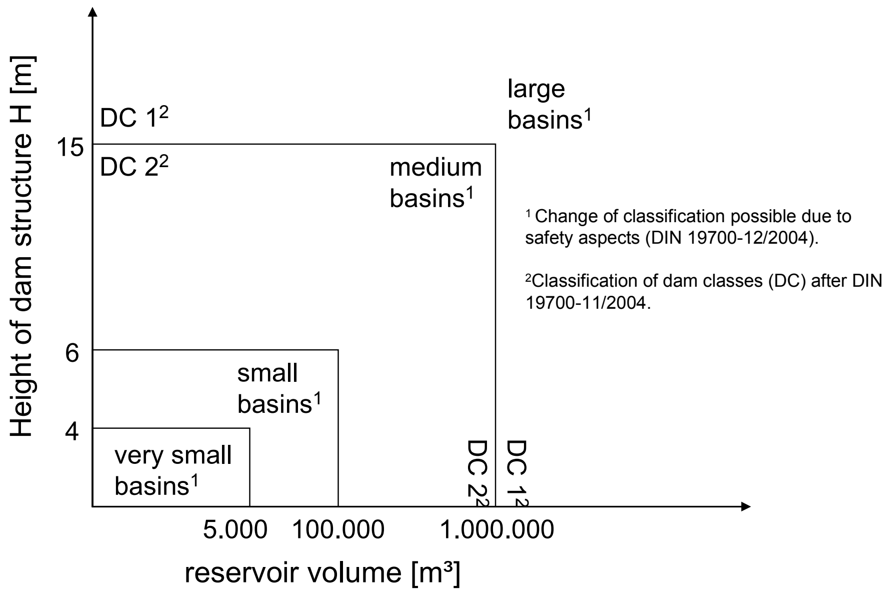


Figure 2: Classification of flood retention basins according to DIN 19700-12/2004

Three different design flood incidents can be distinguished. DFQ_1 represents the flood incident for spillway design. DFQ_2 represents flood incident for respecting the structural stability of the dams and DFQ_3 is used for flood protection or flood retention design. According to the classification of the retention basins the occurrence probabilities of the three design discharges are varying as shown in Table 1.

Table 1: Annual occurrence probabilities of design flood discharges (DFQ_1 and DFQ_2) for basin classifications (DIN 19700-12/2004, Haselsteiner 2007b)

[redacted]

The exact specifications are given by DIN 19700-10+11+12/2004. There it is mentioned that for the design of gated in- and outlet devices (DFQ_1) normally the (n-1)-rule has to be respected and no additional outlet facilities are allowed to be taken in account. For DFQ_2 nearly all outlet devices may be taken account for.

Controlled flood retention basins represent a special structure where a separate spillway structure is not necessary when in- and outlet structures ensure the filling of the basin. The retention effectiveness is based upon a flood event with varying occurrence probabilities regarding the damage potential within the hinterland. The annual recurrence for flood protection measures theoretically range from T = 5 to T> 100 a. (Table 2). In praxis an annual recurrence of T = 100 a serves as orientation for measures along river with subsequent settlements. Local abbreviations due to damage potential can result in design annual recurrences of T $\geq$ 300 a as it is realized at the Lower Rhine or parts of the Iller in Bavaria (South Germany).

Table 2: Annual occurrence probabilities of design flood discharges (DFQ_3) for flood protection measures (Haselsteiner 2007b)

