Schweizerisches Talsperrenkomitee
Comité suisse des barrages
Comitato svizzero delle dighe
Swiss Committee on Dams

FLOATING DEBRIS AT RESERVOIR DAM SPILLWAYS

Report of the Swiss Committee on Dams on the state of floating debris issues at dam spillways

Working group on floating debris at dam spillways **November 2017**

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In 2012 the Swiss Committee on Dams (SCD) decided to set up the working group on "floating debris at dam spillways" with the aim of investigating the current situation of Swiss dams in relation to this phenomenon.

This report has been prepared by the working group and approved and implemented by the Technical Commission (TECO) of the Swiss Committee on Dams on 15.11.2017.

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Title picture: Floating debris obstructing the Palagnedra Dam spillway during the 1978 flood (Photo: Ofima)

Summary

In addition to bed load and suspended load, floating debris such as large wood and other anthropogenic waste materials are often carried during floods, which can lead to problems at inlet structures of dam spillways. In particular, obstruction of dam crests or gates may considerably reduce the discharge capacity and cause unacceptably high water levels in storage reservoirs. The required freeboard clearance can no longer be guaranteed. In addition to assessing the risk of obstruction, the fundamental question is whether large wood should be retained or passed through. Both require a corresponding design of the dam spillway, or appropriate measures in the reservoir.

Since there were no generally accepted and valid guidelines for dealing with large wood and floating debris at dam spillways until now, a working group under the Swiss committee on dams was formed in 2013, with the aim of assessing the international status of rules and "best practices" on the subject. As part of this project, a survey was carried out on the subject of floating debris at 60 Swiss dam sites. It can be seen that at most of these dams, floating debris material does accumulate and is subsequently removed. In addition, problems with floating debris have occurred in the past in several installations. Case studies at these facilities have been carried out so as to learn from past experiences, and support future decisions. In addition, the working group has collected specific experience as well as state of the art guidelines from abroad.

Finally, the working group has developed recommendations for dam operators regarding: (1) the assessment of dam spillways with regard to the hazard potential of floating debris, i.e. the amount of large wood in the catchment area, or the likelihood of dam spillway obstruction; (2) possible concepts for handling floating debris at dams (passage, or retention); (3) possibilities for inlet optimization as well as of possible operational measures.

The main result of this work was the development of a hazard assessment diagram. Based on the observed effects of large wood on dam spillway hydraulics, and the design of dam spillways, the blocking probability and its consequences can be estimated as a first step. The resulting hazard potential for the dam can trigger possible measures (dam spillway adaptations, retention, or transit). Finally, the most important recommendations for consulting engineers, authorities, and operators are summarized.

1. Introduction

1.1 Motivation and Background

In addition to bed load and suspended load, floating substances such as large wood (LW) and other anthropogenic waste materials are often carried during floods, which can lead to problems at inlets of dam spillways. In particular, obstruction of dam crests or gates may considerably reduce the discharge capacity and cause unacceptably high water levels in the reservoir. The required freeboard clearance can hence no longer be guaranteed. Moreover, by obstructing the dam spillway inlets, floating debris can cause an increased load on the dam. In addition to assessing the blocking risk, the fundamental question is whether LW should be retained or passed through. Both require a corresponding design of dam spillways, or appropriate measures in the reservoirs.

1.2 Objectives

The current international status of guidelines and handling practices of debris at dams is discussed in this report. Based on analyses and experiments, as well as experimental research with observed dam spillway obstructions, recommendations are made on the following aspects:

- Assessment of dam spillways with regard to the hazard potential of floating debris; Estimation of blocking probability;
- Possible concepts for dealing with debris at dams, i.e. passage or retention;
- Possibilities for optimizing inlet structure hydraulics;
- Possibilities for operational measures.

The present report summarizes the results of research carried out to date, and provides recommendations for dealing with floating debris at dam spillways for consulting engineers, authorities and dam operators.

1.3 Methodology

In order to make a broad assertion, the following methodologies were used for the study:

- Literature review;
- Questionnaires given to operators of approximately 60 Swiss dams;
- Evaluation of past case studies;
- Presentations by experts during meeting sessions;
- Gathering of experience from neighboring countries

Findings were discussed during the regular meeting sessions, and were supplemented by experiences from working group members.

1.4 Dissociation from Run-of-River Power Plants

The working group considerations are limited to dams for which the provisions of the Swiss Federal Act on Water Retaining Facilities (StAG) and the Swiss Ordinance on Water Retaining Facilities (StAV) are applicable (www.admin.ch). The applicability of the recommendations must be clarified on a case-by-case basis for smaller dams that

are placed under the StAG because there is a specific risk potential. This is especially true for flood and bed-load retention basins that possess a spillway.
Conventional run-of-river power plants without significant storage capacity (in comparison to runoff) are not covered by the present study. Floating debris dynamics in rivers differ from those in storage basins due to higher flow velocities. The present recommendations can therefore not be adopted without restriction for run-of-river power plants.

1.5 Definition of Large Wood (LW) and Floating Debris

Large wood and natural organic floating debris can be mobilized during a flood event above the dam if the catchment area is covered in forest - and can occur in different forms (Lange and Bezzola 2006):

- Natural tree trunks and roots (dead or fresh wood);
- Timber from logging or deforestation;
- Timber from bridge constructions and/or river bank structures.

Deadwood is usually already present in the river systems and is entrained during floods. Rising water levels and bank erosion or landslides also contribute to entraining fresh wood into the water system.
In addition to organic LW, water bodies often also carry considerable amounts of anthropogenic debris in flood situations. These consist of various types of bulky waste material such as silage bales (**Figure 1**) that are stored or disposed of near water, and may even include boats (**Figure 2**) cars, or houses. Unless otherwise specified, the terms "large wood" and “floating debris” refer to both natural LW and anthropogenic waste material. Ice is not considered in the present study.

1.6 Legal Framework in Switzerland

Article 41 of the Federal Act dated 24 January 1991 on the Protection of Water bodies (GSchG) regulates the modalities for handling floating debris at dams. This article states that no removeddebris may be returned to the water body by the dam operator. Dam owners are obliged to periodically collect floating debris in the area of their facilities. Exceptions are however possible in agreement with the competent authorities.
Most of the maintenance of the residual flow section downstream from the dam is transferred to the operator. A high degree of forest stand in the catchment area should be avoided. In the event of a flood, the residual flow section can be flooded and cause further problems downstream due to the accumulation of floating debris.
It is usually impossible to remove all floating debris during a flood event because of the large volumes. In addition, if the dam spillway is activated, a partial discharge of floating debris via the dam spillway can hardly be prevented.
From an ecological perspective, it is desirable to leave wood in the water. The GSchG strives to be consistent, not only with regard to sediments and fish, but also to natural floating matter. Large wood contributes to the formation of riverbeds, by providing shelter as well as habitat and food sources for many species, and generally improves the ecological functioning of a water body.

Figure 1: Obstructed spillway due to silo bales in Trondelag, Norway (Foto: L. Lia, NTNU).

Figure 2: Floating debris in front of the Thurnberg dam spillway on the Kamp river in lower Austria during the extreme flood in 2002 (Photo: Federal Office for Agriculture and Forestry, Environment and Water Management, Austria).

2. Concepts for dealing with Floating Debris at Dams

2.1 Introduction

There are generally three options for dealing with floating debris at dams:

(1) Measures taken in the catchment area to minimize LW accumulation;
(2) Allowing debris to pass through the dam spillway;
(3) Retaining debris and removing it from the reservoir.

Depending on the type of dam spillway, only measure (2) may be possible (sometimes only after modification / adaptation measures have been implemented). Alternatively, measures of type (1) and (3) are permissible from a hazard assessment perspective, so that debris must be kept away from the dam spillway. These three types of measures are discussed in the following chapters. Operational measures are also described in chapter 6.3.

2.2 Overview of Dam Spillway Inlet Structures

Depending on the kind of dam spillway, measures of types (2) passing debris, and (3) retention and removal in the reservoir, are used. The most common types of inlet structures at dam spillways are shown below (**Figure 3** to **Figure 8**) and the most important parameters are defined schematically.

2.2.1 Free Spillway

Bays without weir bridge / superstructures:

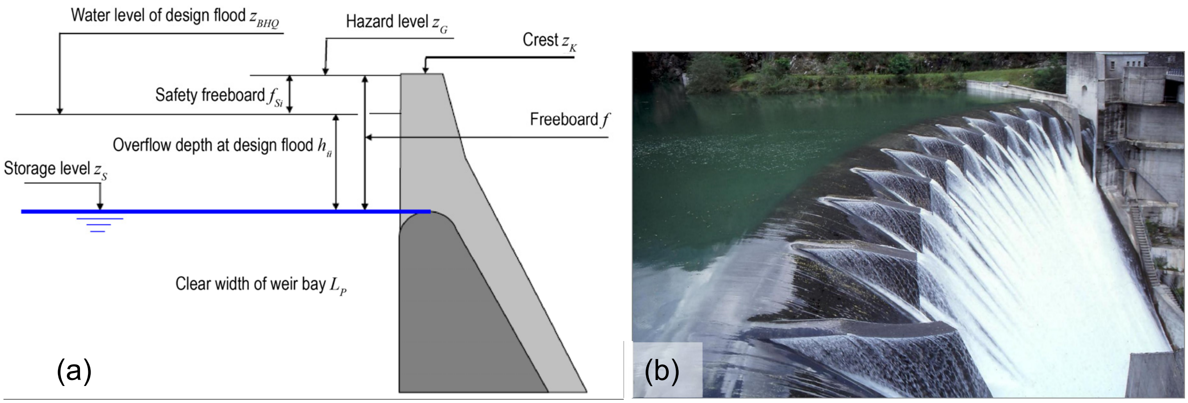


Figure 3: Schematic diagram of free overflow dam spillway inlet structure without weir bridge / superstructure, (b) dam spillway of the Palagnedra dam, Switzerland (Foto: Helga Ammann).

Bays with weir bridge / superstructures:

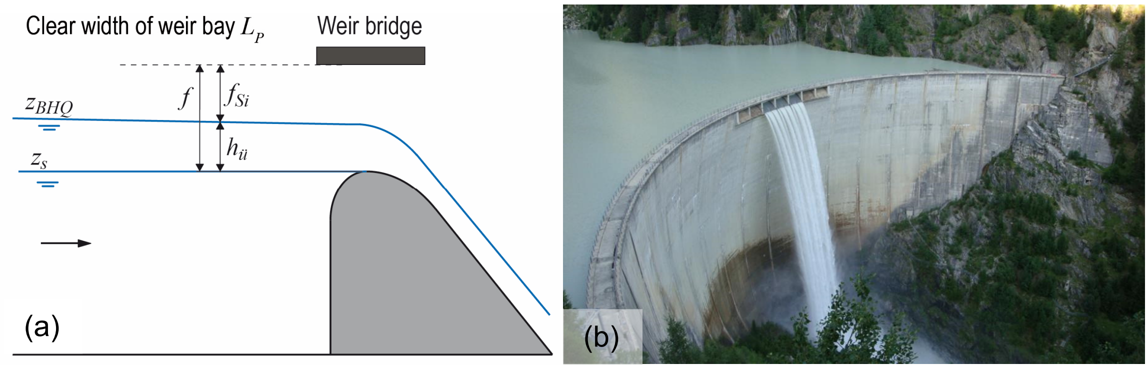


Figure 4: (a) Schematic diagram of free overflow dam spillway inlet structure with weir bridge / superstructure, (b) spillway outlet structure at the Gebidem dam, Valais, Switzerland (Photo: VAW).

f	Freebord
f_{Si}	Safety freebord
L_p	Clear width of weir bay
$h_ü$	Overflow depth at design flood
z_{BHQ}	Water level at design flood
z_s	Storage level

2.2.2 Gate-regulated Spillway

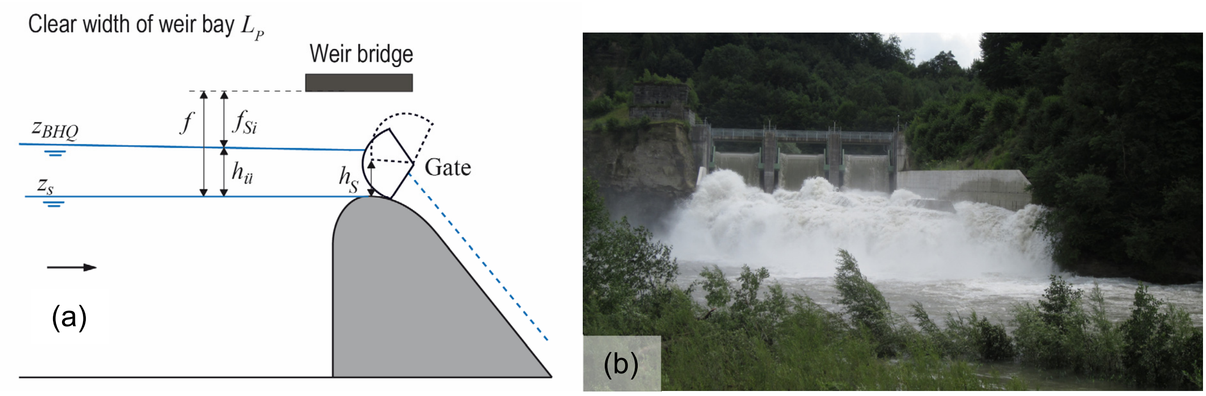


Figure 5: (a) Schematic diagram of a regulated overflow, (b) gate-regulated spillway of the Maigrauge dam, Switzerland (Photo: Group e).

f	Freebord
f_{Si}	Safety freebord
h_S	Gate opening height
L_p	Clear width of weir bay
$h_ü$	Overflow depth at design flood
z_{BHQ}	Water level at design flood
z_s	Storage level

2.2.3 Bell-mouth Spillway

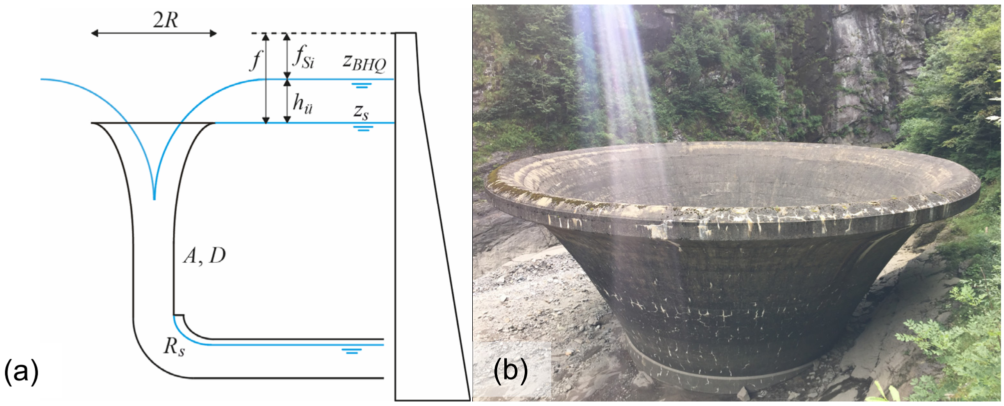


Figure 6: (a) Schematic diagram of a bell-mouth dam spillway (b) bell-mouth spillway at Malvaglia dam, Switzerland (Source: VAW).

A	Shaft cross-sectional area
D	Shaft diameter
f	Freeboard
f_{Si}	Safety freeboard
$h_{ü}$	Overflow depth at design flood
z_{BHQ}	Water level at design flood
z_s	Storage level
R	Spillway radius
R_s	Shaft bend radius

2.2.4 Piano Key Weir

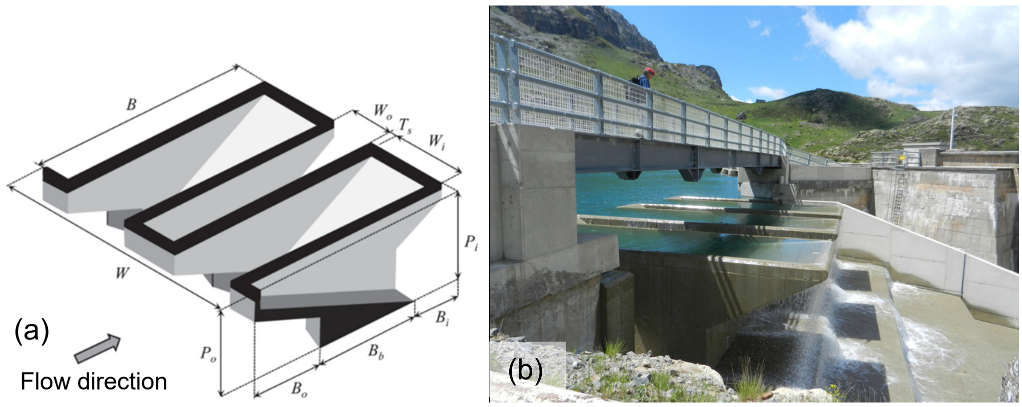


Figure 7: (a) Schematic diagram of the piano key weir spillway inlet structure , (b) Piano key weir spillway of the Gloriette dam in France (Photo: La Fourmi des Montagnes)

B	Length in flow direction
L	Unfolded crest length
P	Wall height
T_S	Wall thickness
W	Total weir width
Index b	footprint
Index i	Inlet
Index o	Outlet

2.2.5 Side-weir Spillway and Side Channel

With or without regulating gates

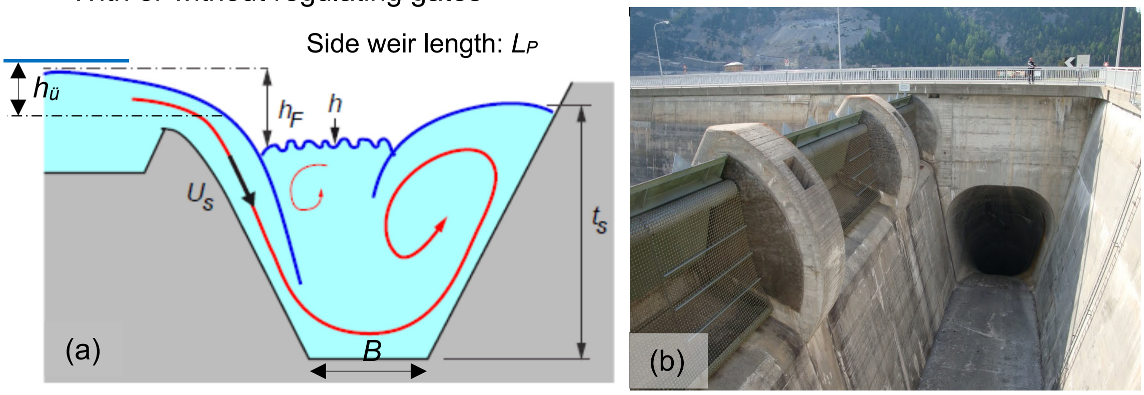


Figure 8: (a) Schematic diagram of a side weir spillway, (b) Gate-regulated side weir spillway of the Punt dal Gall dam, Switzerland (Source: Michael Mülheim)

B	Side channel width at bottom
h	Flow in side channel
$h_ü$	Overflow depth
h_F	Overflow depth in relation to flow depth in side channel
L_p	Side weir lenght
t_s	Wall flow depth in side channel
U_s	Flow velocity of lateral inflow

2.3 Measures taken within the Catchment Area

In order to minimize the amount of large wood in the catchment area, preventive forest protection measures are necessary (Covi 2009). For this purpose, landslides and bank erosion must be avoided. In the medium term, stable bank areas and river slopes as well as well-structured forest resources near reservoir banks should be aimed for. The soil shall be retained by tree roots. Stable and well-anchored trees should be preserved. On the other hand, trees that are prone to falling, or are not anchored well enough should be eliminated. Trees within riverbeds as well as deadwood shall be left lying and / or removed according to the appropriate flood protection measures. Such cleanup operations may be in conflict with the ecological benefits of leaving wood in rivers.

