BLOCKAGE OF RESERVOIR OUTLET STRUCTURES BY FLOATING DEBRIS

INTERNATIONAL COMMISSION ON LARGE DAMS COMMISSION INTERNATIONALE DES GRANDS BARRAGES
61, avenue Kléber, 75116 Paris
Téléphone : (33-1) 47 04 17 80 - Fax : (33-1) 53 75 18 22 http://www.icold-cigb.org./

COMMITTEE ON HYDRAULICS FOR DAMS AND THE COMMITTEE ON DAMS AND FLOODS

SUB-COMMITTEE ON BLOCKAGE OF SPILLWAYS AND OUTLET WORKS

Initially, this bulletin was foreseen as an additional chapter of the Bulletin 172 on “Technical Advancements in Spillway Design - Progress and Innovations from 1985 to 2015” dedicated to the discussion of Debris and High Sediment Flow in Spillway Operation. Due to the importance of the topic, it was decided to prepare a separate bulletin by a Sub-Committee composed of members of the Committee on Hydraulics for Dams and the Committee on Dams and Floods, since the latter worked also on the question.

The Sub-Committee was composed of the following members:

Chairman

Robert (Bob) J WARK	Australia

Vice Chairman

Kit Ng	United States of America

Members

Sam Hui	United States of America
Robert Swain	United States of America
Randy Graham	United States of America
Viktor Pavlov	United Kingdom
Frederic Laugier	France
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1. INTRODUCTION

1.1. PURPOSE

The production of this Bulletin is a joint effort by the Committees on Hydraulics for Dams and on Dams and Floods to pool resources in producing an overview of the state of the art, latest research and industry developments relating to the subject of blockage of spillways, intakes and bottom outlets by floating debris. The topic is of common interest to both committees as the risks involved can be significant, potentially leading to partial or complete loss of hydraulic functionality or even to dam failure with far reaching public safety and economic consequences. A number of previous bulletins have addressed some of these issues in a range of different ways as outlined in the following paragraphs but none of them was specifically dedicated to this rather complex subject. This Bulletin therefore aims to fill this gap by further improving the awareness of the impact of blockage by floating debris on the economy and safety of reservoir projects and by providing practical guidance on the evaluation and management of the risk of blockage. In particular, it updates the topic by dealing in further detail with the relevant processes within the catchment, in the river basin and through the reservoir, while discussing the various methods and best practice techniques for floating debris characterisation and measures for blockage mitigation. In addition, the Bulletin discusses the uncertainties and residual risks associated with the current practices of dealing with floating debris and highlights areas where further research and development would be required.

1.2. OVERVIEW OF PREVIOUS ICOLD BULLETINS AND OTHER GUIDELINES

1.2.1. Bulletin 58: Spillways for Dams

The bulletin briefly mentions the risks posed by siltation on the operation of submerged spillways, highlighting the need to take special precautions to protect them against becoming blocked. The document discusses designing sluices to discharge sediments through density currents or flushing operation at low reservoir level and provides two examples of special screening and flushing arrangements.

It also highlights the significance of the risk of blockage of spillways, submerged intakes and even bottom outlets by floating debris, referring to the Palagnedra Dam (Switzerland) where all outlet structures were completely jammed during the 1978 flood resulting in the dam overtopping. The bulletin very briefly mentions possible mitigation measures such as providing sufficiently high screens (allowing them to be cleaned from the surface) and keeping the deep sluices high above river bottom. The document also highlights the risk associated with waterlogged debris, which cannot be prevented by trash booms from blocking inlet screens and bottom outlets.

The bulletin has examples of the problems of abrasion of spillways and bottom outlets from bed or sediment loads and highlights various abrasion protection and mitigation measures.

1.2.2. Bulletin 119: Rehabilitation of Dams and Appurtenant Works

The bulletin briefly discusses the common problem of obstruction of overflows and low-level outlets by debris highlighting the need for visual diver inspections to detect any blockages. It mentions the adverse consequences of blockage, presenting once again the Palagnedra dam case as an example. In particular, it highlights that:

- infrequent operation of low outlets may contribute to the accumulation of silt and debris near the outlet and resulting blockage problems.
- butterfly valves and cone valves are more prone to blockages than gate valves and
- there is a risk of logs being caught and silt accumulating at gates and stop log slots.

The bulletin briefly discusses possible rehabilitation measures against blockage, including the removal of sediments near the intake by dredging and management of the catchment. The likelihood of natural dams of driftwood forming within the catchment and subsequently being breached, thus causing a sudden release of water and debris, is highlighted.

1.2.3. Bulletin 162: The interaction of hydraulic processes and reservoir management of the impacts through construction and operation downstream impacts of large dams

The bulletin discusses measures to minimise erosion in the upper watershed as well as ways to pass sediments through reservoirs and mitigation of their accumulation. There is also a section dealing with the control of floating debris. This section provides a review of the type and origin of debris, the factors governing the amount of debris produced and the effect of debris on intakes, trash racks and spillways. It then presents seven case histories of clogged or damaged spillways and blocked trash screens. It also discusses the different modes of river transport of debris and the debris transport through control structures.

The document provides a review of the different model testing carried out for floating material approaching spillways. It then provides guidance on the dimensions of spillways and lower outlets to allow the passage of single trees. However, it highlights that the results are relevant only to passage of trees of the species used in the model tests. It concludes that other species of tree with different sizes, shapes and strengths require separate investigations. The bulletin also briefly lists the possible counter measures to mitigate the risk of blockage by debris.