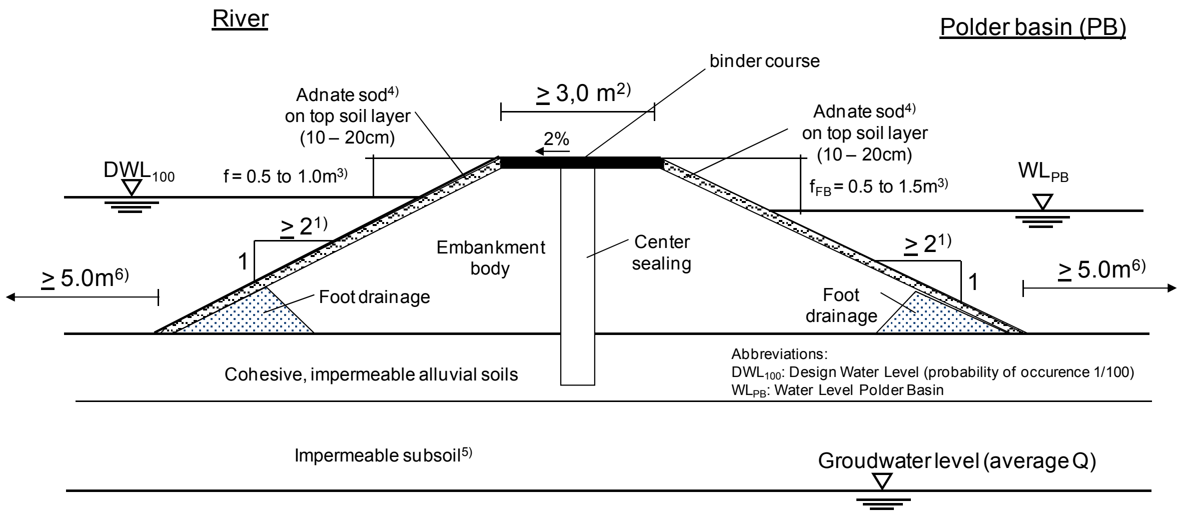
	Sources		
Object	Degree of protection[1] (Bobbe 2005)	T[1] for downstream areas of flood retention basins (DVWK 202/1991 and DIN 19700-12/1986)	T[1] for flood protection structures (LU BW 2008)
Special objects with serious consequences when harmed by floods	Defined for each case seperately.	-	> 50
Settlements / industry	100	100 (valueable building)	50 - 100
Supraregional infrastructure	100	50 - 100	
Regional infrastructure / single houses	25	25 - 50	< 50
Agricultural areas	5	10 - 25 (Intensive use)	-
		5 - 10 (extensive use)	
Landscape areas	-	-	

[1] The degree of protection of flood protection measures is normally expressed by the intervall of the annual recurrence of the flood discharges T.

2.3 Geotechnical design of the basin embankment dams

Regarding loading conditions of the embankment dams within flood retention basins, the according German technical code DIN 19700-12/2004 contains following phrase: *„The normally short term impoundment allows simplifications of the design of the flood retention basin particularly when it is a dry basin. The admissibility of those simplifications has to be proofed by detailed investigations. For the design of the structures many options and combinations are possible."*

A typical cross section of a separation embankment dam according to Figure 1 is given in Figure 3 some structural hints and design specifications included. Haselsteiner (2007a) contains detailed aspects of geotechnical design issues of embankment dams of flood retention basins regarding material specifications as well as more construction specifications or seepage considerations.



[1] Due to hydraulic loads the embankment slopes have to be flattened more than V:H = 1:3.
[2] If the crest road should be accessable for vehicles Strobl et al. (2004) suggest a crest width of minimum 5.0m.
[3] Normally the freeboard heights of the river and of the basin side are different. The absolute crest height of the separation embankment results from the maximum water level plus freeboard.
[4] For heavy wave loads the whole slopes has to be protected with riprap or similar protection measures.
[5] As the polder basin are often ecolocically valuable wet plains a complete sealing of the subsoil may be not necassary particularly when relatively thick cohesive alluvial soil layers ensure the subsoil stability.
[6] Similar to flood protection dikes a safety zone of a few meters with restricted allowance of use has advantages for stability and maintenance.