The management of river catchment areas and reservoir banks is generally difficult, technically complex, and usually very expensive. In order to meet the needs of both safety and ecology, close cooperation between forest services, conservation officers, and other stakeholders is of great importance.

Large wood retention systems as technical measures can be provided in the catchment area and in rivers upstream from dams. Large wood retention can be achieved directly in the river or in a dedicated retention area, such as in a debris retention basins and / or in channels using trash racks, large wood nets, selective large wood retention, etc. (**Figure 9**; Zollinger 1983, Bänziger 1990, Rimböck 2003).

In difficult terrain, the cost of airlifting tree trunks by helicopter is prohibitively high. In such necessary cases, trunks are rather cut to non-hazardous lengths (common, for example in the canton of Bern). It is obvious that despite forest management and large wood retention measures within the catchment area, the occurrence of floating debris in case of flooding cannot be ruled out.

Figure 9: Large wood retention by means of (a) trash rack at the retention basin in Sachseln, canton Obwalden (photo: VAW), (b) cable net at Faukengraben, Upper Bavaria, Germany (photo: Institute for Hydraulic Engineering and Water Resources Management, TU Munich) and (c) Combination of large wood and trash cable racks on the Chiene river , Canton Bern (Photo: Emch + Berger AG).

2.4 Passing of Floating Debris

During high flood events with large amounts of floating debris, passing the debris downstream is the only option, as the LW is carried by the current in the reservoir towards the dam spillway. Floating debris passing is only possible if the possibility of spillway blocking (**Figure 10a**) is excluded. For this purpose, either the weir bays of the spillway inlet structure are built large enough (see Chapters 3.1, 3.2 and 5.3), or there must be a free spillway structure, sufficiently wide, without superstructures (**Figure 10b**). The structural design of the dam spillway must facilitate the passage of LW (smooth surfaces, round shapes, trumpet-shaped inlets). Tree trunks floating transversely to the flow direction can be reoriented by means of a free-standing pillar in front of the dam spillway (bottleneck) (see chapter 6.1.2). This would allow tree trunks to pass through

the dam spillway. Possible operational measures such as weir control through gate-regulated dam spillway are described in Chapter 6.2.
While passing floating debris mitigates the dam spillway blocking hazard, this hazard may be simply shifted downstream. Therefore, the effects of passing floating debris to the downstream reach of the dam have to be examined, in particular if narrow river sections, bridges, or other obstruction-prone structures are present.

Figure 10: (a) Blocking of the dam spillway inlet structure (spillway with weir bridge) at the Palagnedra dam, Canton Ticino, 1978; (b) new dam spillway inlet structure without weir bridge (Photos: Ofima).

2.5 **Debris removal from Reservoir**

Reservoirs generally allow for the removal of accumulated debris, if accessibility of large machinery is ensured. The small flow velocities allow for floating debris to be collected by boats. This can prevent LW from reaching the dam spillway in the event of a flood or sinking and obstructing and / or impairing the functioning of penstocks or low-level outlets. Fresh wood usually remains buoyant for several months (Zollinger 1983), which means that withdrawing it twice a year is sufficient. LW is usually not distributed over the entire reservoir, but is blown by wind in bays or on certain shore areas. Floating chains have proven themselves useful for collecting wood at the surface of reservoirs. However, forces are usually too strong during floods due to the high amount of LW, and floating chains are therefore not very reliable, and have also exacerbated problems when broken.

In the event of a flood involving a large amount of floating debris, it is almost impossible to remove it all, since the performance of excavators or rake cleaning machines is usually too low (**Figure 11**). Clearing a blocked dam spillway using excavators is practically impossible due to the amount of floating debris, flow velocities, and the wedging of debris. It is therefore advisable to keep any debris from entering the dam spillway right from the start, if it cannot be passed through. Floating debris that has been intercepted can be removed from the reservoir after the flood, with associated costs for removal, transportation, and disposal.

Figure 11: Removal of floating debris with excavators at the Yarzagyo dam, during the 2015 flood in Myanmar (Photo: M. Wieland).

3. Regulations and current state of the art

Guidelines and regulations relating to the problem of floating debris at dam spillways are available in various countries. In most cases, these relate to the minimum dimensions of dam spillways to be met. The following equations and recommendations were largely derived based on hydraulic model experiments and actual experience. The respective formulas are thus limited to testing conditions or for specific dams, but can nevertheless be used for initial gross estimations.

3.1 Switzerland

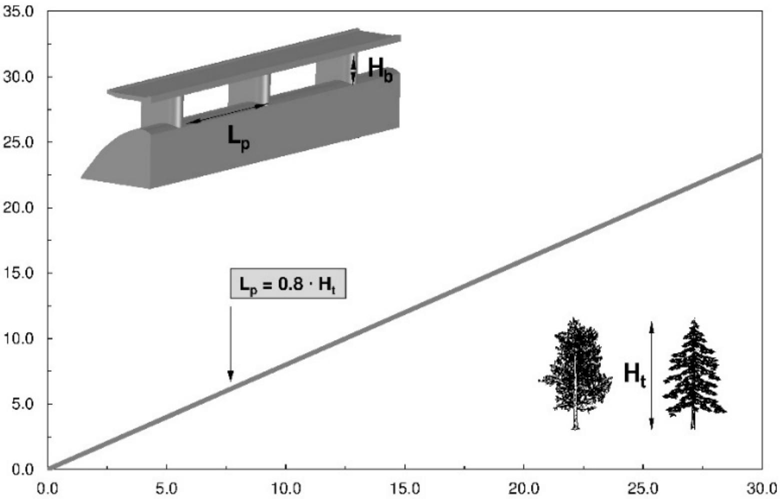
According to the basic documentation on dam safety (SFOE 2016), spillways and structure inlets should be built sufficiently wide so that dam spillway obstructions due to trees and other floating debris can be avoided. A width of 10 m can, as far as the topographical and spatial conditions permit, be considered sufficient according to experience, since observations have revealed that tree trunks in mountain rivers and streams that are transported by floods are rapidly reduced to maximum lengths of about 10 m. In nature reserves / national parks or in unprotected natural mountain rivers, the situation regarding floating debris and its dimensions should be assessed ad hoc. For dams and barrages at major rivers and in the plains, the spillway width should be superior to 10 m.

When designing dam spillways, an adequate freeboard clearance of at least 1.5 to 2 m must be available under a weir bridge or superstructure. If necessary, a weir bridge should be designed so that it can be removed or carried away in the event of extraordinary floods.

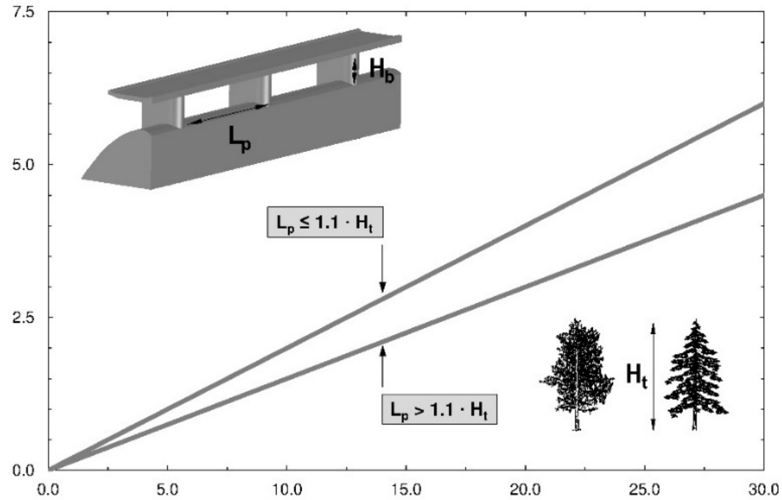
The SFOE (2016) gives recommendations for the minimum clearance width L_p and the minimum clearance height H_b of the individual dam spillway openings as a function of the expected tree length H_t (**Figure 12**):

$$L_p \geq 0.8H_t \quad (1)$$
$$H_b \geq 0.15H_t \quad \text{for } L_p > 1.1H_t \quad (2a)$$
$$H_b \geq 0.2H_t \quad \text{for } L_p \leq 1.1H_t \quad (2b)$$

These recommendations are based on the study by Godtland & Tesaker (1994). The expected tree length H_t can be estimated in the field on the basis of the prevailing forest stand. The corresponding information can also be found in the Swiss National Forest Inventory (www.lfi.ch). Alternatively, observed tree lengths in past floods can be taken as a reference (Bezzola & Hegg 2007, 2008).



(a)



(b)

Figure 12: Characteristics for determining (a) minimum clearance width of weir bay L_p; (b) minimum clearance height of weir bay H_b.

3.2 International

3.2.1 France

The French national Committee on Dams (Comité français des barrages et reservoirs Cfbr) estimates that dam spillways with weir bridges and superstructures are prone to obstructions if for the BH*Q* design flood levels (HQ_{1000} for concrete and brick wall dams, circa HQ_{5000} for gravity dams and $HQ_{10'000}$ for embankment dams), one of the following criteria applies (Cfbr 2013):

$h_{Kr} < 0.5$ m		(3a)
$f_{li} < 2$ m	if $0.5 \text{ m} \leq h_{Kr} \leq 2$ m	(3b)
$f_{Si} < 1.5$ m	if $h_{Kr} > 2$ m	(3c)

where f_{li} = shortest vertical distance between the water level and the lower edge of the crossing weir structure, h_{Kr} = overflow height in the respective section (f_{li}) at the dam crest, and f_{Si} = safety freeboard upstream of the drawdown curve (**Figure 13**). As a rule, $h_{Kr} \approx h_{cr} \approx 2/3 h_{ü}$, with h_{cr} = critical flow depth, which typically occurs at the dam crest.

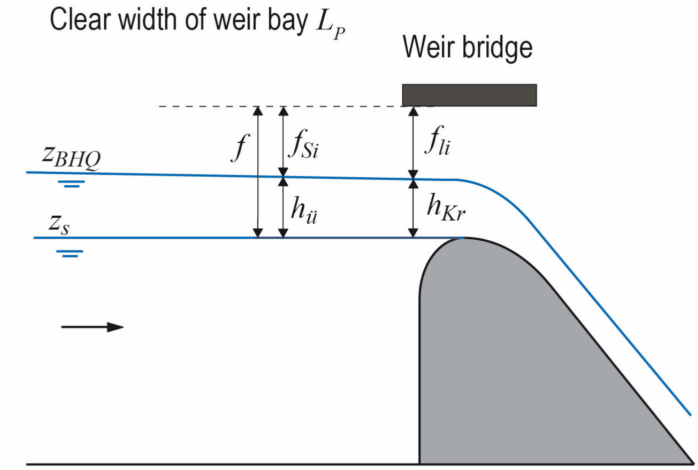


Figure 13: Schematic diagram of dam spillway inlet structure with crossing weir bridge.

For newly built structures, a minimum clear width of the weir bay of 10 to 15 m is recommended. According to Cfbr (2013), when determining the required weir width L_p, the altitude z [m a.s.l.] of the dam must be taken into account (**Figure 14**):

$L_p \geq 15$ m	for $z \leq 600$ m.a.s.l.	(4a)
$L_p \geq 20.5 - 11z/1200$	for $600 < z \leq 1800$ m.a.s.l.	(4b)
$L_p \geq 4$ m	for $z > 1800$ m.a.s.l.	(4c)

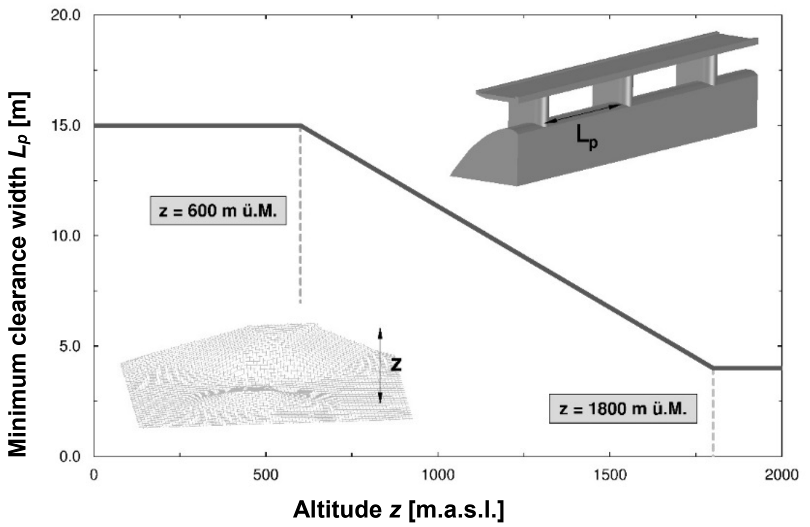


Figure 14: Minimum required clearance width of weir bay L_p as a function of altitude z of the dam (according to Cfbr 2013).

3.2.2 Austria

There are no general regulations regarding floating debris at dam spillways in Austria. Dam spillways with a weir width L_p < 20 m are however considered to be prone to obstructions. 15 m wide weir bays are acceptable depending on the catchment area and its height clearance H_b (if there is a dam spillway bridge). Weir widths of smaller dimensions are considered susceptible to obstructions in any case (Czerny 2015).

3.2.3 Germany

There are no general regulations regarding floating debris at dam spillways in Germany. The Ruhrverband carried out a survey on dam spillway obstruction by floating debris at dams during floods among 23 operators and for 83 dams (Roesler & Bettzieche 2000). The survey showed that at 88% of the dams, no dam spillway obstruction had been detected, and that the LW occurence had been very low until then. Obstructions had however already been observed at 10 dams, but with never more than 10% of the dam spillway being obstructed. A realistic threat posed by floating debris for dam spillways could not be deduced from the survey. It should be noted that major floods in Germany which occurred after 1999 are not included in this study. This problem would otherwise probably have greater weighing today. The Glashütte dam failure in August 2002 is attributed among other factors to an obstructed bottom outlet (Bornschein et al. 2002).

3.2.4 Italy

The following recommendations apply in Italy regarding the functioning of dam spillways (Ruggeri 2015):

- The dam spillway must be designed so that the passage of floating debris between the water level and any superstructure is ensured.
- **At regulated spillways with *n* gates**, a round number of gates is assumed to fail for the calculation of the overflow discharge capacity, namely:
  ≥ 0.5n at Embankment dams,
  ≥ 0.2n at Concrete dams.
- In this case, it must be demonstrated that when discharging a design flood BHQ (HQ_{1000} for concrete dams, H$Q_{3000}$for embankment dams) the actual safety freebord f_{Si} (**Figure 5**) is still at least f/3 in the event of floating debris accumulation, i.e. $f_{Si} \geq f/3$.
- **For spillways with underflow gates**, it must be assumed for calculating the discharge capacity, that at least 30% of the gate opening h_S (**Figure 5**) is obstructed. In the case of clear width of weir bay L_p <12 m, at least 50% of the gate opening h_S must be assumed to be obstructed.
- For fixed-crested spillways with overflows, it must be assumed for the design discharge, that at least 20% of the freeboard height clearance f (**Figure 4**) is obstructed. In the case of clear width of weir bay L_p < 12 m, at least 50% of the clear height of the weir bay f must be assumed to be obstructed.

3.2.5 Norway

In Norway, the obstruction risk for dam spillways with a fixed overfall and multi-pillar bridges was examined by means of model experiments (Godtland & Tesaker 1994). The following recommendations were derived from the model simulations and adopted in SFOE (2016) (see chapter 3.1):

- The minimum width of the dam spillway L_p should be at least 80% of the expected trunk length H_t;
- The minimum clearance height H_b of the dam spillway (**Figure 12b**) should be at least 15% of the expected trunk length H_t;
- If there are no superstructures, trees are passed over the weir crest for flow depths higher than approx. 10-15% of the trunk length H_t (see chapter 5.3.2).

3.2.6 Comparison of Regulations

The general values regarding minimum weir bay dimensions according to Austrian recommendations can be used as a rough rule of thumb. The guidelines of the Swiss regulatory authority SFOE have been taken from the Norwegian recommendations, which are based on only one model investigation. The database for determining the minimum required weir bay opening dimensions is therefore very modest. In the French guidelines, the minimum weir bay opening width depends on the altitude of the dam and the existing trunk lengths. Directly applied to Switzerland, the partially different climatic conditions (temperature, precipitation, etc.), which significantly determine tree growth, render this method not meaningful. In Italy not only the geometric criteria are considered, but also discharge capacity criteria. It is assumed that there is a certain degree of obstruction, which seems realistic and meaningful.

The minimum required dimensions of dam spillways mainly depend on the dimensions of LW. In particular tree lengths play a key role in the obstruction hazards of dam spillways. Since dam spillway safety considerations in extreme flood events are at stake, a conservative assumption should be made regarding the maximum expected tree lengths.

3.3 Numerical Modelling

Early approaches to numerical simulations of complex river systems and vegetation-flow behavior typically date from the period around 1990 to 2000, as Bertoldi & Ruiz-Villanueva (2015) show. These approaches often focused on the interaction of vegetation, biological growth, wood types, river morphology, and simplified hydrodynamics. The reference scale is often the entire catchment area (Lancaster & Hayes 2001). Technical structures and their complex flow behavior were rarely considered. These studies mostly refer to semi-natural and natural river basins. Recent approaches take into account the entrainment of wood, looking at the interaction between trunks and flow, and simultaneously for different wood types (Braudrick & Grant 2000, Bocchiola et al. 2002). The results of the numerical simulations are mostly simplified 1D or 2D projections, which are rarely compared to physical model experiments. A deterministic hydrodynamic simulation was reported by Ruiz-Villanueva et al. (2014) whereby hydrodynamic 2D calculations were correlated to wood entrainment.

Representing wood geometry in a numerical model is challenging. Allen & Smith (2012) investigated how geometric simplifications affect flow interactions. They focused on fish habitats in root systems but not on interactions between trunks with engineering structures.

In addition to the entrainment of LW, the obstruction process at bridges was numerically modeled (Mazzorana et al 2010, Ruiz-Villanueva et al. 2014). Simulations of bridge obstruction processes with models as well as in prototype could be reproduced satisfactorily with the numerical model. Through multiple simulations of the same scenario with different wood and bridge dimensions, conclusions could be drawn on the likelihood of obstructions. Numerical modelling can thus be used for risk analysis at dams, e.g. for the early identification of dam spillways that are in danger of being obstructed.