Figure 3: Typical cross section of a separation embankment dam

The embankment dams of dry basins have to withstand the same loading conditions as temporary impounded flood protection levees. Nevertheless an explicit link to the national technical code for flood protection levees DIN 19700/1997 is missing the analogue design of the embankment dams of flood retention basins is favourable due to similar loading conditions. As mentioned above for the design of embankment dams according to DIN 19700-12/2004 simplifications are allowed. These simplifications have to be checked carefully. The separation embankment dam can be impounded one-sided or both-sided. If a hinterland embankment is necessary due to topography it is normally impounded only one-sided by the reservoir water level.

Due to temporal impoundment the necessity of an explicit sealing element within the separation embankment dam can be discussed. In that case unsteady seepage modelling has to be conducted for the assessment of the necessity of a sealing and drainage element. Although geohydraulic and geotechnical soil parameter can be determined with sufficient limited tolerance a major concern lies upon the hydrological data. The provision and forecast of precise design water level hydrographs is quite difficult. As various hydrological sceneries have to be respected different hydrographs has to be applied for different design issues. For the stability of the landside slope a long term impoundment will be critical. For the stability of the waterside slope a hydrograph with rapidly lowering water level have to be taken into account. This considerations count for one-sided impounded embankments. For both-sided impoundment the mentioned loading conditions can occur on both slopes. Thus, within the basin the draw down is a result of the emptying process. Within the river section the falling water level is dependant on the natural hydrological process.

For unsteady seepage modelling a start soil moisture distribution has to be determined. Normally measured data or water balance models are missing or too complex. Therefore average values have to be applied. Scheuermann (2005) suggests to apply the moisture field capacity as rough estimation for a starting conditions. For a better estimation complex water balance modelling is necessary. In most cases it is too time consuming and costly because even if the mathematical model has been developed, a lot of measurements will be necessary to calibrate and verify the model regarding special circumstances such as rainfall or micro scale discontinuities.

Often all this complex methodology is avoided by choosing an adequate design with drainage bodies and sealings. Nonetheless for homogenous embankments (crown width ≈ 3m, slope inclination V:H = 1:3) consisting of soils having saturated permeabilities of $k_{Sat} < 10^{-6}$ to 10^{-5} m/s a seven day impoundment is necessary to lead to steady seepage conditions. Applying a permeability relation of $k_{Sealing}/k_{Embankment} >$ 1.000 the reduction of most the hydraulic potential takes place within the sealing. Here, the critical hydraulic gradients of sealings shall be respected to avoid erosion processes within the sealing. A more detailed description of seepage in flood embankments is presented by Haselsteiner (2007c).

In case of core sealing is applied both classical methods such as sheet piles, diaphragm walls and cut-off walls and new techniques such as soil mixing methods are well proven and state of the art. Here, two aspects have to be respected. An incomplete sealing that does not reach to an impervious layer will lead to a disproportionate increase of seepage within the embankment with a rising unsealed subsoil area. Due to safety aspects the failure of a sealing element has to be assessed, too. In DIN 19700 and BAW MSD (2005) according load cases are specified. In case of cement-based sealing the occurrence of cracks or other weakening processes has to taken into account. Here the fact should be remembered that two dimensional seepage and slope stability modelling always overestimate the loading conditions and underestimates resistance forces (Haselsteiner 2007c).

3. CONTROL PROCESS

The main advantage of a controlled retention basin is the flexibility in using it. With being located next to the main river, there is no hydraulic connection between river and the retention basin until the intake structures will be opened. In Figure 4, three different control processes at a certain bypass retention basin with the capacity k are shown.