However, the reliability of numerical models regarding hydrodynamic processes of obstructions is still low. Hydrodynamic calculations during obstructions are only adjusted gradually. In addition, the residual dam spillway capacity in case of obstruction and the resulting backwater are not depicted accurately enough.
The accuracy of numerical simulations resides in the modeling precision of LW occurrences, and its transport within the catchment area down to the reservoir, or in the prediction of where the wood is likely to drift within the reservoir as a function of prevailing winds and waves. The informative value of numerical models for small-scale obstruction processes, and the impact of wood on dam spillways, is still very vague.

4. Survey and Case Studies

4.1 Hydropower Plant Operator survey in Switzerland

In December 2013, questionnaires were distributed to 60 operators of hydropower plants with reservoirs (no run-off river power plants), of which 52 were returned in full. The questionnaire can be found in Annex 1 and is structured as follows: The first part contains information on the dam, spillways and hydrology. The second part deals with the accumulation and handling of, and problems and damages due to LW. The results of the survey can be summarized as follows:

- At 46 out of 52 dams (88%), LW occurs;
- LW is removed at 32 of these 46 installations (70%);
- At 18 of these 46 installations (39%), LW is discharged through dam spillways (of which 7 of these installations also remove floating debris);
- Debris removal volumes are known at 5 installations;
- LW dimensions are known at 7 installations (of which the volume is also known at one installation);
- At 8 out of 52 installations (17%) problems (usually obstructions) have already been reported, and at 5 installations damages have been reported.

Figure 15 shows a geographical overview of the situation in Switzerland. Of the 52 dams of this survey, all have a forest-covered catchment area (altitude < 2000 m a.s.l.). Thus, LW occurs at virtually all dams below the timberline.
Since only 8 out of 52 dams have already incurred damage, a detailed statistical evaluation of the hazard potential was difficult to carry out due to the small sample size. In addition, many smaller dams were not included in the survey (e.g. Schlattli reservoir, where problems have been reported in 2010, see Annex 2).
The case studies in chapter 4.2 show that when there are large amounts of LW, the situation is often uncontrollable, and obstruction hazards and damage increase rapidly. A comparison with the guidelines also shows that many dam spillways do not meet the minimum recommended dimensions. It must therefore be assumed that at most dams no major flood containing large quantities of LW have occurred, and hence no problems have so far been observed. With a LW occurrence similar to the one at Palagnedra in 1978 or Schlattli in 2010, many current dam spillways in Switzerland would presumably get obstructed.

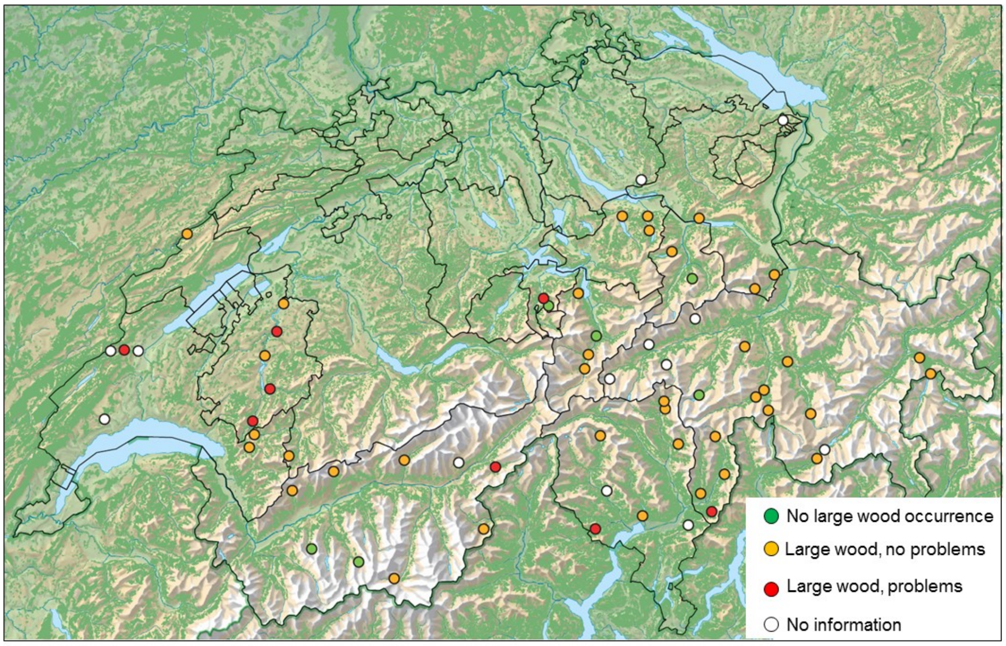


Figure 15: Results of the dam operator survey; no feedback was received from eight dam operators.

The feedback received was evaluated to establish correlations between the main features of the dam and problems caused by LW. From the available data, the type of dam spillway, the size of the catchment area, and the altitude of the dam were selected as criteria. **Figure 16** and **Figure 17** show the effects of these criteria on the occurrence of LW and the occurrence of problems at dam spillways. The following statements can be derived:

- Bell-mouth spillways generally present more problems than other dam spillway inlet types. Free overflow systems are the least troublesome. A higher risk of obstruction is to be expected at bell-mouth spillways due to their construction design.
- Problems related to LW occurred regardless of the catchment area size. However, larger catchment areas see a greater number of problems, as the LW accumulation potential increases with catchment area size among other factors (section 5.1.1). Since small volumes of LW can already lead to problems at dam spillways, the hazard potential for the latter in small catchment areas is not necessarily lower.
- Dams at lower altitudes are generally more vulnerable. The reasons for this are twofold: there is typically a larger forest cover in the catchment area, and larger tree lengths can be expected at lower altitudes.

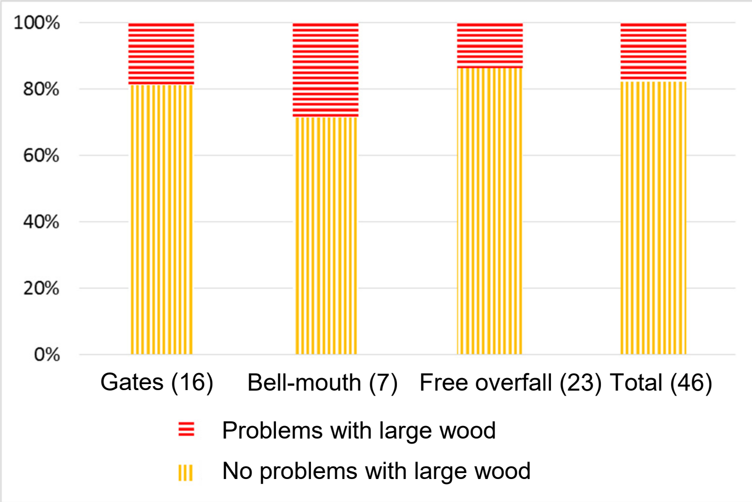


Figure 16: Influence of dam spillway type on the occurrence of problems due to LW. Number in brackets: No. of dams with respective spillway type.

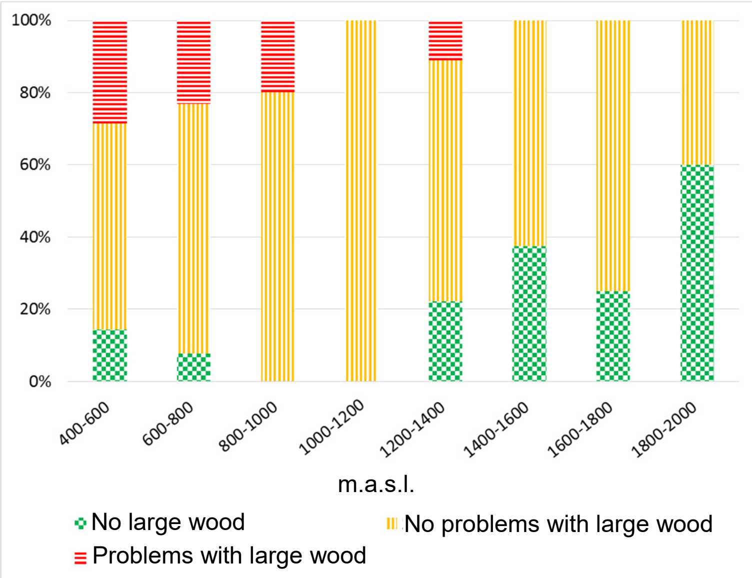


Figure 17: Influence of dam altitude on the occurrence of problems due to LW.

According to the survey, 17% of dams in Switzerland have experienced problems and damages due to LW (see above). In order to further estimate the existing hazard potential, the recommended dam spillway minimum dimensions according to the existing guidelines (chapter 3) can be compared with the actual dimensions. **Figure 18** shows the proportion of dam spillways that meet the required minimum width according to the Swiss Directive ($L_p \geq 0.8H_t$). Expected trunk lengths between 5 and 20 m were considered. With trunk lengths of 10 m, only about 50% of dam spillways fulfill the recommendations of the Swiss Directive. With trunk lengths of 15 m, there are only just under 15% of directive compliant dam spillways. A high dam spillway obstruction hazard potential therefore exists in case of a flood occurrence with a high amount of LW with long trunks.

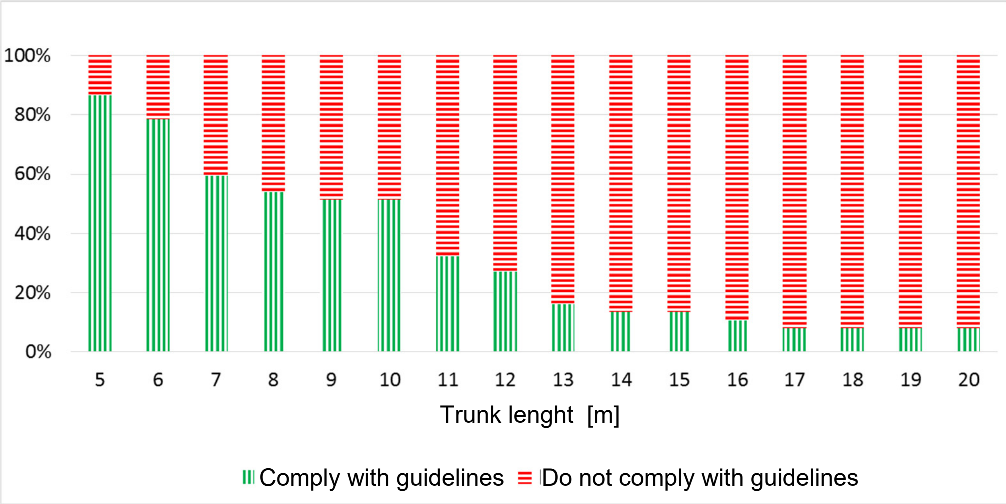


Figure 18: Percentage of dam spillways that comply or do not comply with the Swiss Guidelines (SFOE 2016) on minimum weir bay width, respectively, as a function of expected trunk lengths.

4.2 **Case Studies**

Several case studies from Switzerland were selected based on questionnaires and were further reviewed in detail (Annex 2). The following dams and flood events with LW accumulation and resulting problems were selected:

- Käppelistutz, flood event of August 2005;
- Schlattli, flood event of July 2010;
- Palagnedra, flood event of August 1978;
- Montsalvens, flood event of May 2015.

In addition, individual case studies from abroad are also discussed (Annex 2).

5. Criteria for Assessing Dam Spillways with regard to Potential Hazards

5.1 Entrainment and Transport of Large Wood

Smooth trunks with a mean wood density of 500 kg/m^3 can be entrained and transported in a body of water if the flow depth h is greater than half the trunk diameter d (Lange & Bezzola 2005), i.e. $h > d/2$. In model simulations for the Riemenstaldner torrent with supercritical flow (Froude number Fr = 2), smooth trunks were transported for a minimum flow depths of $1.0d$ to $1.2d$. To set trunks with branches in motion, flow depths of $1.2d$ to $1.5d$ were required. Trunks with roots only started being entrained at flow depths of $1.7d$ (Bezzola et al. 2002). According to Braudrick & Grant (2000), the following minimum flow depths h are required in subcritical flow with Fr = 0.75 for trunks with densities of 500 kg/m^3 that are located on the river bed parallel to the flow: (i) for branch- and root-free single trunks with relative lengths of $L/d = 15$, $h = 0.45d$; (ii) for single trunks with roots (index R) of dimensions $d_R/d = 2$ and relative lengths of $L/d = 15$ and 20, $h = (0.6 \ldots 0.65)\ d$; (iii) for single trunks with roots of dimension $d_R/d = 4$ and relative lengths of $L/d = 20$, $h = 0.9d$. A comparison of the minimum required relative flow depths results in smaller LW entrainment for subcritical flow than in supercritical flow. However, it should be noted that flow depths are higher in subcritical flow than in supercritical flow with identical discharge, roughness and slope (Boes et al. 2013).
For branch- and root-free single trunks, the effect of relative length L/d on the required relative water depth h/d is low for $L/d > 15$. The required relative depth of water increases for higher wood densities. For trunks with $L/d = 30$ and wood densities of 750 kg/m^3, h/d increases by about 20-30% compared to a density of 500 kg/m^3 (Braudrick & Grant 2000). The upper limit corresponds to root-free trunks, the lower limit to trunks with roots.

5.2 Large Wood Occurrence within the Natural Catchment Area

The amount of LW occurrence to be expected in case of a flood must first be clarified as a basis for any hazard assessment. In case of flooding, LW can enter into the reservoir tributaries or directly into the reservoir as a result of bank erosion or landslides. In addition, existing deadwood in the river ismobilized. The determination of LW potential is subject to great uncertainties. Estimates of the amount of LW can differ by a factor of two or more from the amount of LW actually being entrained. However, for obstructions to occur, the exact quantity of LW is of minor importance since even single large trunks and roots are sufficient to block a cross section. Any further LW would then be wedged in the accumulated wood and further reduce the cross-section.
There is no particular correlation between floods and the occurrence of LW, as the presence of LW and its entrainment are affected by many different factors. The shape and dimensions of LW have an influence on the time when it is carried downstream. The type of channels (e.g., narrow ravines) through which LW passes also influences the time as well as the distance of transport. Flow depths are an important factor in the transportation of LW, as shown in chapter 5.1. For example, the largest amount of wood is usually transported during flood peaks, as well as shortly before and afterwards.

The volume of wood in the catchment area and its entry into a reservoir can be determined with estimation formulas, which are based on databases of observed wood volumes (chapter 5.2.1). However, exceptional amounts of LW should be expected in design and extreme flood cases. For this purpose, as is the case with extreme hydrological considerations, it is recommended to use envelope curves (chapter 5.2.2). The most

costly yet very accurate method for assessing the risks posed by LW is a detailed analysis of the catchment area through field inspections and GIS analyzes (Schalko et al. 2017a). In addition to the amount of LW, information about its dimensions (chapter 5.2.3), buoyancy, and residence times (chapter 5.2.4) are also necessary.
Based on the flood history of the catchment area, even minor flood events can cause an accumulation of LW, while subsequent larger floods can displace less LW, if the remaining wood potential is small. Therefore, different scenarios must always be considered when estimating the amount of LW by means of empirical formulas or field assessments. The time interval since the last flood event with an important amount of LW entrainment is to be accounted for as well.

5.2.1 Empirical Estimation Formulas

Rickenmann (1997) evaluated documented amounts of LW during the flood events of 1987 and 1993 for several catchment areas in Switzerland, and derived empirical estimation formulas for actual LW quantities and potential. The database was further completed by documented flood events in Japan, Germany and the USA (Ishikawa 1989 and Uchiogi et al. 1996). Empirical estimation formulas allow to estimate the actual **LW volume *H*** [m^3] based on the following characteristics of the catchment area and the flood event:

- Catchment area size (Rickenmann 1997):

$$H = 45 \cdot EG^{2/3} \tag{5}$$

where EG = catchment area size in [km^2]. Validity range: EG = 0.054 - 6‘273 km^2. LW quantity H [m^3] defines the volume of loose wood (bulk factor a = V_L/V_F = 2 where V_L = loose volume and V_F = solid volume).

- Discharge volume (Rickenmann 1997):

$$H = 4 \cdot V_W^{2/5} \tag{6}$$

where V_W = discharge volume [m^3]. Validity range:
V_W = 2.16 - 390·10^6 m^3.

- Sediment load (Ishikawa 1989 and Uchiogi et al. 1996):

$$H = 0.02 \cdot F \tag{7}$$

where F =sediment load of flood event [m^3]. Validity range:
F = 380 - 50‘000 m^3.

Additional empirical estimation formulas are available to estimate the existing **LW potential H_{pot}** [m^3] based on the characteristics of the catchment area:

- Vegetation type in catchment area (Ishikawa 1989 and Uchiogi et al. 1996):

$$H_{pot} = C \cdot EG \tag{8}$$

where C = dimensionless coefficient depending on vegetation type. A distinction is made between coniferous forest ($10 < C < 1000$) and deciduous forest ($10 < C < 100$). Validity range: $EG < 100$ km^2.

- Forested catchment area (Rickenmann 1997):

$$H_{pot} = 90 \cdot EG_W \quad (9)$$

where EG_W = Forested catchment area [km^2], valid for EG = 0.76 - 78 km^2 and EG_W = 0.3 - 21.1 km^2.

- Forested bank lenght (Rickenmann 1997):

$$H_{pot} = 40 \cdot L_W{}^2 \quad (10)$$

where L_W = Forested bank length [km], valid for $L_W < 20$ km.

Further explanations on empirical formulas are given by Lange & Bezzola (2006). The formulas generally show large variations and are subject to uncertainties, as factors like annual flood frequency, history of the catchment area (last flood), bank conditions, or loss of slope and bank stability due to flooding are not taken into account. Empirical equations are also mainly based on surveys and observations in mountain streams with relatively small catchment areas.

5.2.2 Analysis of Past Flood Events

Analysis of past flood events regarding the actual entrained LW volume provides good indications for assessing hazards. If no flood events with LW entrainment are known in the catchment area under consideration, data from comparable catchment areas with similar hydrology, topography and forest cover conditions can be used. Results of observed LW volumes in Switzerland can be found in the analysis of the flood events of 1987 and 1993 (Rickenmann 1997), and 2005 (Bezzola & Hegg 2008). **Figure 19** shows observed LW volumes (solid volumes) depending on the catchment area, as well as the envelopes of Uchiogi et al. (1996, equation 8), and Rickenmann's estimate (1997, equation 5). Extreme events such as the 1978 one in Palagnedra come close to the upper limit for coniferous forests according to Uchiogi et al. (1996). For Swiss conditions with catchment areas EG <300 km^2, coefficients up to $C \approx 400$ in equation (8) appear realistic as initial indications or an extreme flood event.