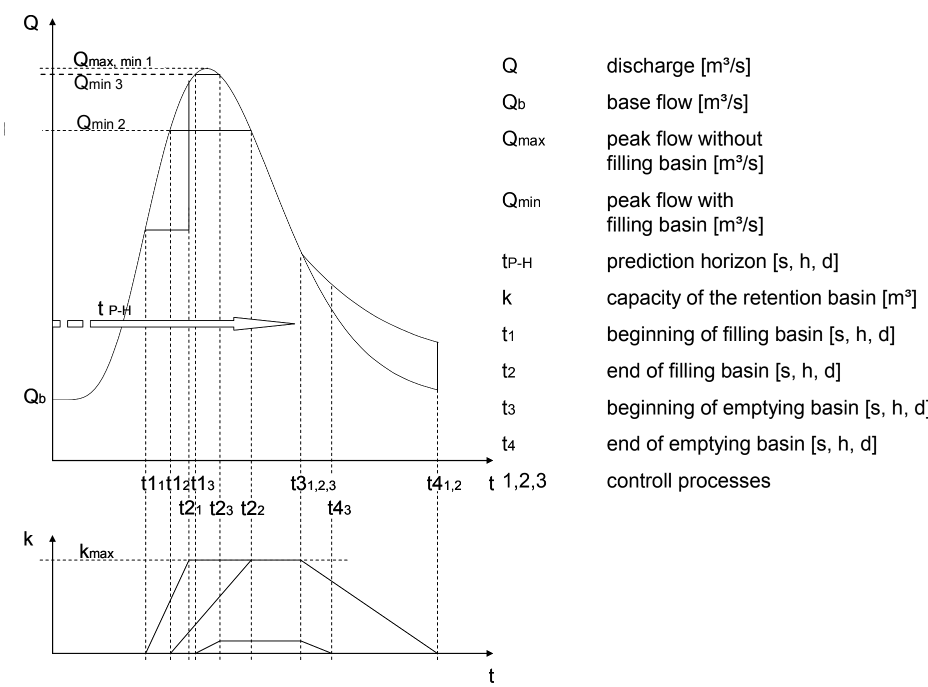


Figure 4: Control process and utilization of the capacity k based on Fischer (2007)

Each control process starts filling the basin at time t_1. At time t_2, the filling process is stopped by closing the intake gates. The maximum flood peak reduction is achieved by using the whole capacity k of the retention basin and cutting off the flood peak horizontally. In control process 1 the beginning of filling the basin (t_1) is actually too early for creating any flood peak reduction. In this case the maximum capacity k_{max} is reached before the flood peak is running off. In control process 3 the beginning of filling the basin (t_1) is too late for using the full capacity k_{max} for flood control. The maximum possible flood peak reduction is reached in control process 2. Therefore the prediction of the floodwave before beginning with the filling process of the basin should ideally be exactly the same then the flood wave is running off. In addition, the length of the prediction horizon $t_{P\text{-}H}$ has to be at least t_2 minus t_1. The emptying process of the basin starts at time t_3 and ends at time t_4.

3.1 Control strategies

There are three general control strategies which could be used for controlling a bypass retention basin during flood. The first one is a control strategy with fixed rules concerning the beginning of flooding the retention basin, e.g. the basin will be flooded if there is a discharge in the river higher than a 100 year flood. The advantages of this control strategy are that the flood prediction has minor priority and the decision makers in controlling the basins have strict rules. This is important during flood times but also after the flood concerning judicial aspects like e.g. indemnities for damages. If there is a flood which is little higher than a 100 year flood, the filling of the retention basin will create a positive effect depending on the capacity k. If the flood is much higher, the retention basin could be already filled before the flood peak is reached (compare with control process 1 in Figure 4). In this case the capacity k of the retention basin will be used up to k_{max} but there will be no flood reduction effect in the river downstream of the basin. If the flood is much lower than the 100 year flood, there will also be no flood reducing effect.

The second general possibility for controlling a bypass retention basin is to control with fixed rules within certain flood prediction zones. The flood prediction zones can be based on flood statistics for the river system where the retention basin is located. The zones could be for example 20 to 50 year flood, 50 to 100 year flood etc.. The flood is predicted in one of the zones and the control process can be fulfilled through the rules within the prediction zone. In this case, a reliable flood prediction is necessary. The spectrum in which the retention basin creates flood peak reduction is broader than in the first general control strategy. An ecological zone could also be integrated when the retention basin is flooded for example in 1 to 20 year floods as well. The discharge can then depend on the ecological needs in order to reestablish floodplain forests.

The third possibility for controlling a bypass retention basin is a flexible control strategy depending totally on the flood prediction. In this case there is the theoretical possibility to use the whole capacity k in an optimum way (control process 2 in Figure 4). The prediction horizon $t_{P\text{-}H}$ (Figure 4) has to reach its minimum until time t_2 and the predicted flood wave within $t_{P\text{-}H}$ has to have exactly the same shape and flood peak of the actual flood wave. How exact the flood prediction can be is depending on the watershed characteristics like form, amount and intensity of lateral tributaries, as well as the influence of non-controlled retention areas, the interaction between surface and ground water and the amount and quality of prediction gauging stations and rainfall measurements.

3.2 Efficiency of flood prediction and flood control

The efficiency of bypass retention basins controlled with a flexible control strategy is depending on the quality of the flood prediction. As the error in the predicted shape of the flood wave is normally not so crucial, the quality of a flood prediction system can be specified by the difference between the actual and the predicted flood peak discharge (equation 1).

[1] $$f = 100 \cdot \frac{Q_{max} - Q^*_{max}}{Q_{max}}$$

with:

f prediction error [%]

Q_{max} peak discharge of the actual flood wave [m³/s]

Q^*_{max} peak discharge of the predicted flood wave [m³/s]

At the Danube River in Germany, which runs through the state of Bavaria for about 360 km the reactivation of former floodplains with controlled bypass retention basins is planned. Up to the year 2020 the construction of four basins with a capacity of about 30 Mio. m³ is planned (Goettle 2007). Further the search for suitable locations for reactivating floodplains is in progress. The hundred year flood peaks at the Bavarian Danube range from 1.250 m³/s to 8.800 m³/s along the river. For using the planned retention basins in an optimum way, prediction horizons at the particular inlet structures between 24 and 48 hours are necessary. Figure 5 shows the prediction errors against the prediction horizons at the Bavarian Danube River in the years 2003 up to 2006 (nine flood events) at four selected gauging stations along the river (equation 1). The errors in the prediction horizons between 24 and 48 hours are situated between 10% and 40 %.

In years 2003 to 2006 the flood predictions were done mainly with a hydrological approach. From the year 2006 to 2008 the prediction model at the Bavarian Danube is supported with results of several 2d-hydraulic calculations along the river (about 200 km) done at the Institute of Hydraulic Engineering and Water Resources Management of the TU München, which are and will be integrated into the hydrological models. Its flood routing will then be supported by 2d-effects of non-controlled retention areas. The quality of flood prediction will increase the oncoming years, but nevertheless too many different local parameters like rainfall prediction, the degree of saturation of the soil, the growth stage of plants concerning roughness effects etc. will lead to errors in the flood prediction.