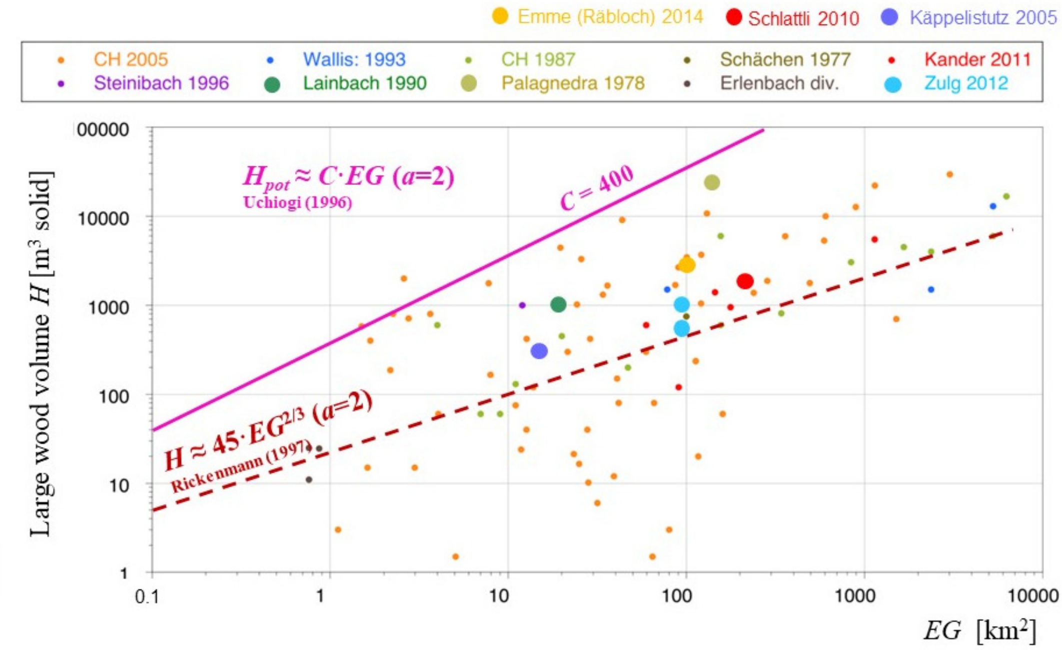


Figure 19: Observed solid large wood volumes in past flood events and estimation formulas according to Rickenmann (1997) and Uchiogi (1996) (bulk factor a = 2).

5.2.3 Large Wood Dimensions

According to Zollinger (1983), LW is exposed to enormous forces during entrainment. Trunks are quickly debranched in mountain streams after a few meters, peeled, and usually broken down into 1 - 5 m long pieces. **Figure 20a** shows the distribution of trunk sizes deposited after a flood along different Italian rivers (Lucía et al. 2015). About 50% of the recorded trunks were longer than approx. 5 m. Steeb et al. (2016) estimate that transported trees are reduced in size to about 20% of their original length (**Figure 20b**). The physical forces (sliding, passing through gorges) or the entrainemnt process (landslides, debris flows) play a greater role in reducing trunk sizes than the transport distance. There is also a relationship between trunk lengths and their diameters. The analysis of the 2005 flood event included systematic measurements of LW (Bezzola & Hegg 2007). Approximately 35% of the trunks were 4-6 m long. Almost 10% were longer than 8 m.

Flow depth and river width can also limit the maximum transportable trunk lengths. However, past flood events show that LW can also exhibit quite large dimensions (**Figure 20a, Figure 21**). Especially when landslides occur into a reservoir, trunk lengths are not much reduced. In many cases, large trunks or roots are sufficient to block the cross section of a dam spillway and initiate obstructions. For this reason, trunk lengths of up to 25 m were taken into account in the hazard assessment of the Swedish Trängslet reservoir (Boes et al. 2013). In order to estimate the hazard potential or the blocking probability (section 5th3), tree dimensions near banks or near reservoirs should therefore be used.

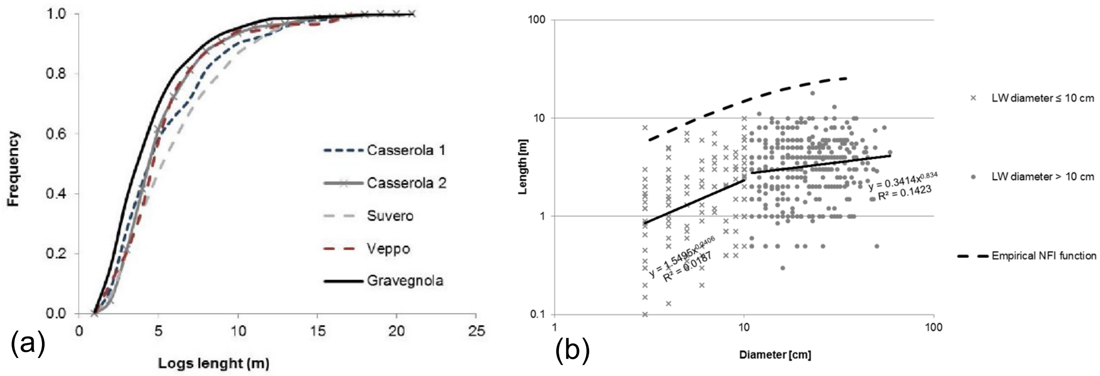


Figure 20: (a) Frequency distribution of trunk lengths that were deposited in different Italian river channels after a flood (Lucía et al. 2015); (b) Comparison of trunk lengths and diameters of transported trees during floods with the empirical NFI equation (relationship between stem length and diameter at breast height) (Steeb et al. 2016).

Figure 21: Large wood with trunk lengths of up to 15 m, which was removed from Gebidem reservoir (Photo: VAW).

5.2.4 Large Wood Floatability

According to Zollinger (1983), fresh wood usually remains buoyant for several months, which means that a withdrawal from the reservoir twice a year is sufficient. Concerning the floatability of wood, Zollinger (1983) also provides the following information:

- Spruce almost never sinks;
- Pine and larch wood may sink over time;
- Fir sinks after 2 - 4 weeks in wet conditions / after several weeks if initially dry when put in water;
- Beech rarely floats, it is completely submerged below the surface at best.

Deadwood that enters a body of water during a flood is sometimes no longer buoyant and may sink immediately. Further literature on the density of wood present in rivers can be found e.g. in Ruiz-Villanueva et al. (2016). Heavily loaded roots sometimes lose their buoyancy. LW of such type can also endanger inlet structures as well as low-level outlets. However, obstruction processes of these inlet structures is not part of the present investigation.

5.3 Reservoir and Tributary Influence on the Supply of Large Wood at Dam Spillways

The reservoir location and characteristics can affect potential LW hazards. Depending on the altitude, the existing LW potential is low (practically zero above the tree line), and high at lower altitudes. In addition, LW dimensions decrease with increasing altitude. Steep forested reservoir slopes increase the potential supply of wood due to wind, landslides, or falling trees. Landslides can occur in moderately to steeply sloping terrain. Landslide risks significantly increase for slopes > 25°. Wind, waves as well as rapid drawdown in reservoir water level can additionally destabilize banks, and thus lead to entrainment of LW in the reservoir itself.
Reservoir tributaries have a further influence on LW supply. In the Alpine region, streams are often narrow and/or feature gorges with steep banks. Trees that have fallen into the riverbed can remain in the water for years and prevent additional wood from being transported downstream (**Figure 22**). In the case of a flood, accumulated wood could suddenly break loose and be carried away into the reservoir (see Palagnedra case study).

Figure 22: Mountain torrent in Joffre Lake Provincial Park, British Columbia, Canada (Photo: Boes 2009).

Should wood find its way into a reservoir, it could further be transported not only by currents, but also significantly by wind. The shape and orientation of the reservoir thus has an immediate effect on whether entrained wood could move to the dam spillway without any actual flow current in the reservoir. LW can also accumulate over long periods of time in the back of a reservoir or near bank areas because of wind and only be transported to the dam in the event of a flood. In addition, the location of various reservoir flows can influence the overall flow pattern and hence transport LW around the reservoir. Low-level outlets of dams where reservoir water levels are drawn down for operational reasons such as desilting flushing cycles, must also be included in the hazard assessment. The lowering of water levels can generate relatively high flow rates, so that wood can be transported and get entrained into low-level outlets.

5.4 **Blocking Probability of Dam Spillways**

Various physical modeling tests on dam spillway blocking due to LW were performed in the past. Many attempts, however, have only focused on one particular structure. No generally valid statements are therefore possible. A further distinction needs to be made between dam spillway inlet structures, which are generally at the normal operation level, and discharge facilities with inlet structures sometimes located well below the storage water level, i.e. with pressurized flow. The following sections discuss general findings on the entrainment and transport of LW. LW transport over dam structures and blockage probability are subsequently considered, whereby a distinction is made between weir structures approached by frontal, radial, or lateral flows. Finally, special piano key weir features are discussed. In addition, analog conclusions are drawn for dam spillways with superstructures such as dam bridges, and on the blocking probability of bridges crossing water bodies.
The present study is limited to obstructions due to LW and other floating debris. There are no systematic studies on obstructions due to large floating objects such as silo bales, cars, etc. to the authors' knowledge.

5.4.1 Blocking Probability at Weirs

LW can remain on the dam spillway due to low overflow levels. The required flow depths at dam spillways for ensuring safe passage are little known. According to Zollinger (1983), the following minimum flow depths h are required for the transport of trunks with relative lengths up to twelve times their diameters, i.e. for $L/d < 12$, at overflow sections: (i) $h_{Weir} = 1.0d$ for single trunks; and (ii) $h_{Weir} = (2\ldots4)d$ for relatively loose LW stacks or clusters. h_{Weir} is the flow depth on the broad-crested weir, where the crest length is at least three times the overflow depth $h_{ü}$, i.e. $h_{Weir\ crest} \geq 3h_{ü}$. Since critical flow establishes on the broad-crested weir with $h_{Weir\ crest} = h_{cr} = 2/3H$, where H = energy head relative to the weir crest, the required flow depths (neglecting the small flow velocity) can also be given as follows: (i) (i) $h_{ü}/d = 1.5$ for single trunks; and (ii) $h_{ü}/d = 3\ldots6$ for relatively loose LW clusters.
According to Johansson & Cederström (1995), a single piece of LW at a dam spillway with large flow depth and only one open weir bay has the lowest likelihood of being blocked, since the trunk can align itself in flow direction. If several neighboring weir bays are open, or if LW emerges in clusters, obstruction hazards increase. Basically, the blocking risk increases with an increasing trunk length to weir width ratio H_t/L_p (Figure 12).
Hartlieb (2012) investigated the obstruction risk at dam spillways with segment gates on the basis of model simulations. Among various LW characteristics (length, density, number, and length of branches), its length in relation to weir bay width had the greatest influence on blocking probability. Individual trunks could almost always be passed,

since they were aligned with the flow. For clusters of five trunks the blocking probability increased. As the number and length of branches increased, so did the blocking probability. Density, however, had no significant effect on the blocking probability.
For a frontal and free overflow dam spillways with gates, Hartlieb (2015) presented the following formula to determine the blocking probabilty P:

$$P = (H_t/L_p - 0.96) \cdot 0.73 \tag{11}$$

where H_t = trunk length and L_p = weir bay width.

5.4.2 Blocking probability of Piano Key Weirs

To estimate the blocking probability of Piano Key Weirs (PKW) (**Figure 7**), a further development of labyrinth weirs, Pfister et al. (2013a, b) carried out model simulations. PKW are, as described by Pfister (2015), spillways with a disproportionately high unfolding length relative to the clear weir width. Accordingly, they have a relatively efficient discharge-level ratio (Leite Ribeiro et al. 2012). The complex crest geometry could, intuitively, be unfavorable for the accumulation of large wood, thereby increasing the blocking probability, at least in comparison to conventional overflow structures. Model simulations have shown, however, that this assumption is false. Two extensive series of model tests have led to this result. The following aspects were examined in the context of these series of tests:

- Blocking probability of single trunks to determine the beginning of the obstruction.
- Backwater in the reservoir as a function of a LW carpet.

If only individual trunks (without branches and roots) are considered with regard to the blocking probability, and if a reservoir with negligible flow velocities is assumed (no run-off river powerplant), model observations allow the following statements regarding PKW:

- If the diameter d of a trunk is greater than the overflow depth $h_ü$ or the approach flow energy head H, i.e for $h_ü/d$ < 1, the trunk usually remains blocked.

- If the trunk diameter equals about 2/3 of the overflow depth and thus the critical flow depth on the weir crest, i.e. for $h_ü/d$ ≈ 1.5, the blocking probability is about 50%. This observation was discussed by experts before the study, but never published to the authors' knowledge.

- If the trunk diameter is less than about 1/3 of the overflow depth, i.e. for $h_ü/d$ > 3, the trunk typically passes over the dam without obstructing.

Trunk lengths are not relevant, because the clear PKW width is usually much greater than the longest passing trunks. Rootstocks can obstruct passages more easily than trunks even for smaller overflow depths. However, data from model simulations scatter, as the possible rootstock configurations and shapes are unforeseeable. Yet, the observed relative overflow depths described above for trunks can be approximately halved for rootstocks. Aspects concerning overflows are discussed in chapter 5.4.2.

5.4.3 Blocking probability of Weir Bridges

Godtland & Tesaker (1994) have investigated, among other things, the influence of weir bridge structures at unregulated dam spillways. Blocking hazards were higher for dams with bridge structures than for those without. In addition, LW could remain blocked on these structures and exert additional forces. Due to the lack of literature on the general blocking risk for dams with weir bridges, a comparison with corresponding research on river bridges is given below.
Various formulas are available in the literature on the blocking of river bridges or bridge piers (Melville & Dongol 1992, Bezzola et al. 2002, Schmocker & Hager 2011). These formulas can be used to roughly estimate the blocking probability at dam spillways. However, most of the tests on bridges were carried out at high Froude numbers and flow rates, which can especially occur during torrent and river floods. Large debris such as trunks are therefore usually aligned in the flow direction, which generally reduces the blocking risk. Flow velocities in the case of incoming flows towards dam spillways are usually much lower, and do not support the alignment effect, which increases the blocking probability. The latter tends to be greater at low flow velocities and Froude numbers, as trunks may already be trapped at bridges and dam structures as a result of branches touching the bridge deck, weir crest, pillars, abutments or gates. The formulas given below thus only provide guidance and should be used carefully with respect to dam spillways.

The Lange & Bezzola (2006) equations were empirically determined with the help of 1'200 model tests. Various bridge cross sections and LW dimensions were examined and statistically evaluated. The blocking probability posed by single trunks P_L according to Lange & Bezzola (2006) depends primarily on the relation between trunk length L and width of the bridge cross-section B and is defined as follows:

$$P_L = 0 \qquad \text{for} \qquad \frac{L}{B} < 0.5 \tag{12a}$$
$$P_L = 0.133\frac{L}{B} - 0.066 \qquad \text{for} \qquad \frac{L}{B} \geq 0.5 \tag{12b}$$

The blocking probability for individual rootstocksP_R depends on the ratio between the mean dimension of the root plate D_R^* and the clearance height H of the bridge cross-section, i.e. the clear height between rivebed and bridge underside, and can be described as:

$$P_R = 0 \qquad \text{for} \qquad \frac{D_R^*}{H} < 0.6 \tag{13a}$$
$$P_R = 1 \qquad \text{for} \qquad \frac{D_R^*}{H} \geq 1.0 \tag{13b}$$
$$P_R = 2\frac{D_R^*}{H} - 1.2 \qquad \text{for} \qquad 0.6 \leq \frac{D_R^*}{H} < 1.0 \tag{13c}$$

where $D_R^* = (D_{RM}^2 \cdot D_{Rm} \cdot L_R)^{1/3}$ and D_{RM} = maximum root plate diameter [m], D_{Rm} = minimum root plate diameter [m] and L_R = trunk length [m].

Four types of bridges are distinguished according to Schmocker & Hager (2011) for calculating the blocking probability: (a) beam bridges, (b) truss bridges, (c) railing bridges and (d) baffle bridges. The larges blocking probability for individual trunks P_{LM} and individual rootstocks P_{RM} can be expressed as follows, depending on the Froude number Fr and the flow depth h:

$P_{LM} = 0$	for	$\frac{h}{H} \leq 0.9$	(14a)
$P_{LM} = 0.25z + (4 - z)(\mathrm{Fr} - 0.8)^2$	for	$\frac{h}{H} = 1$	(14b)
$P_{LM} = 1 - y(\mathrm{Fr} - 0.3)^2$	for	$\frac{h}{H} = 1.07$	(14c)
$P_{RM} = 1.17 - 0.55\mathrm{Fr}$	for beams, trusses and railings		(14d)
$P_{RM} = 0.91 - 0.69\mathrm{Fr}$	baffle bridges		(14e)

where h = flow depth, H = bridge clearance height and constants z = 2 and y = 1 for beam bridges, truss bridges and railing bridges and z = 0 and y = 2.5 for baffle bridges.

5.5 Backwater Rise due to Obstruction

An obstruction can have very small permeability due to the piling-up of branches, leaves or organic matter. It must initially be assumed for any hazard assessment, that the dam spillway obstructed by large wood is not permeable. Backwater rise in the reservoir due to partial or full dam spillway obstruction can be estimated by a retention calculation. Assumptions for partial obstructions may be taken from the Italian recommendations (Ruggieri 2015, chapter 3.2.4). As a result of obstruction, pressure from the water and wood on the dam spillway increases. These load factors must be taken into account for structural designs (chapter 5.5).

5.5.1 Frontal Approach Flow

General information on backwater as a result of dam spillway obstructions is seldom available in the literature. Yang et al. (2009) have run model simulations for the Laxede dam spillway in Sweden. As a result of the obstruction of the three-bay dam spillway, there was an increase of the reservoir water level by 16-27% compared to unobstructed conditions. In similar experiments, Hartlieb (2015) has observed a backwater rise of 20-30% caused by an obstruction. Schmocker (2017) has investigated the accumulation process at a two-bay dam spillway, and observed a backwater rise of about 30%. Schalko et al. (2017b) have investigated the dependence of backwater rise on the inflow Froude number, trunk diameters and the bulk factor of the accumulation, applied to bridge obstructions. The results can be used indicatively, but hold greater validity for high inflow velocities v > 1.0 m/s.

5.5.2 Piano Key Weirs

The study by Pfister et al (2013a, b) on piano key weirs has shown that excess backwater in the reservoir (**Figure 23**) is rather low. The following aspects can be given as reasons for this (Pfister et al., 2015):

- Piano key weirs fan out horizontally. The first contact point of LW with the weir, typically also being the point of obstruction, lies in the upstream predominant part of the weir crest length. The hydraulic pressure in this area is still low and a possible LW carpet is hardly ever compressed or pushed forward, but rather remains loose in a single layer.
- A significant portion of the incoming water rises steeply in front of the piano key weir and mainly reaches the inlet key. The water can thus flow underneath the obstruction, and is only slightly influenced by the latter.
- Piano key weirs built to date usually do not have pillars, and are often wider than transported trunks.

Practical experience has shown that the obstruction pattern is similar to the one obersved in hydraulic scale models (Pfister et al., 2015).

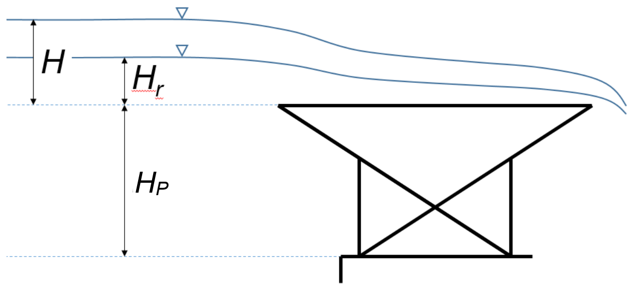


Figure 23: Overflow on a piano key weir for a given discharge, with H_r for overflow depth without LW, H for overflow with LW wood occurrence, and H_P for piano key weir height.

The relative overflow H/H_r in the reservoir caused by an obstructed piano key weir depends on the specific incoming large wood volume V/W (with V as solid wood volume, and W as total weir width), and on the overflow depth H (vertical distance between water level and weir crest with LW). The vertical distance between the water level and the weir crest without LW is referred to as the reference overflow depth H_r (for the same discharge as H, Leite Ribeiro et al., 2012). The following applies:

$$\frac{H}{H_r} \cong 1 + \tanh\left(0.007 \cdot \frac{V}{{H_r}^2 W}\right) \tag{15}$$

This backwater rise is generated by several incoming LW piles, which contain a representative distribution of different trunk lengths and roots. It can generally be observed that the initial pile already generates an obstruction. The blocking probability P is approximately:

$$P = \tanh\left(0.15 \cdot \frac{V}{H_r^2 W}\right) \tag{16}$$

Equation (16) allows an estimation of the probability that a LW pile will lead to an obstruction. If this is the case, its influence, and that of all subsequent LW piles at the surface of the reservoir can be estimated with equation (15). The application limits of both equations are described in Pfister et al. (2013a).
Piano key weirs seem to be less sensitive to LW, as the resulting pressure applied to the structure is low, and the LW carpet that forms remains loose However, floating trunks can get caught under the overhangs, as first experiments have shown (BAW 2016).

5.6 Impact Forces on Dam Spillways

LW can put the operational safety of dam spillways at risk in a number of ways: (1) damages due to impact of debris, and pressure due to obstructions during high water levels; (2) blocking flap gates, underflow gates or other mobile devices, including their mechanisms (e.g., automatic regulation); or (3) discharge reduction due to obstructions and backwater rise in the reservoir.
The dam spillway and all associated equipment must withstand the impacts of laLW. Depending on the shape of the reservoir and the location of the dam spillway, flow

velocities may increase sharply, especially near the overflow and outlet sections (e.g. Schlattli dam, see Appendix 2). The "trunk impact" load case should therefore be checked during flood relief, although it is usually not decisive (e.g., Kälin et al. 2005).
However, individual trunks can already jeopardize the operational safety of flaps and gates. A wedged trunk is already sufficient for blocking their drive mechanisms or for affecting automatic regulation systems. Due to the pressure of the incoming flow, the manual removal of wedged debris during a flood is not possible. When there are high amounts of LW, it is best to prevent the use of movable regulation devices.
If the dam spillway is partially or fully obstructed, the flow capacity decreases, leading to backwater rise in the reservoir (section 5.4). This can lead to an additional load on the dam structures.
Additional load forces occur during obstructions at dam spillway. Based on model simulations Godtland & Tesaker (1994) recommend the following empirical formula for the additional force F (dynamic pressure, currents underneath the obstructing material, and the influence of wind on the latter) on a dam structure as a result of an obstruction:

$$F = C_w b_k \left(30 \cdot T + L_K\right) \rho_w \frac{v_s^2}{2} \qquad (17)$$

where:
- C_w Drag coefficient
- C_w 0.06 for $v_s < v_{su}$; C_w = 0.08 for $v_{su} < v_s < 1.1 \cdot v_{su}$; C_w = 0.1 for $v_s > 1.1 \cdot v_{su}$
- v_s flow velocity at water surface [m/s]
- v_{su} flow velocity underneath the obstructing material [m/s]
- b_k Width of the obstructing body [m]
- T Height of the obstructing body [m]
- L_k Length of the obstructing body [m]
- ρ_w Density of water [kg/m^3]

As a result of high flow velocities, not only do the compactness of the obstructing body and the upstream water level increase, but so do the additional pressure loads. For a flow velocity of approximately v = 0.4 m/s, the forces increase as the obstructing material begins to be submerged in the water.

6. Measures

6.1 Structural Measures for the Passage of Large Wood

6.1.1 Adjustments of spillway Dimensions

One way to minimize obstructions due to LW is to ensure sufficiently large dimensions at the dam spillway inlet structures. The guidelines for width and height dimensions according to chapter 3 can be used as a design specification. An unregulated dam spillway (e.g. free overflow) has a smaller risk of getting obstructed than a regulated dam spillway under identical conditions. Although trunks can be deposited on the weir crest at low flow depths (see chapter 5.3.2), they are usually removed with increasing discharge. Intermediate pillars, flaps, vertical gates, weir bridges, etc. generally increase the likelihood of obstruction. However, the type of regulating structure also has an influence on the likelihood of obstruction. Undercurrents (e.g. at vertical lifting / lowering gates) are to be avoided in critical conditions, whereas overflowable regulating structures such as flaps, drum and sector weirs tend to be less susceptible to obstructions. Such regulating structures may even be advantageous because overflows can be directed and concentrated at the center of dam spillway inlet structures. These structures may be able to loosen blocked single trunks due to the high hydrodynamic forces (Hartung & Knauss 1976). Flaps are advantageous for producing locally larger flow depths which reduce the likelihood of wood blocking (Boes et al. 2013, **Figure 24**).

Figure 24: Flood spillway inlet structure in a collecting channel with flaps. Left: top view of a dam spillway model of the Trängslet Dam in Sweden with single-bay flap gate at the downstream side of the weir (Lucas et al. 2015); right: multiple-bay weir with flap gates and flow disturber at the Punt dal Gall dam (Photo: Boes, 2009).

An adaptation of the weir bay clearance dimensions can e.g. be achieved as follows:

- Removal of dividing pillars to increase the clearance width of the weir bay (e.g. Reservoir Gstins, see Annex 2);
- Remove or relocate weir bridge to increase clearance height (Palagnedra Reservoir, see **Figure 10**);
- Removal of movable regulation structures and replacement by a fixed but longer overflow weir crest (**Figure 25**).

Figure 25: Spillway inlet structure in the form of a labyrinth weir with a large overflow crest and clearance width at Sternenweiher (Canton of Zurich, Switzerland) (Photo: Boes, 2015).

Hydraulic model simulations are advantageous, particularly in the case of new projects where there is a risk of dam spillway obstruction.

6.1.2 Design of Spillway Inlet and Transit Structures

In the case of LW occurrences of high likelihood or frequency, various recommendations from the literature (Hartung & Knauss 1976, USBR 1987, Gotland & Tesaker 1994, Wallerstein et al. 1996) should be taken into account for the design of weirs, pillars and dam spillway transit structures which are summarized hereafter:

- In general, dam spillways should be as smooth as possible, rounded and built without installations. Structural components which are obstruction-prone should be protected with casings;
- Drive shafts, cylinder, hydraulic lining, etc. of regulation structures should be located outside the area of LW impact;
- Self-regulating systems should be avoided;
- In weir bays with gates the flow should be concentrated in the center. In the case of several weir bays, it is optimal to obtain asymmetric flow dynamics as long as possible, i.e. two adjacent gates should not be opened at the same time which would cause a debris wedging flow effect;
- In the event of backwater rise following obstruction, the weir superstructure should also be able to withstand the impact of LW (chapter 5.5.);
- In general, coarse rakes should not be placed directly at the weir crest as this will facilitate obstruction and thus reduce the discharge capacity, even for small amounts of LW;
- Pillars always increase the risk of obstruction due to low flow velocities that facilitate wood blocking at individual pillars. Because of such obstructions, an entire weir bay may become blocked;
- Model tests on bridge pillars indicate that rounded pillar heads are generally less vulnerable to LW obstructions than rectangular pillars or pillars with sharp edges;
- Abutments, plant ducts, railings or truss constructions favor obstructions;

- Bridges and pedestrian footbridges should have a minimum clearance of 1.5-2 m from the water level of the design flood according to SFOE (2008). In addition, footbridges should be built so that they can be quickly removed or washed away in an emergency;
- According to Rickenmann (1997), new or modified weir systems have to be dimensioned with weir width clearances of at least 10 m, even better with 15 m. In addition, new structures should be constructed so that in the event of an overflow, they do not represent an obstacle for LW, i.e. without superstructures;
- For circular spillway cross sections, the minimum diameter should be 5 m. Care should be taken to ensure a smooth lining without constrictions or obstacles and sharp bends (Hartung & Knauss 1976). For non-circular tunnel cross-sections with a surface A_{St}, a computational equivalent minimum diameter $d_{eq,min} = (4 \cdot A_{St}/\pi)^{0.5}$ may be used;
- Piano key weirs present several advantages regarding LW. The excess backwater caused by a small discharge is rather low, and LW tends to be transported downstream over the weir during a large discharge.

Hydraulic model simulations including LW are applicable especially in the case of new projects where the obstruction hazard and the damage potential are high, so that the design of the dam spillway can be checked and optimized if necessary.

According to Hartung & Knauss (1976) and Hartlieb (2015), LW can also be retained by means of a single or several pillars, or aligned longitudinally and thus discharged via the dam spillway. **Figure 26** shows such a rectifying pillar in front of a bypass tunnel on the Rovana (Canton of Ticino, Switzerland). The pillars should be built with sufficient distance to the dam spillway. Since the pillar shape has little effect on the effectiveness of aligning woods, a circular cylindrical pillar is advisable for cost and construction method reasons (Waller et al. 1996).

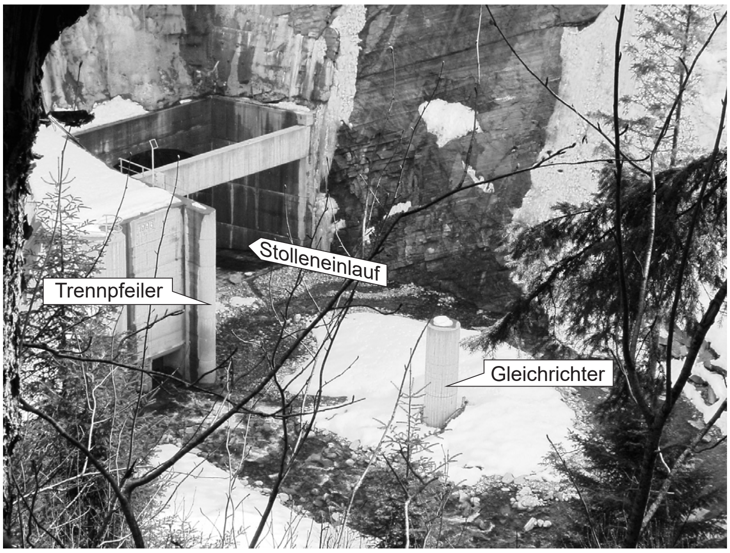


Figure 26: Rectifier in front of the bypass tunnel on the Rovana River, Switzerland (Lange & Bezzola 2006).

6.1.3 Design of Energy Dissipation Structures

The energy dissipation structure must also be considered for the passage of LW. LW transported at high flow velocities would damage the internal protrusions in stilling basins, such as various obstructions and rows of blocks. Hartung & Knauss (1976) recommend spatial (three-dimensional) stilling basins with an ascending base in the direction of flow (**Figure 27**). Chute blocks at the end of the inlet channel leading to the stilling basin usually do not pose problems regarding LW, since they are flush with the bed at their upstream end so that any debris is transported over them. However, there are abrasion and damage hazards due to LW especially on steps and end sills.

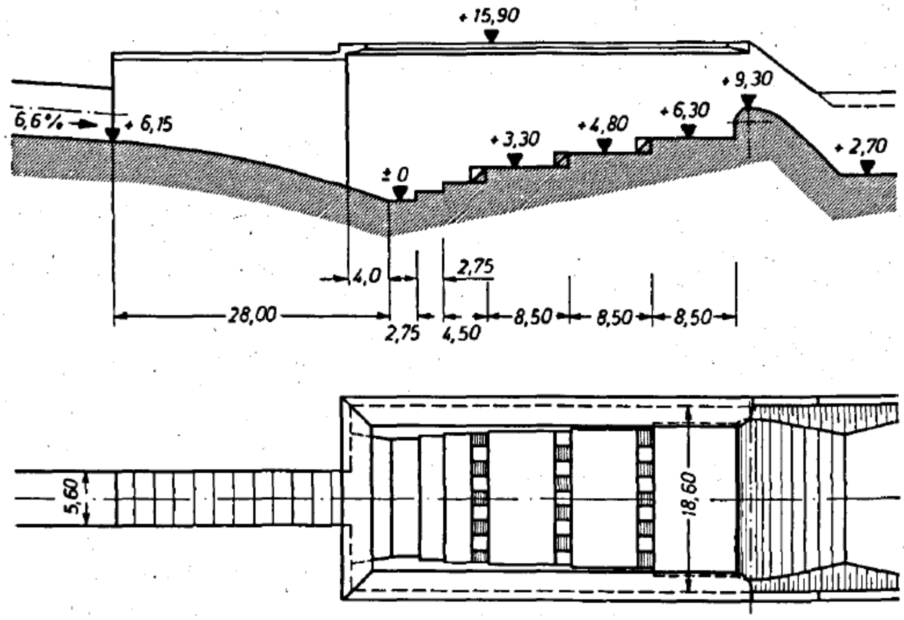


Figure 27: Example of a spatial stilling basin (Hartung & Knauss 1976)

6.2 Retention Measures

6.2.1 Dam Spillway Protection with Trash Racks

As a rule, coarse rakes should only be installed in front a dam spillway if other adaptations, i.e. in shape/design of the dam spillways are impossible and/or passage of debris is not permitted. Racks can prevent the blocking of movable parts and thus guarantee the operational safety of gates, flaps, etc. In addition, the complete obstruction of the dam spillway is prevented. In case of a flood, however, the rack itself can be blocked and result in a backwater rise in the reservoir. In order to keep the backwater rise low, the rack should have a correspondingly large surface and be located fairly upstream of the dam spillway. Thus, even when the rack is completely blocked, water can flow beside or under the rack in direction of the dam spillway. The average flow velocity with regard to the cross section of the rack should be less than 1.0 m/s. Various examples are shown in **Figure 28** to **Figure 31**.
Hartlieb (2015) has carried out hydraulic model tests with an oblique up-sloping rack in front of a dam spillway. The rack was inclined (15° to 30°) and the bar distance corresponded to half the width of the weir bay. As a result, the backwater could be reduced by up to half in comparison to an obstructed weir. The reason for this are the smaller flow velocities that act on the upstream rack, so that wood rather deposits in the form of a loose, single-layer carpet.

Instead of a rack placed directly in front of the spillway inlet (**Figure 31a**), Hartlieb and Overhoff (2006) installed ten vertical rack pillars in the hydraulic model for the Grüntensee dam (Bavaria, Germany). These are arranged in a semicircle and are placed far away from the inlet (**Figure 31b**). The clearance distance between the pillars is around 1.6 m (approximately the width of the narrowest part of the dam spillway). Compared to the existing rack, the inflow velocities as well as rack losses are much lower. This prevents LW from being pulled down, completely blocking the rack cross section. At the surface of the water, a LW carpet forms which continues to grow. Should individual trunks pass the retention structure and reach the dam spillway, they would already be aligned in the direction of flow and can be transported downstream. After a flood, remaining LW must be removed.
The clear bar spacing of LW racks should not be too small. Small pieces of wood and finer material which are not critical for the dam spillway should not be retained. However, large trunks exceeding the dimensions of the smallest clearance of the dam spillway should be blocked at the racks. According to Lange & Bezzola (2006), it can be assumed as a guideline that wood with a length of $L \geq 1.5 \cdot s$ can be retained at a rack with a clear bar spacing of s.

Figure 28: Large wood rack at the Paalbach dam in Austria (Photo: Federal Ministry of Agriculture, Forestry, Environment and Water Management Austria).

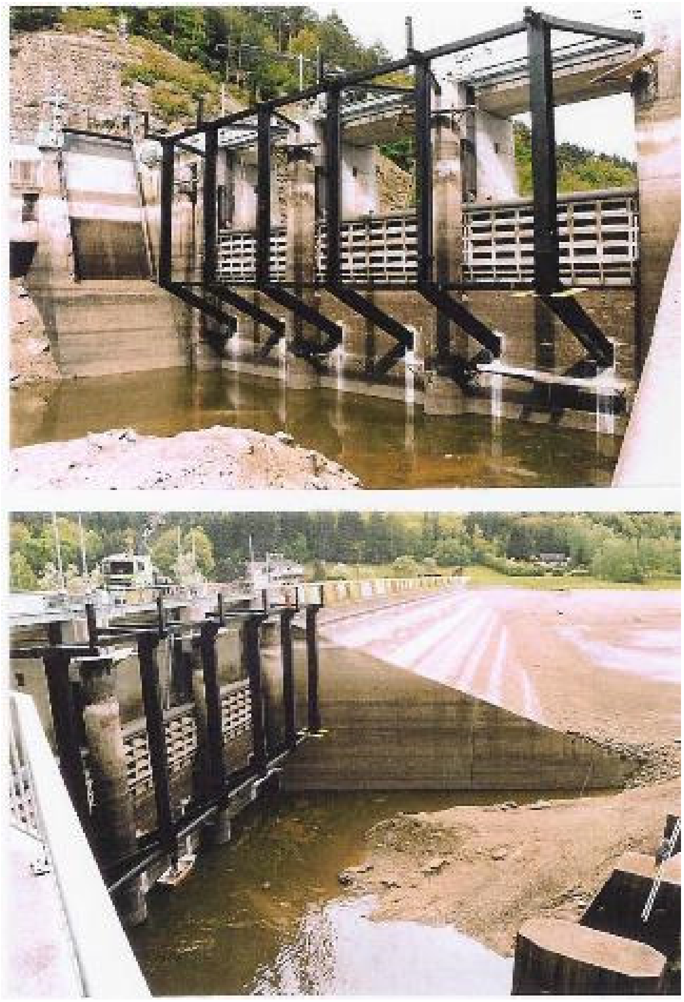


Figure 29: Large wood rack at the Thurnberg reservoir at RiverKamp in Austria (Photo: Federal Ministry of Agriculture, Forestry, Environment and Water Management Austria).

Figure 30: Upstream large wood rack at Rotlech Dam in Austria (Photo: Federal Ministry of Agriculture, Forestry, Environment and Water Management Austria).

Figure 31: a) Old spillway with large wood rack at Grüntensee and b) new upstream rack pillars (Photo: Hartlieb 2015).

As an alternative to the use of racks, LW can be retained by means of scum boards or skimming walls. Installation of an upstream skimming wall has proven to be a suitable measure to prevent the entry of wood into the bell mouth spillway at the Kelchbach in Naters, Switzerlan (**Figure 32**).

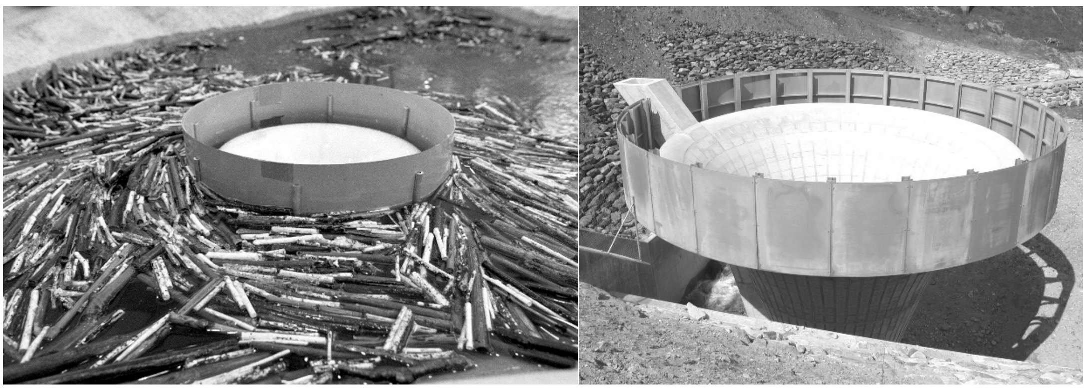


Figure 32: Bell mouth spillway with skimming wall in debris retention basin at the Kelchbach in Naters, diameter of approximately 14 m. Left: Model Experiment; right: Prototype (Photos: Lange & Bezzola 2005).