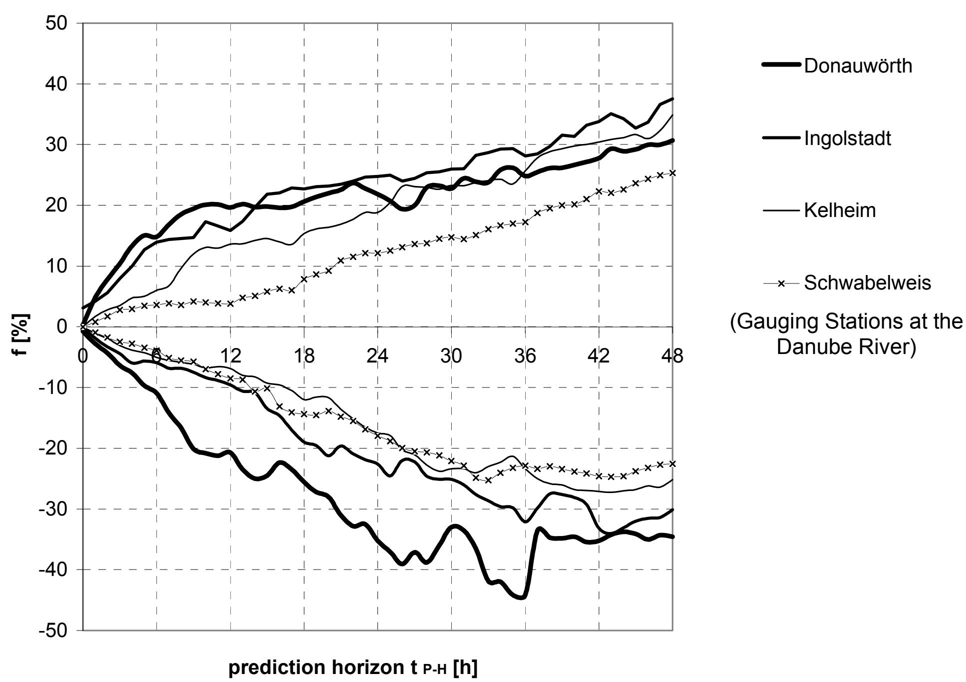


Figure 5: Prediction Errors at the Danube River based on Vogelbacher (2007)

In order to evaluate the influence of a flood prediction errors on the flood peak reduction of bypass retention basin, Fischer (2008) made a parameter study by combining several predicted with actual flood waves and by controlling the retention basin after the predicted flood waves. The flood waves are synthetically defined by the Maxwell distribution function (compare for example with Hager and Sinniger

1985) and with a dimensionless discharge (0.1…0.7). The discharge 0.1 stands for a discharge which 10 % is higher than the bankfull discharge in the river. At the Bavarian Danube River a 0.1 flood is in average a 2 year flood, a 0.7 flood is in average a 1,000 year flood. The control strategy in the parameter study was flexible with the aim of horizontally cutting off the flood peak by using the total capacity k_{max} of the retention basin.

Figure 6 shows the utilization levels $\mu\Delta Q$ of the theoretical flood peak reduction depending on the predicted and the actual peak discharge by using a controlled retention basin with the capacity k = 40 Mio. m³. Thus values of the volume retention basin divided by volume of the flood wave (V_{RB}/V_{FW}) between 4.2 % and 9.4 % are shown (compare with Figure 7). Figure 7 shows the actual flood peak reduction depending on the utilization levels of the theoretical flood peak reduction.

The results of the parameter study show, that the attenuation of the utilization levels is above and below the 100 % line different. It becomes evident that the attenuation by overestimating the predicted the flood peak is going on not so rapidly than by underestimating the flood peak. By underestimating the flood peak, the controlled retention basin was almost filled before the actual flood peak was reached. By overestimating the flood peak, there is still the possibility to cut off the flood peak, albeit the capacity k is not used in an optimum way.