However, it is important to ensure that skimming walls have a sufficient depth of at least 1 m below the water surface. For highly fluctuating water storage levels, this can only be achieved with floating baffles. Nevertheless, depending on the LW residence time in the water, there is a risk that floating debris will be transported underneath such baffles.

6.2.2 Retention by means of Floating Barriers (Tuff Booms)

According to Hartung & Knauss (1976), floating barriers (**Figure 33**) can be used to retain LW during flood events. Examples are (Perham 1987, 1988):

- Interconnected long trunks and floating steel tubes with diameters of at least 0.25 m. Typical diameters are 0.6 m to 1.0 m. Trunks wear out quickly in the area where they are attached together, and are only suitable as a temporary measure;
- Light and walkable steel bridges on floating elements. These also serve as a working platform for the removal of LW after a flood event. Platforms however show a tendency to be lifted onto LW carpets in case of large amounts of wood.

Floating barriers can be equipped with an underwater net made of chains to reduce the passage of wood in general, and of floating fresh wood in particular. Floating barriers can be used to retain LW or to deflect it in a certain direction. Deflection serves to guide the LW to a specific passage area, or to keep it away from critical areas.

Figure 33: Large wood barriers on Lake Brienz during the 2005 flood event (Photo: Federal Office for the Environment, Switzerland).

Bradley et al. (2005) give an overview of measures for the retention of LW and also refer to floating barriers. In their opinion, these can be used only in a very limited way. They are suitable as a measure for ‘small’ and ‘medium’ LW dimensions and volumes. Perham (1987) describes practical experiences with floating barriers in detail.

The following aspects should be considered when using floating barriers:

1. Chain stability and its attachment to the shore;
2. Wear of the floating elements and their temporal change in buoyancy (wood saturation);
3. LW retention capacity;
4. Fluctuating water levels in the reservoir.

Aspect 3 can only be answered to a limited extent by physical model simulations. Usually only flow forces are applied in a model, while the influence of wind and waves is typically neglected. Nevertheless, model simulations show which arrangement has a high retention capacity. The model simulations by Perham (1987) provide information on the required shape of the floating barrier, its retention capacity and the permissible discharge velocity.

With very long floating barriers in the reservoir, there is a risk that LW may sink under the floating barrier, especially if the wood has been in the water for a long time and exhibits a higher density. In strong currents, the wood can also be transported underneath the retention structure. The corresponding forces of LW on the retaining elements should also be taken into consideration. In the case of dams that are not subject to flooding in winter, floating barriers should be removed during the cold season as possible ice drifts could damage or destroy them. For the calculation of the barrier length, consideration should be given to a possible emptying of the reservoir, so that the chain is not left hanging in the air.

Forces acting on an obstructed floating barrier are considerable. These are induced by waves, the water flow pressure, and by wind. The barrier and its attachments (abutment, anchor, buoys, etc.) are to be dimensioned accordingly. In addition to static aspects, the flexibility of the barrier must also be considered since the water levels can sometimes fluctuate considerably.

A floating barrier failure would lead to the sudden emergence of a large and compact volume of large wood. Experience has shown that this is one of the most sensitive scenarios for a dam spillway inlet structure obstruction. In addition, a broken floating barrier consisting of interconnected long cylinders could itself cause an initial obstruction, and thus worsen the situation.

In some dams on the Kamp River in Austria so-called floating racks are used (floats with suspended tension cables approximately 1 m below the water surface) (**Figure 34**). However, problems were also encountered when underdesigned tension cables snapped during floods (Czerny, 2015). This caused a sudden LW accumulation at the dam spillway.

Figure 34: Floating rack (Photo: H. Czerny, Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria).

Experience with the application of LW barriers on Lake Thun, Lake Brienz and Lake Biel in Switzerland have shown the following:

- Due to strong currents, LW barriers should not be placed directly in front of weirs, but rather further upstream in the lake;
- Attachment buoys often have to be placed in shallow areas of large lakes, where the currents are still very strong. LW can thus pass more easily under the floating barrier;
- Floating barriers are only fastened during daylight and with little wind (max 3 – 4 Beaufort or 3.5 to 8 m/s) as operations are otherwise too dangerous and buoys may be lifted or pushed down by LW due to waves;
- Since the wind often turns after heavy precipitation, LW is removed as quickly as possible from the barrier. Otherwise it could be blown away from the retention structure by the wind, and scattered over the entire lake.

In summary, it can be stated that at low flow velocities, floating barriers can be used as a tool for retaining and guiding LW. In flood situations with high amounts of LW, however, the robustness of floating barriers cannot be guaranteed as shown by several failures (**Figure 35**); see also the Montsalvens reservoir case study in Annex 2. Such failures are to be avoided under any circumstances during extreme flood events since this could massively increase the dam spillway obstruction risk, thus negatively affecting dam safety.

Figure 35: a) Broken Large wood barrier at the Montsalvens dam (Canton of Fribourg, Switzerland) during the 2015 flood event (Annex 2, Photo: Groupe E); b) Hydroelectric power plant Tulu Ter, Malaysia: Floating barrier with large volumes of large wood at the bypass tunnel inlet (Photo: Worthington).

6.3 Operational Measures

To avoid obstructions in multi-bay regulated weir systems, a complete opening of a few weir bays is preferable compared to the partial opening of several or all bays. In weir bays with gates the flow should be concentrated in the center of the weir bays to reduce the probability of obstructions at the pillars. Optionally, asymmetric operation may be sought for multiple weir bays, i.e. only non-adjacent weir bays are opened (**Figure 36**) as long as the flood discharge permits. Trunks would thus align more easily in the direction of flow and the probability that they should remain stuck at separating pillars between two weir bays is reduced.
However, apart from Hartlieb (2015), there are generally no systematic investigations on weir spillway control, and the effectiveness of measures is therefore not conclusively proven. In extreme cases, most of the weir bays would usually be needed, and asymmetric operation is therefore no longer possible.

Figure 36: Obstruction at opened weir bays of a three-bay weir system (Hartlieb 2015)

7. Conclusions and Recommendations

The recommendations of this study are summarized as follows:

Hazard assessment diagram

When examining an existing dam spillway and/or building a new one, it is recommended to use the hazard assessment diagram (**Figure 37**). Thus, a rough hazard assessment of the dam spillway and the dam itself can be performed. The procedure is as follows:

1. Collecting/determining basic information on the dam spillway (type,dimension, etc.) as well as determining the impact (flood loadcases, volume of large wood, dam spillway hydraulics);
2. Review of the recommendations for minimum dam spillway dimensions and estimation of the blocking probability;
3. Assessment of the obstruction consequences;
4. Decision as to whether there is a risk for the dam due to LW or not;
5. Development of measures to reduce the risks for the dam

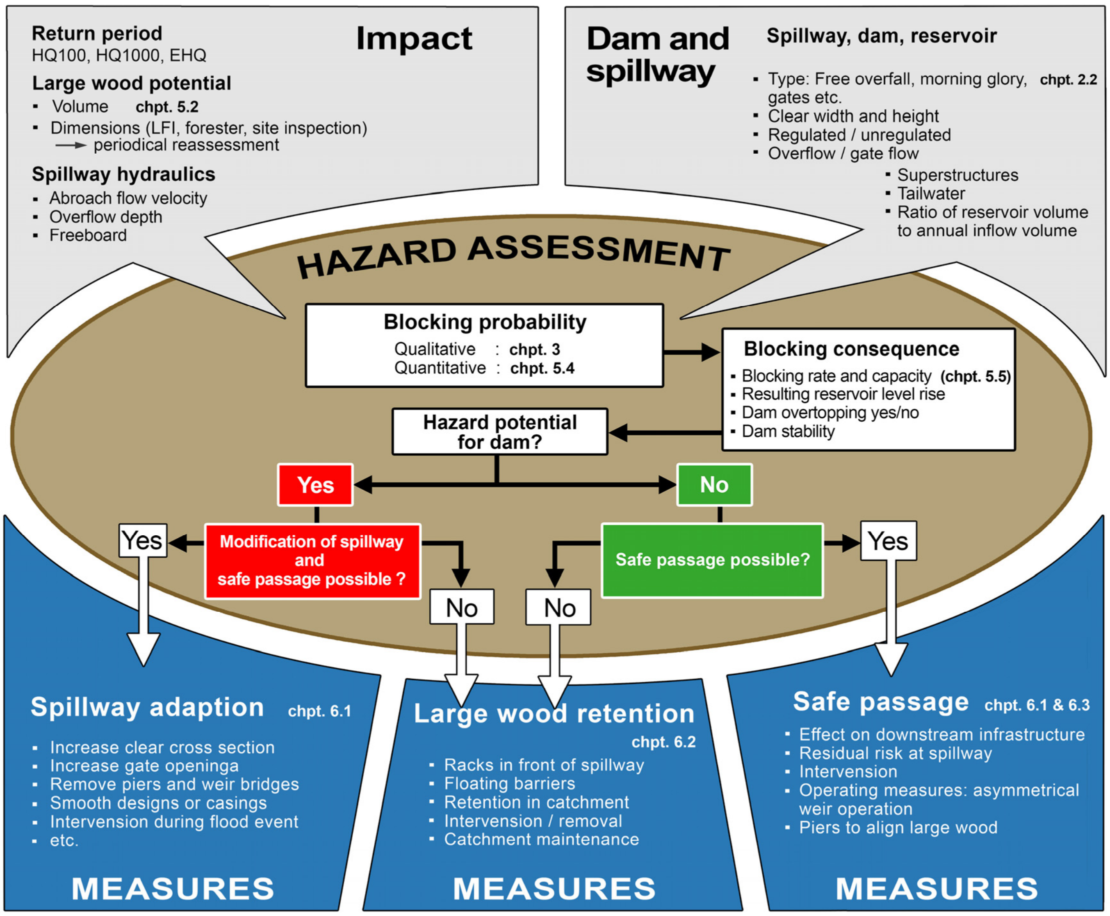


Figure 37: Hazard assessment diagram regarding floating debris at dam spillways.

Impact on spillway

- Dam spillways must ensure a safe flood discharge capacity in the case of an extreme event (safety check flood) and must not increase the probability of dam failure. Complete failure of the dam is not acceptable. However, in the case of the safety check flood, damage to the dam spillway may occur as long as it does not lead to major water releases. Load case assumptions with extreme amounts of LW must therefore be assumed. For LW potential under Swiss standards, equation 8 (chapter 5.1.1) of Uchiogi et al. (1996) with a coefficient of C = 400 can be used as a first reference value. However, a detailed analysis of the catchment area is imperative in order to obtain reliable data regarding the amount of LW. In addition to LW, large buoyant bodies such as boats, silo bales, containers, etc. must be expected in situations with settlements and infrastructure in the catchment area.
- For calculating the blocking probability, estimation equations from the field of flood mitigation give initial indications. Trunk dimensions should be chosen in a conservative way. In extreme cases, this corresponds to the maximum tree height available in the shore area of the reservoir or in the nearer catchment area.
- To estimate backwater rise in the reservoir as a result of an obstruction in an extreme event, it is assumed that a rack is blocked completely. Estimation of the forces on the rack and the dam spillway must be made on this basis.
- Uncertainties with regard to the amount of LW and the processes of obstructions persist even with elaborate studies. In case of doubt, hydraulic model tests are indispensable.

Dam Spillway Design / Adaptation

- Broad and fixed overflow structures without superstructures have the lowest risk of being obstructed and are preferable to regulated weirs with narrow gates and weir bridges.
- Smooth, rounded components are less conducive to LW blocking. Casings for system components which are subject to obstruction risks increase the efficiency for the passing of floating debris.
- If possible, measures should be considered to ensure that the dam remains fully or partially overload-resistant, even if the dam spillway is obstructed. A separate emergency dam spillway may be included which can come into effect only when higher water levels are reached.
- The geometrical dimensions of the dam spillway should preferably be determined according to chapter 3.1.

Retention

- When choosing retaining structure types, local conditions (amount of LW, design of dam spillways, flow velocities, etc.) must be taken into account. Likewise, the removal and transportation of floating debris (in particular, costs and accessibility), disposal, as well as the cleaning of racks must be included in planning considerations.
- No racks should be placed immediately in front of or on top of the weir. Racks should be placed at a sufficient distance from the dam spillway crest and have both a sufficient bar immersion depth and height above the highest attainable

level of the reservoir. The average flow velocity regarding the cross-section of the rack should be less than 1.0 m/s. For rack structures, an adequate bar spacing must be selected. The clear bar spacing should be $s \leq L/1.5$ to retain LW of length L.

- Floating barriers are not recommended for use at dam spillways that must function safely in extreme event situations.
- If a partial flow is directed away from the dam spillway (for example partial outflow during floods directed to another dam spillway), the rejection of floating debris by means of skimming walls may be interesting for reservoirs with small water level variations (about ±0.3 m). These should protrude at least 1.0 m below the water level to prevent wood from being transported underneath the wall.
- The retention volume is to be dimensioned according to the estimated amount of LW.
- Accumulation of LW in a reservoir during flood events cannot be ruled out, even with measures taken within the catchment area.

Passage of Floating Debris

- If conditions downstream of the dam, and the design of the dam spillway permit, it is desirable to enable the passage of floating debris.
- Management of residual risks such as overload cases should be included in safety considerations.

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Annex 1: Survey Questionnaire

Questionnaire

1. General data

Name of Dam (if necessary of the Reservoir): ____

Name of River: ____

Operator: ____

Contact person: ____

2. Hydrology and water resources

Please indicate whether measured (M), calculated (R) or estimated (S)

Low discharge NQ [M^3/ s]: ____

Average discharge MQ [M^3/ s]: ____

Flood discharge HQ1 [M^3/ s]: ____

Flood discharge HQ100 [M^3/ s]: ____

Design flood HQ1000 [M^3/ s]: ____

Safety check flood SHQ [M^3/ s]: ____

Catchment area of the Dam [km^2]: ____

Full Supply Level [m asl]: ____

Minimum Operating Level [m asl]: ____

Reservoir volume at full storage (water level at full supply) [m^3]: ____

3. Information on the dam spillway type

Type of inlet structure (e.g., bell mouth, frontal/lateral weir,...): ____

____

Regulated/unregulated (if regulated, how?): ____

Number *n* of spillway sections (e.g. n= 3 weir bays, n = 1 bell mouth, ...): ____

Other discharge structures (without headrace, e.g. bottom outlet, middle outlet, ...): ____

____

Capacity of dam spillway at full storage [m^3/s] (without bottom or middle outlets): ____

Calculated water level for the design flood of n spillways (excluding bottom or middle outlets) [m]: ____

Calculated water level for safety check flood [m]: ____

Dimensions of dam spillway, W x H or D [m]: ____

Flow depth at spillway inlet for flood discharge [m]: ____

Dam spillway inclination in relation to water surface [-]:

How often is the dam spillway in operation on average?

Capacity of the bottom outlet at full storage [m³/s]:

Dimensions of bottom outlet B x H or D [m]:

How often is the bottom outlet in operation on average?

Capacity of any other spillway systems (e.g. middle outlet) [m³/s]:

4. Large wood / Floating Debris

Does large wood occur at this installation? Yes ☐ No ☐

If yes, is large wood removed? Yes ☐ No ☐

If yes, type, location and removing frequency?

Is large wood passed through/over the dam spillway? Yes ☐ No ☐

If yes, what operational measures are being implemented (if applicable)?

Is there information on the amount and dimensions of removed large wood? Yes ☐ No ☐

If yes, please separately include data (amount, date)

Is there any available information on large wood dimensions? Yes ☐ No ☐

5. Damages

Have any problems due to large wood ever been encountered? Yes ☐ No ☐

If yes, description of the problems or damage?

Have damages been documented (photos, sketches, etc.) Yes ☐ No ☐

6. Documents

Is it possible to obtain plans of the dam spillway? Yes ☐ No ☐

Is it possible to obtain documentation of the damage? Yes ☐ No ☐

7. Other / Remarks

Is a large wood rack or other measures planned? Yes ☐ No ☐

If yes, are there plans / sketches? (please enclose)

Completed on (date): Name:

Signature

Annex 2: Case Studies

1) Käppelistutz

Käppelistutz

Name of dam	Käppelistutz
Name of river	Secklis river
Operator	Kantonales Elektrizitätswerk Nidwalden
Reservoir volume	60‘000 m^3
Lake surface area at full supply level	10‘050 m^2

Hydrology		**Catchment area**	
Flood HQ_{100}	96 m^3/s	Surface area	24.2 km^2
DesignFlood HQ_{1000}	118 m^3/s	Vegetation cover	28%
Full supply level	795.50 m asl	Dam crest level	795.5 m asl

(Dam Spillway) (Type, inlet structure, regulated/unregulated, number of oulets, bottom outlets etc.)

Type	Fixed overflow, unregulated
Dimensions	3 weir bays, (WxH)= 8.25 m x 1.9 m, 9.5 m x 1.9 m, 8.25 m x 1.9 m
Capacity	130 m^3/s

The flood discharge system consists of a frontal and fixed overflow at an altitude of 795.5 m asl (Figure 1). Clearance height is limited due to the weir bridge. In addition, a bottom outlet with a capacity of 24 m^3/s of dimensions (WxH) 1.8 m x 2 m is available, the inlet level is located at 781.7 m asl

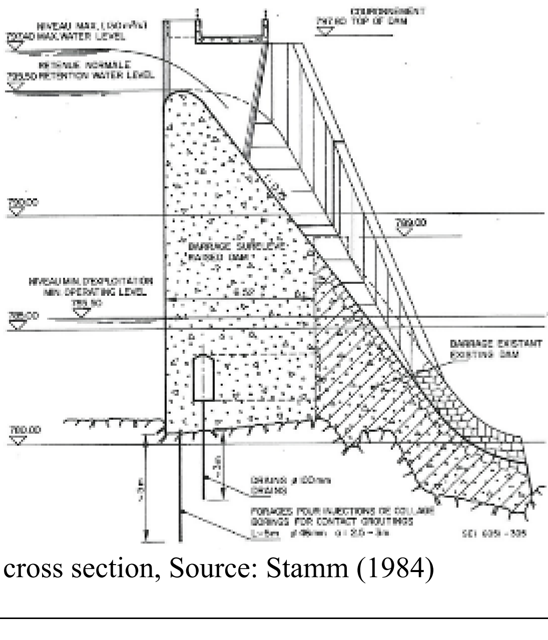


Figure 1: Käppelistutz dam cross section, Source: Stamm (1984)

Large wood (Is large wood passed through the dam spillway or removed? Existing measures against large wood?)

Large wood occurs at this installation and will only be taken out during or after extreme flood events. In case of flooding, large wood is discharged via the dam spillway. In the event of flooding and large wood occurrence, monitoring takes place on site.

Flood event August 2005	
Annuality	≈HQ_{30}, maximum discharge of Seckli river approx. 30-40 m^3/s
Large wood occurrence	300 m^3
Event description	As a result of landslides and bank erosion, large quantities of sediment and large wood were entrained. The Käppelistutz reservoir acted like a debris trap and a total of approx. 60'000 m^3 of debris and 300 m^3 of large wood (fixed volume) were deposited (Fig. 2-4). The large wood consisted mainly of fresh wood with trunk lengths up to 10 m and root-stocks with diameters up to 3 m. Also a lot of small wood was entrained from wood stacks.
Problems at dam spillway	Part of the wood was diverted via the flood discharge system. However, there were also weir bay obstructions (Fig. 3).
Assessment	Specified Guidelines CH: $L_p \geq 0.80^* H_t = 8$ m → in compliance $H_b \geq 0.20^* H_t = 2$ m → not in compliance Specified Guidelines FR: $L_p \geq 13$ m → not in compliance $H_b \geq 2.0$ m → not in compliance (L_p = weir bay clearance width = 8.25 m, H_b = weir bay clearance height = 1.9 m, H_t = trunk length = 10 m) According to the guidelines, the weir bay dimensions are too small and an obstruction had to be expected. This was confirmed by the 2005 flood event. Since the outflow quantities were relatively low with just under a value of HQ_{30} the water could nevertheless be drained via the partially obstructed dam spillway.
Measures / experience	Large wood at Käppelistutz was mechanically removed after the flood. Flushing of the reservoir, and additional mechanical removal of sediments were carried out according to environmental regulations. This has enabled part of the reservoir volume to be restored. In order to be able to act preventively in the event of hazards, alarm services like "Weather Alert" (Meteosuisse) and the Natural Hazard Bulletin of the FOEN (hydrodaten.admin.ch) are now being actively used. In dangerous situations (at "high" and "very high" levels), this allows for the initiation of preventive measures (i.e. inspections of installations, provision of equipment, etc.) on the basis of checklists. A certain amount of preparation for possible obstructions and the protection of powerplants from inundation due to flooding is thus possible.

Photos	 Figure 2: Dam spillway obstruction due to large wood during the 2005 flood (Source: EW Nidwalden)  Figure 3: Dam spillway obstruction due to large wood during the 2005 flood event (Source: EW Nidwalden)

Figure 4: Sediment deposits in the Käppelistutz reservoir after the 2005 flood event (Source: EW Nidwalden)

2) Schlattli

Schlattli

Name of dam	Schlattli
Name of river	Muota
Operator	ebs Energie AG
Reservoir volume	approx. 350‘000 m^3
Lake surface area at full supply level	approx. 100‘000 m^2

Hydrology		**Catchment area**	
Flood HQ_{100}	280 m^3/s	Surface area	210 km^2
Design flood HQ_{1000}	610 m^3/s	Vegetation cover	approx. 16 %
Full supply level	550.0 m asl	Dam crest level	552.0 m asl

(Dam Spillway) (Type, inlet structure, regulated/unregulated, number of oulets, bottom outlets etc.)

Type	1) low-level outlet, regulated (main- and regulating gates) 2) Overflow, regulated flap gate) 3) Bypass tunnel, regulated
Dimensions	1) low-level outlet, (WxH) = 7.0 m x 6.0 m 2) Overflow, (WxH) = 6.0 m x 3.0 m 3) Bypass tunnel (WxH) = 4.0 m x 4.5 m
Capacity:	(1) 530 m^3/s + (2) 12 m^3/s + (3) 194 m^3/s = 736 m^3/s

The Schlattli Weir is equipped with a total of three flood relief systems. a frontal low-level outlet at an altitude of 537.00 m asl, and a similar frontal overflow at a level of 549.00 m asl. The low-level outlet is closed with both a main and regulating gates, and the overflow with a 1.0 m high flap (Fig. 2).
There is a bypass tunnel at the orographic left bank (Fig. 1). Furthermore, the weir has two bottom outlets with a total capacity of approx. 62 m^3/s and dimensions of (WxH) 1.2 m x 1.9 m and 0.8 m x 1.9 m, respectively. The inlet of the bottom outlets is located at 534.00 m asl.

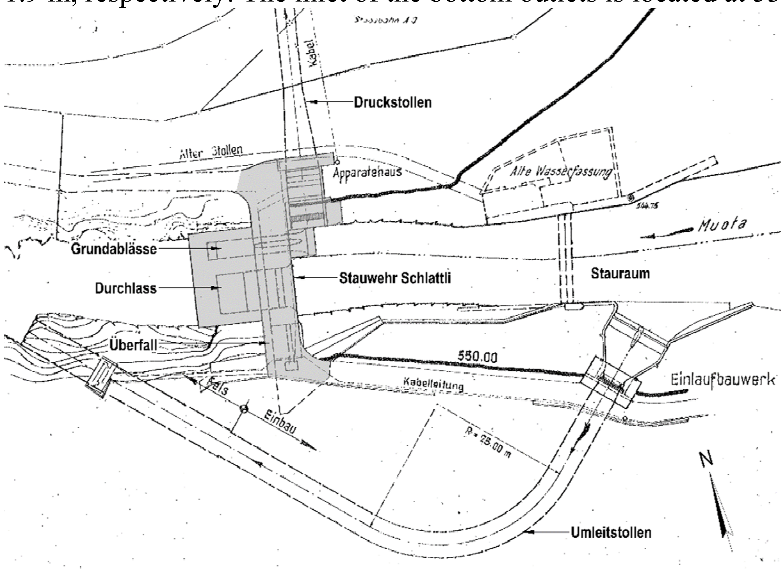


Figure 1: Schlattli weir overview (Source: ebs Energie AG)

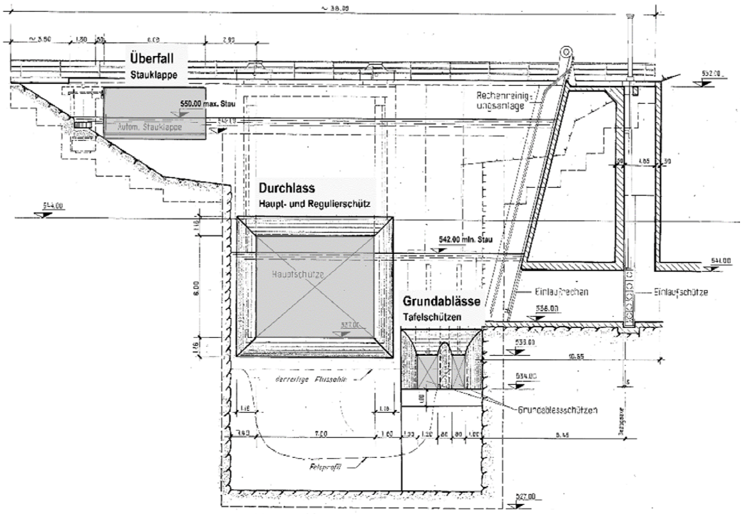
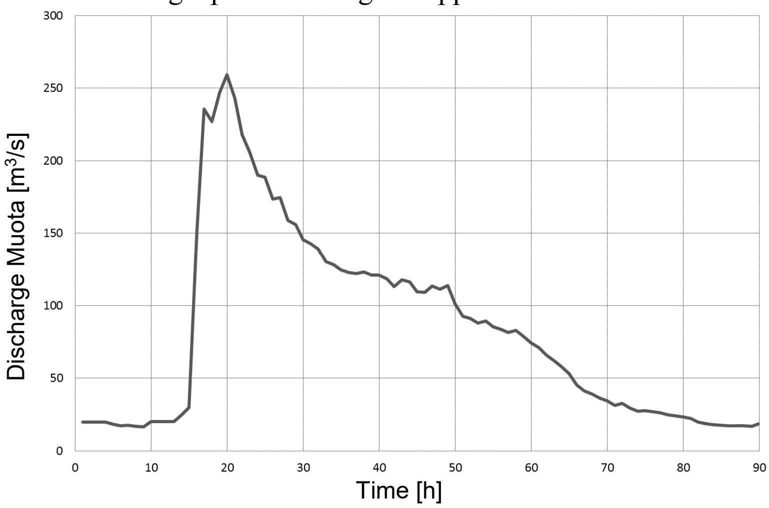


Figure 2: Upstream view of Schlattli weir (Source: ebs Energie AG)

Large wood (Is large wood passed through the dam spillway or removed? Existing measures against large wood?)

Large wood occurs at this installation and will only be taken out during or after extreme flood events. In case of flooding, large wood is discharged via the dam spillway (low-level outlet). In the event of flooding and large wood occurrence, monitoring takes place on site.

Flood event of July 2010

Annuality	≈ HQ_{60}, maximum discharge of the Muota river is approx. 258 m^3/s
Large wood occurrence	approx. 1‘800 m^3 (compact volume)
Event description	On July 12, 2010, Switzerland was hit by heavy thunderstorms. The Canton of Schwyz, among other areas, was particularly affected, especially the Muota valley area where heavy thunderstorms developed, which led to great damage. Within a very short time, roads were under water from overflowing streams, which was further accompanied by massive volumes of debris and large wood. The occurrence of a thunderstorm over a short period in the Muota catchment area led to a very rapid increase in runoff (Figure 3), with the muota reaching a peak discharge of approx. 258 m^3/s.  Figure 3: Hydrograph of the 2010 flood at the Schlattli weir (Source: ebs Energie AG)

	The rapid increase in runoff resulted in an unusually rapid entrainment of large wood. This led to an obstruction of the Schlattli weir regulation gate opening, which made it impossible to further open the outlet. Due to the obstructed outlet, the water level in the reservoir rose relatively quickly. Due to technical problems and the increased hydrostatic pressure, the gate of the bypass tunnel could not be opened. Thus, water flowing into the reservoir was only diverted via the bottom outlets and the overflow. As a result almost all the large wood was retained in the reservoir (Fig. 4).
Problems at dam spillway	The regulating gates were obstructed (Fig. 5), which significantly reduced the flood discharge capacity.
Assessment	Specified Guidelines CH: $L_p \geq 0.80^* H_t = 8$ m → not in compliance $H_b \geq 0.20^* H_t = 2$ m → in compliance Specified Guidelines FR: $L_p \geq 13$ m → not in compliance $H_b \geq 2.0$ m → in compliance (L_p = weir width clearance = 6.0 m, H_b = weir bay height clearance = 3.0 m (flap gate), H_t = trunk length = 10 m) According to the guidelines, the outlet dimensions were too small and obstructions had to be expected, which the 2010 flood event confirmed. Even though the overflow and the bottom outlets were still in operation after the outlet had failed, the decisive factor that the weir was not overtopped was that the flood wave faded away after around two hours. Usually, flushing of reservoirs is carried out during flood events by opening the regulating and main gates, allowing the downstream passage of large wood together with other debris through the outlet. In this case, large wood upstream of the weir is aligned parallel to the current and is thus passed through the outlet. The flushing method has not encountered any problems regarding the dimensions of the outlet since the installation was put into operation in 1966, up until the flood event of 2010.
Measures / experience	Large wood retained in the Schlattli weir reservoir was mechanically removed after the flood (Fig. 6). Several flushings were carried out according to environmental regulations. Sediments were flushed downstream and the reservoir volume was restored. In the meantime, ebs Energie AG made plans for the structural adjustment of the dam spillway.

Photos

Figure 4: Large wood carpet in the Schlattli reservoir after the 2010 flood event (Source: ebs Energie AG)

Figure 5: Outlet obstruction due to large wood after the flood in 2010 (Source: ebs Energie AG)

Figure 6: Mechanical removal of large wood at the water intake after the 2010 flood event (Source: ebs Energie AG)

3) Palagnedra

Palagnedra

Name of dam	Palagnedra
Name of river	Melezza
Operator	Ofima
Reservoir volume	4‘260‘000 m^3
Lake surface area at full supply level	255‘000 m^2

Hydrology		**Catchment area**	
Flood HQ_{100}	1050 m^3/s	Surface area	140 km^2 / 444 km^2 including water transfer tunnels
Design flood HQ_{1000}	1800 m^3/s	Vegetation cover	unknown
Full supply level	486.70 m asl	Dam crest level	487.50 m asl

(Dam Spillway) (Type, inlet structure, regulated/unregulated, number of oulets, bottom outlets etc.)

Type	Fixed overflow, unregulated
Dimensions	L = 80 m weir bays Old dam spillway: 13 bays each with 5.40 m clearance width and 0.80 m strong intermediate pillars with a discharge capacity of 450 m^3 / s
Capacity	2‘200 m^3/s

The spillway consists of a frontal, fixed overflow with a length of 80 m. After the flood event in 1978, the dam spillway was rebuilt. The old dam spillway consisted of 13 bays of 5.40 m clearance width, each with 0.80 m strong intermediate pillars, with a clearance height of 3 m, and with a flushing capacity of 450 m^3/s (Figure 1). Water is returned to the Melezza river via a ski-jump at an altitude of approx. 455.00 m asl with a width of 23.80 m.

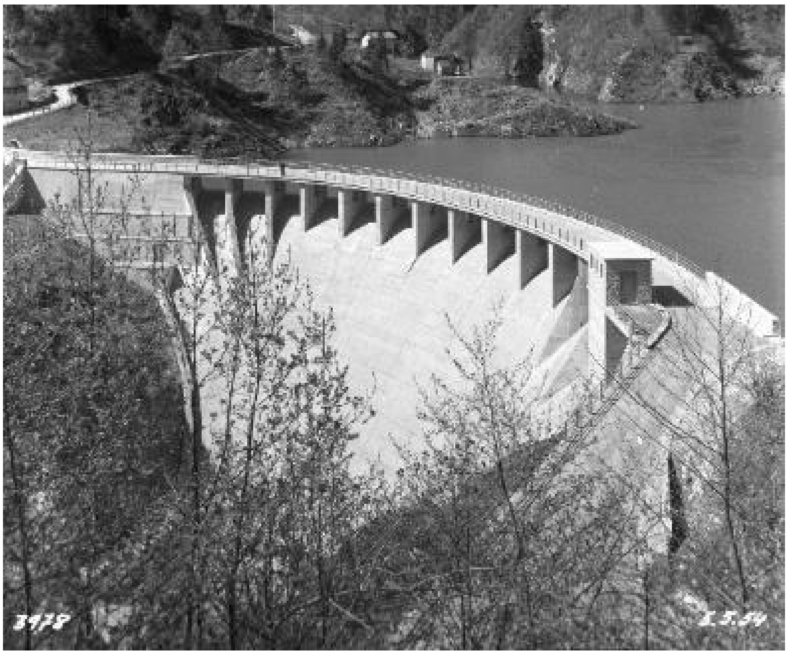


Figure 1: Old spillway of the Palagnedra dam (Source: Ofima 1954)

Large wood (Is large wood passed through the dam spillway or removed? Existing measures against large wood?)

Large wood occurs at this installation and is not removed, but discharged via the dam spillway.

Flood event of 7.8.1978 (see also Bruschin et al. 1981)

Annuality	≈HQ_{100}, maximum discharge of the Melezza river approx. 900 m^3/s
Large wood occurrence	30‘000 m^3
Event description	Towards the evening of August 7, 1978, large parts of the Canton of Ticino and the Misox, as well as neighboring Italian territories, were hit by a storm with unprecedented strength. In the area of Palagnedra, the rain started already at 4 a.m. on 7 August and lasted 23 hours, where the rain level was measured at 314 mm at the Maggia powerplant. Since the operational start of this installation in 1964, this precipitation value had only been exceeded in 1965 with 348 mm. The Melezza catchment area discharge in neighboring Italy, measured at the station near Camedo showed the following values: • on 6 August 1978 — approx. 10 m^3/s • increase on 7 August 1978 — 150 m^3/s at 13:30 240 m^3/s at 15:30 500 m^3/s at 18:00 900 m^3/s at 19:00 The reservoir level reached the road bridge over the dam at an altitude of 490.00 m asl. According to an eyewitness account at that time, a huge 2 - 3 m wave of water and wood flowed over the bridge. Subsequently, the lake surface was completely covered with tree trunks. Estimates of the amount of wood are around 30‘000 m^3. The water discharge subsequently determined by marks on the river edges, is estimated at 2000 m^3/s. Trunks got stuck in the 5.40 m narrow bays of the spill`way and created an obstruction. More trunks formed obstructions at the road bridge (Figures 2 and 3). As could be noted from the helicopter, the exceptional heavy rain, in combination with the steep upper valley of the Melezza and its countless tributaries, have flushed away extensive pasture and grass lands as well as forest covered areas. Roads, railways and bridges were torn away and dumped into the Palagnedra reservoir. The entrained amount of debris was estimated at approx. 2 million m^3. The original reservoir volume of approx. 4.8 million m^3 was filled with a total of 3.2 million m^3 of solid debris(mostly sand). The deposits at the dam reached an altitude of 456.00 m asl. Unfortunately, on the orders of the cantonal police at the time of the peak discharge of water and debris, the flushing outlets were closed. Thus, the accumulation of debris reached an altitude of 487.00 m asl. The bottom outlet was covered up to 27.0 m, and the intermediate outlet to 13.0 m, and partially blocked by wood. However, the most worrying damage affecting dam safety was due to flooding of the 3 m thick core wall on the orographic right bank. The wall was submerged by an overflow of approx. 8.00 m and the water tore a breach into the loose rock valley-side of 20.0 to 25.0 m wide, 33.0 m in height and entrained a volume of approx. 50,000 m^3 (Fig. 3). On the main road however, no damages affecting safety were recorded.