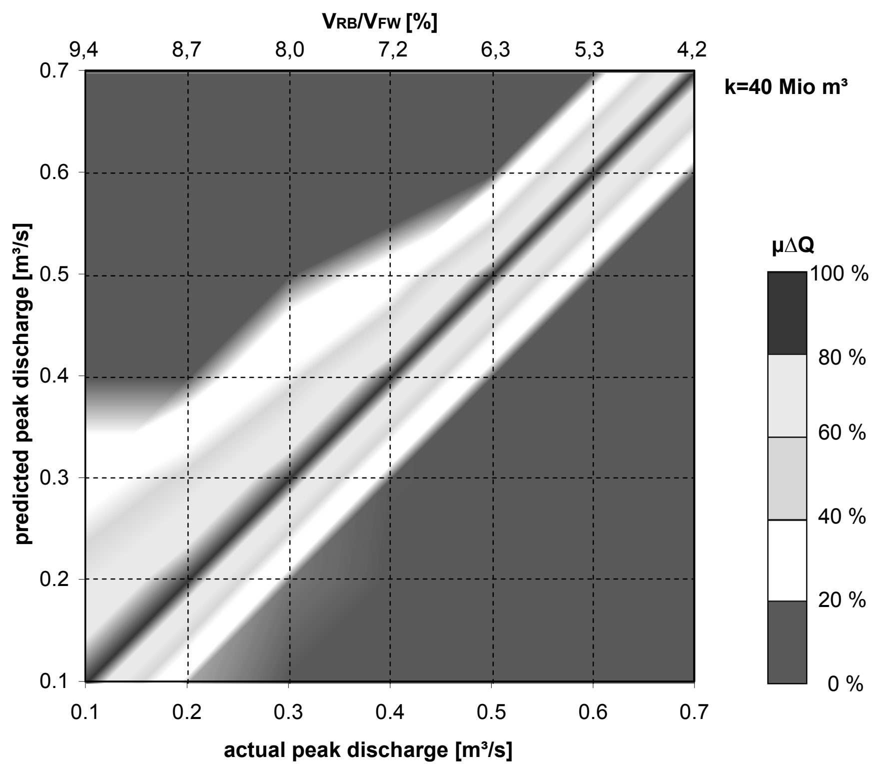


Figure 6: Utilization levels of the theoretical flood peak reduction

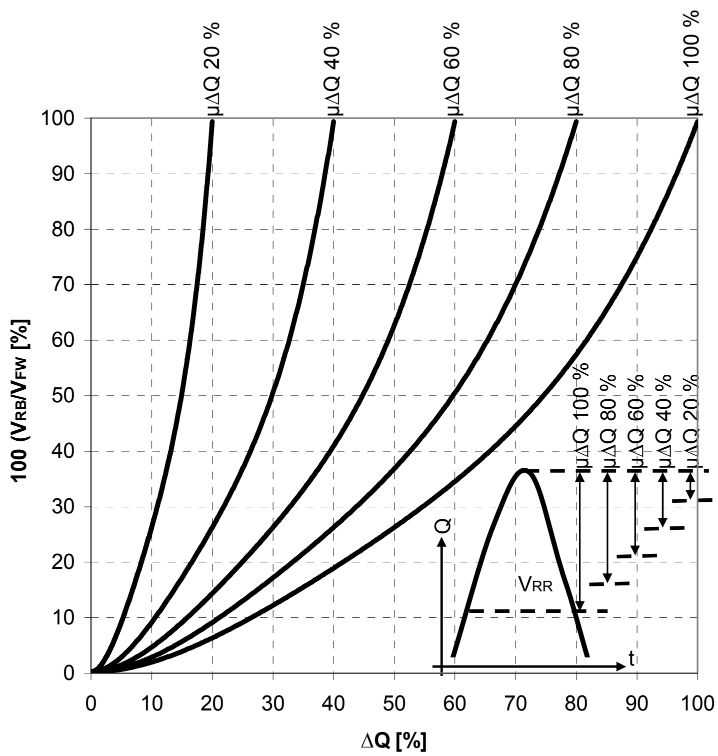


Figure 7: Actual flood peak reduction depending on the utilization of the theoretical flood peak reduction

4. CONCLUSION

The presented results have shown, that the efficiency of bypass retention basins in middle reaches of rivers is depending mainly on its capacity and the control process. By using a flexible control strategy, the control process is depending especially on the flood prediction. As the flood prediction models and their input data sets like rainfall prediction, saturation of the soil etc. are currently not sufficient for using the basins in an optimum way, the major task of the next years is to improve the prediction models. With precise flood prediction models and adequate capacities, controlled bypass retention basins are an effective way to retain water and to reduce or even avoid flood damages along rivers.

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