Problems at dam spillway	The dam spillway was completely obstructed by large wood (Figure 2).
Assessment	Old dam spillway: Specified Guidelines CH: $L_p \geq 0.80^* H_t = 8$ m → not in compliance $H_b \geq 0.20^* H_t = 2$ m → in compliance Specified Guidelines FR: $L_p \geq 15$ m → not in compliance $H_b \geq 2.0$ m → in compliance (L_p = clear width of weir bay = 5.4 m, H_b = weir bay height clearance = 3 m, H_t = trunk length = 10 m) According to the guidelines, the width of the old weir bay openings was clearly too small. The new dam spillway fulfills all conditions with the free overflow.
Measures / experience	**Rebuilding the dam spillway** The basis of the dam spillway reconstruction project in November 1978 was the assumption of a maximum flood peak level of 2'200 m^3 / s and a resulting reservoir level at approx. 492.00 m asl. This new maximum storage level required a change in the level of the road bridge (at 490.00 m asl). In order to maintain the desired flood point, the outlet bay clearance had to be enlarged and, above all, built in such a way to prevent being obstructed by tree trunks. These two conditions led to the demolition of the existing road bridge and its pillars down to the height of the overflow crest. The new bridge crosses the Melezza 25.0 m down the valley from the old bridge. The road on the right-hand bridge head is at 492.80 m asl. The new prestressed concrete bridge crosses the valley without intermediate pillars, with a length of 60.0 m. The pillar foundations are embedded in the rocks. The bridge is thus connected to the existing road, and provided with side walls such that lateral overflowing at max flood level is prevented.
Photos	

Figure 2: Dam spillway obstruction due to large wood after the 1978 flood event (Source: Ofima)

Figure 3: Dam spillway obstruction due to large wood and partially eroded core wall after the 1978 flood event (Source: Ofima)

Figure 4: Large wood deposition in reservoir after the 1978 flood event (Source: Ofima)

Figure 5: New dam spillway without pillars and with new bridge (Source: Ofima)

Figure 6: New dam spillway in operation (Source: Ofima)

4) Montsalvens

Montsalvens			
Name of dam	Montsalvens		
Name of river	la Jogne		
Operator	Groupe E SA		
Reservoir volume	9.257 Mio m^3		
Lake surface area at full supply level	693‘000 m^2		
Hydrology		**Catchment area**	
Flood HQ_{100}	267 m^3/s	Surface area	173 km^2
Design Flood HQ_{1000}	346 m^3/s	Vegetation cover	31%
Full supply level	800.80 m asl	Dam crest level	802.30 m asl

(Dam Spillway) (Type, inlet structure, regulated/unregulated, number of oulets, bottom outlets etc.)	
Type	1) Bottom outlet gates 2) Bypass tunnel, regulated 3) 4 Hydroplus fuse gates
Dimensions	1) Outlet (WxH) = 1.098 x 1.8 m 2) Outlet (WxH) = 5.05 x 4.42 m 3) Outlet (WxH) = 10.3 x 5.85 m
Capacity	1) 56.5 m^3/s 2) 134 m^3/s 3) 309 m^3/s

The Montsalvens dam is equipped with three flood relief systems.

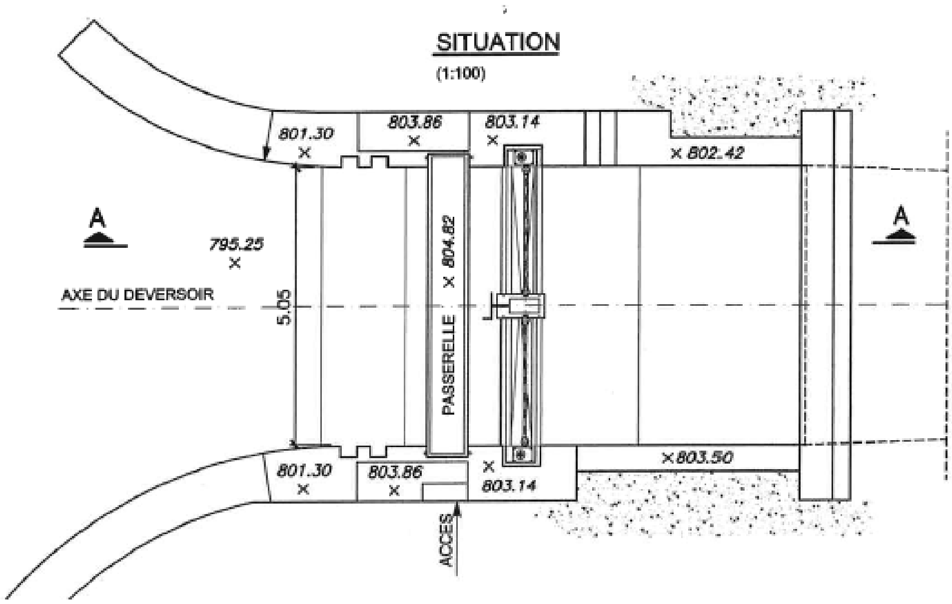


Figure 1: Overview of bypass tunnel equipped with sliding gates

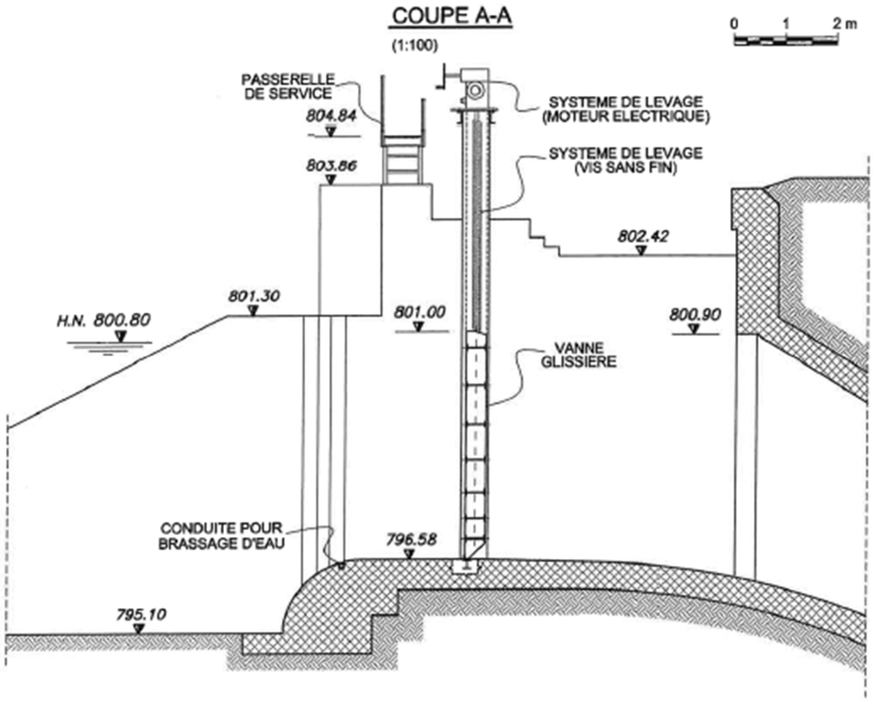


Figure 2: Cross section of bypass tunnel equipped with sliding gates

The bottom outlet tunnel is equipped with two gates. The bypass tunnel is regulated by a sliding gate. The 4 fuse gates tilt around various altitudes: 802.04, 802.13, 802.18 and 802.21 amsl.

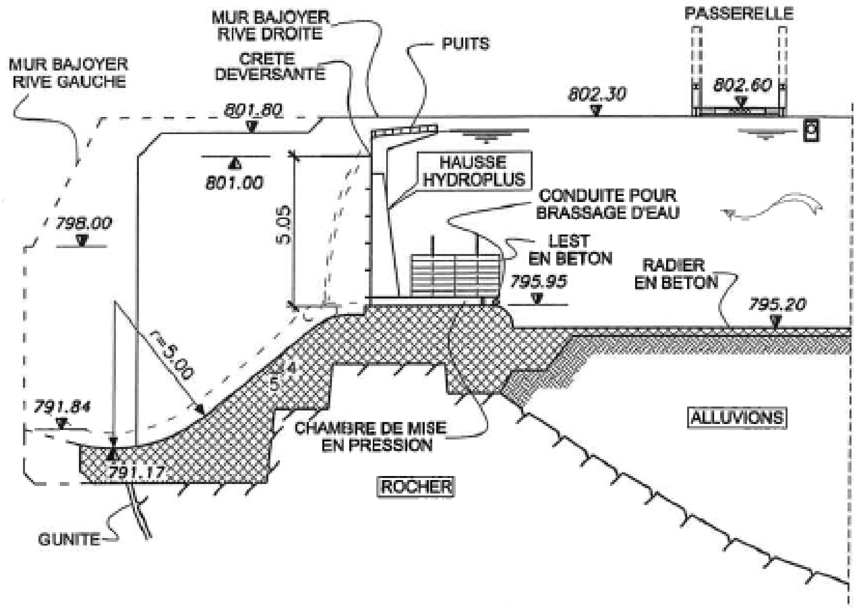


Figure 3: Cross section of the overflow equipped with fuse gates

Large wood (Is large wood passed through the dam spillway or removed? Existing measures against large wood?)

Until 2015 the overflow gate of the right bank was protected by a TuffBoom. Because of the orientation of the dam (West - East), it is very difficult to collect and extract large wood in one single place. It is only made possible with the assistance of a push boat and a crane truck.

Flood event of May 2015

Annuality	HQ = 137 m^3/s (<HQ_{10})
Large wood occurrence	300 m^3
Event description	The flood of May 2015 occurred after a period of 7 years without large discharges (Q < 80 m^3/s). The overflow gate was opened. The discharge changed from a regulated discharge type to a free discharge, which caused a sudden discharge increase of 20 m^3/s. The anchors that held the central buoy broke. Another anchor also snapped. The elements of the TuffBoom have passed under the surface gate. The chain was then cut so the gate could be closed.
Problems at dam spillway	A floating barrier was installed to protect the bypass tunnel and in particular the passage of the gate against an obstruction and to ensure its closure. With the destruction of the floating barrier, the situation in case of a flood is not sufficiently guaranteed and a more suitable solution must be found.
Assessment	Specified Guidelines CH: $L_p > 0.80^* H_t = 20$m → not in compliance $H_b > 0.20^* H_t = 5$ m → in compliance Specified Guidelines FR: $L_p \geq 13.2$ m → not in compliance $H_b \geq 2.0$ m → in compliance (L_p = Clear width of weir bay = 5.05 m, H_b = weir bay height clearance = 5 m, H_t = trunk length = 25 m) According to the guidelines, the dimensions of the weir bays are too small and obstruction had to be expected. This was confirmed by the 2015 flood event.
Measures / experience	According to the experience, a HQ_{10} could lead to complications for the operation of the surface gate and cause obstruction risks for the bypass tunnls. A solution for deflecting or retaining long trunks (25m) is being sought.

Photos

Figure 4: Situation before the floating barrier breach of May 2015

Figure 5: Large wood volumes at Montsalvens reservoir during a flood

Figure 6: Current situation in a flood event; the obstructions risk remains unacceptably high

5) Sylvenstein reservoir (Germany)

The Sylvenstein reservoir (rock fill dam, H = 44 m, Reservoir volume = 124 hm^3, catchment area = 1'138 km^2, altitude = 767 m asl, catchment area mostly wooded) was built in the 1950s mainly for flood protection, and elevation of low-water levels. In the period between 1994-2001, the existing dam spillway was adapted to encompass an enlarged flood protection volume, and a second dam spillway was built. Since the flood relief system includes tunnels and the large wood potential in the catchment area is very high, both dam spillway inlets had to be protected from large wood (Hartlieb 2014). For this purpose model simulations were carried out (Hartlieb et al. 1996). The existing dam spillway has a tunnel cross section of W = 5.1 m and H = 4.7 m. The inlet was protected from large wood by means of two rack pillars with a clearance width of 4 m (**Figure 38a**). Wood clusters and trunks with large dimensions are thus reliably retained. Individual trunks can pass the racks and are often evenly aligned by the columns in the direction of flow.
The new dam spillway was also optimized in the hydraulic model at the Technical University of Munich. It consists of an inlet with two 12 m wide overflow barriers and a 6.5 m high and 5.0 m wide tunnel. Upstream of the inlet there are five vertical pillars with a diameter of 1.0 m and a clear pillar spacing of 4.0 m (**Figure 38b**). The rack is in turn passable for individual trunks, whereby they align and can safely pass the inlet. Dangerous wood clusters are held back with sufficient distance in front of the overflow barrier. Due to the large inflow area and the resulting low velocities, a less compact obstruction mass is created, so that the discharge capacity of the dam spillway is thus only slightly reduced (Hartlieb 2014).

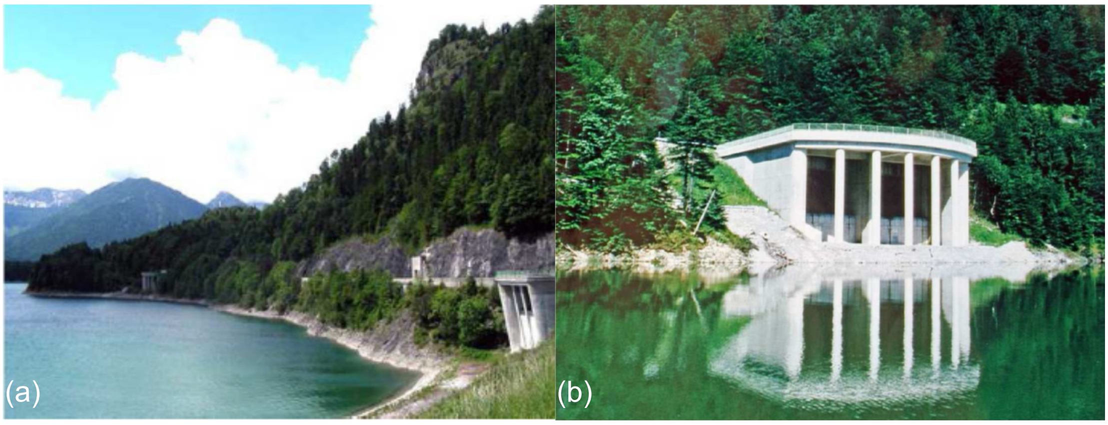


Figure 38: (a) Old and (b) new spillways of the Sylvenstein reservoir with upstream wood rack (Photos: Hartlieb 2014)

During the flood event of August 2005, a very large amount of wood occurrence was recorded in the Sylvenstein reservoir (**Figure 39a**). However, problems due to obstructions did not occur. More recently large wood barriers have been increasingly used in the upstream current (**Figure 39b**).

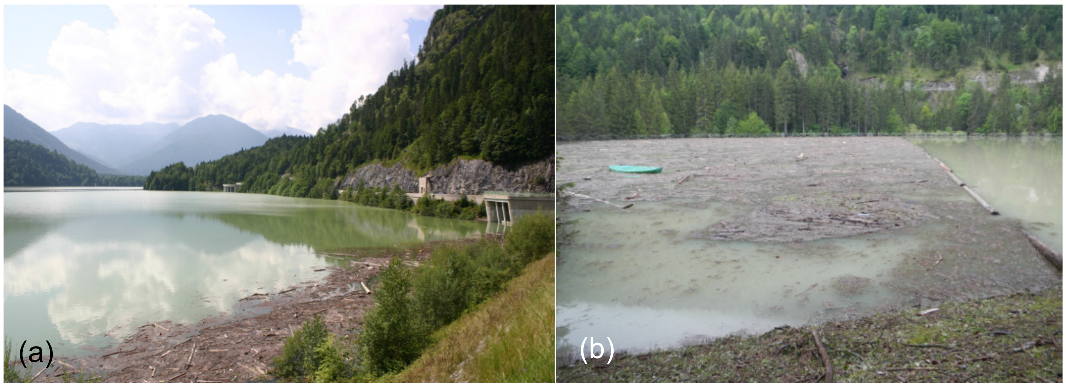


Figure 39: (a) Large wood during the floods of August 2005 (Photo: A. Hartlieb) and (b) Large wood barriers during the floods in June 2013 (Photo: Bavarian State Office for the Environment)

6) Reservoirs on the Kamp River (Austria)

The following three dams are located along the Kamp river:

Ottenstein: Catchment area = 889 km²
Arch dam, H = 69 m
Reservoir volume = 73 hm³
Dam spillway: 2 overflow flaps at dam crest, B = 26 m
BHQ = HQ_{5000} = 650 m³/s

Dobra: Catchment area = 940 km²
Arch-gravity dam
Reservoir volume = 20 hm³
Dam spillway: free overflow, B = 65 m
BHQ = HQ_{5000} = 680 m³/s

Thurnberg: Catchment area = 1011 km²
Embankment dam, H = 15 m
Reservoir volume = 0.8 hm³
Dam spillway: 3 Weir bays with gates; B = 8.6 m, H = 3.4 m including coarse large wood retention racks
BHQ = HQ_{5000} = 720 m³/s

The flood of August 2002 resulted in discharge volumes of approximately HQ_{500} - HQ_{1000} (in some cases even higher) along the Kamp river. In addition, a lot of large wood was entrained. There were no problems with the Ottenstein and Dobra dams due to the large dimensions of the dam spillway and the free-overflow design (**Figure 40a**). At the Thurnberg dam, however, there was a large accumulation of large wood. The coarse rack was installed 12 years before in front of the narrow weir bays of the spillway, and prevented their obstruction (**Figure 40b**). Since the weir structure has a relatively long adjacent fill dam, an obstruction of the weir bays could have meant an overflow of the dam. Other similar coarse racks have since been installed at two other dams with narrow weir bays.

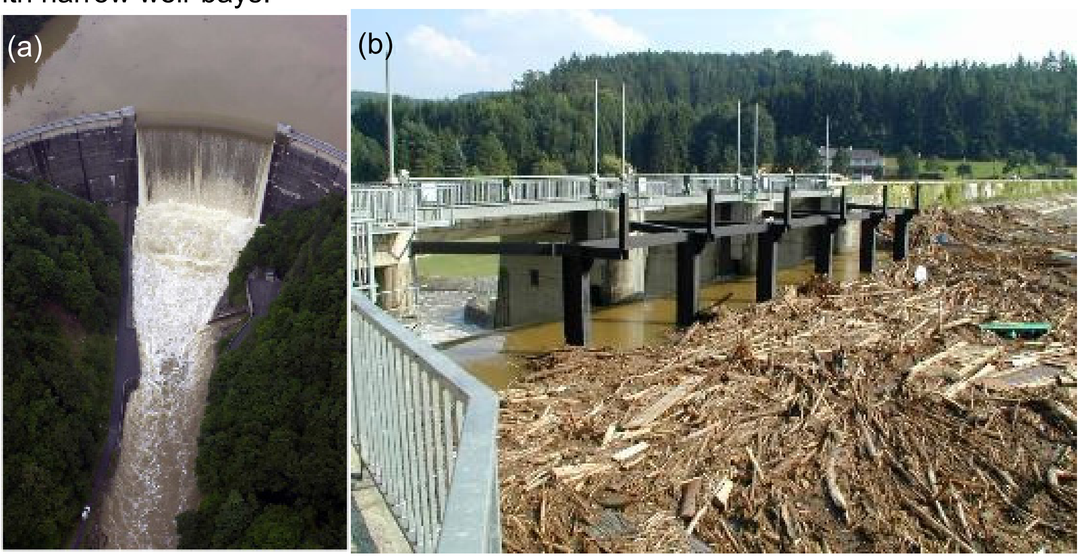


Figure 40: (a) Dobra reservoir with free spillway overflow and (b) Large wood at the rack of the Thurnberg reservoir spillway during the 2002 flood event (Photos: Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria).

7) Gstins Reservoir (Austria)

The Gstins reservoir is located on the river Lutz in Voralberg, at an altitude of approx. 900 m asl. The catchment area is 184 km^2 and is mostly forested. The spillway system consists of two weir bays, each with 10 m wide flap gates (**Figure 41a**). The flood of August 2005 had a discharge of 300 m^3/s ($<$BHQ, $>>$ HQ_{100}). In addition, approx. 3'000 m^3 of wood was transported to the reservoir. As a result, both weir bays were completely obstructed (**Figure 41b**). During the flood it was attempted to clear the left weir bay of debris by means of wood grippers.
In order to prevent any future obstruction at the dam, the spillway is being rebuilt. The pillar between the two weir bays are to be removed, creating a weir bay with a width of 20 m. The two flap gates remain permanently lowered until further design considerations of the dam spillway have been completed.

Figure 41: Gstins reservoir: (a) Dam spillway with two flap gates (Photo: VAW) and (b) obstruction during the 2005 flood event (Photos: Vorarlberger Illwerke AG).