1.2.4. Bulletin 172: Technical advancements in spillway design - Progress and Innovations from 1985 to 2015

The bulletin offers a brief discussion of the effect of floating debris on the operation of labyrinth and piano key weirs by addressing the probability of blocking and the resulting water level increase in the reservoir (Pfister et al., 2013, 2015).

1.2.5. Other Guidelines

Specific guidelines for dealing with floating debris at reservoirs have been recently produced in some countries in acknowledgement of the significant risks that they pose to dam safety. The latest guidelines produced in the USA (2016), Sweden (2017) and Switzerland (2017) are briefly discussed below.

Reservoir Debris Management, USBR, Research and Development Office Science and Technology Program, September 2016

This report primarily focuses on the available new technologies developed to manage woody debris at grated outlet works intakes. It highlights the limitations of the current debris management options which are not necessarily applicable to saturated (waterlogged) submerged debris. The report emphasises the merits of the debris prevention and conveyance management options which are more sustainable and would prevent dam owners from the burden of retrofitting outlet infrastructure.

Methodology for Analysing and Managing Floating Debris at Dams and Reservoirs, Energiforsk, October 2017

The report provides a methodology for analysing the dam vulnerability to floating debris and for selecting and prioritising suitable mitigation measures considering the vulnerability of any upstream and downstream facilities.

The methodology presented consists of the assessment of three main components, namely: potential for formation of floating debris, potential for their transport to the respective hydraulic structure and potential for its blockage.

Floating Debris at Reservoir Dam Spillways, Swiss Committee on Dams, November 2017

The report summarises the current international status of guidelines and debris handling practices at dams and provides recommendations on the following aspects:

- Assessment of dam spillways with regards to the hazard potential of floating debris;
- Estimation of blocking probability;
- Methods of dealing with debris at dams, including measures taken in the catchment area, debris retention/removal, debris passage and operational measures.

The report recommends a diagram for assessing the hazards posed by floating debris to dams and their spillways referred to in Section 5, Evaluation and management of the risk of blockage. It also provides seven case studies from Switzerland, Germany and Austria illustrating the problems posed by floating debris and the solutions adopted.

Impact of wooden debris on dam spillways under extreme conditions, Swiss Federal Office of Energy (OFEN), November 2019, summarized by Bénet et al. (2020) and Pfister et al. (2020).

This report completes the aforementioned report of the Swiss Committee on Dams. Systemic and parametrical studies on a physical model were carried out, to properly analyse the effect of driftwood on the head upstream of a standard weir equipped with piers. In the conducted experiments, only an extreme volume of driftwood arriving instantly at the spillway was tested, presenting an extreme scenario. Mitigating measures, such as upstream rack or extended piers towards upstream, were also tested.

1.3. SCOPE AND LIMITATIONS

The scope of this Bulletin is to:

- Improve awareness of the impact of blockage by floating debris on the economy and safety of reservoir projects;
- Provide guidance on the floating debris characterisation;
- Provide guidance on the evaluation and strategies for management of the risk of blockage;
- List the methods and currently available best practice techniques for floating debris blockage mitigation while highlighting the relevant uncertainties, residual risks and further work required;
- Provide information on any ongoing investigations and further work required relating to this subject.

Excluded from the scope of this bulletin are the following issues:

- Quantification of the rate of transport of floating debris to the spillway/intake/outlet structure;

- Evaluation of the probability of the occurrence of different degrees of blockage of spillways, or the joint probability of the occurrence of an extreme flood and specific degree of spillways blockage

2. FLOATING DEBRIS CHARACTERISATION

2.1. TYPE AND ORIGIN

Floating debris found in reservoirs could be of natural origin, could be man-made or result from other human activity. Natural debris typically include: grass, bushes, tree branches, tree trunks, root balls or entire trees, floating mires and rafts of reeds, bulrushes and other aquatic plants, carcasses, material from beaver dams, ice etc. Floating debris resulting from manufacturing could comprise timber, plastics and rubber products or trash of various form and shape including entire boats, wrecked cars or event wooden houses. Agricultural activity (silage balls), non-sanitary landfills or parks and viewports near roads, river banks and reservoirs could also become the source of floating debris. Also, vegetative debris could be left over from timber harvest and logging operations.

These debris could find their way to reservoirs during severe storm events after being extracted and washed down by the flood water or dispersed by the wind. Natural dams of driftwood forming within the catchment and subsequently being breached, could also cause a sudden release of water and debris. The main mechanisms by which debris enters water courses and reservoirs are further discussed in Section 2.3.

As wood remains in the water, it could become waterlogged and therefore submerged. Plastic debris, or debris entangled with plastic bags could also become submerged as highlighted in ICOLD Bulletin 119 (ICOLD, 2000). Some floating debris such as mires, peat bogs and reeds (bulrushes), as well as plastics or other debris may have the tendency to form floating islands. These and other related questions have also been discussed in some detail in ICOLD Bulletin 162 (ICOLD, 2010). The following photographs (**Error! Reference source not found.** through to Fig. 2.4) illustrate floating debris occurring in reservoirs.

Fig. 2.1

Floating rafts of bulrushes Kununurra Diversion Dam, Australia

Fig. 2.2
Wood floating debris accumulated at the Palagnedra Dam, Switzerland

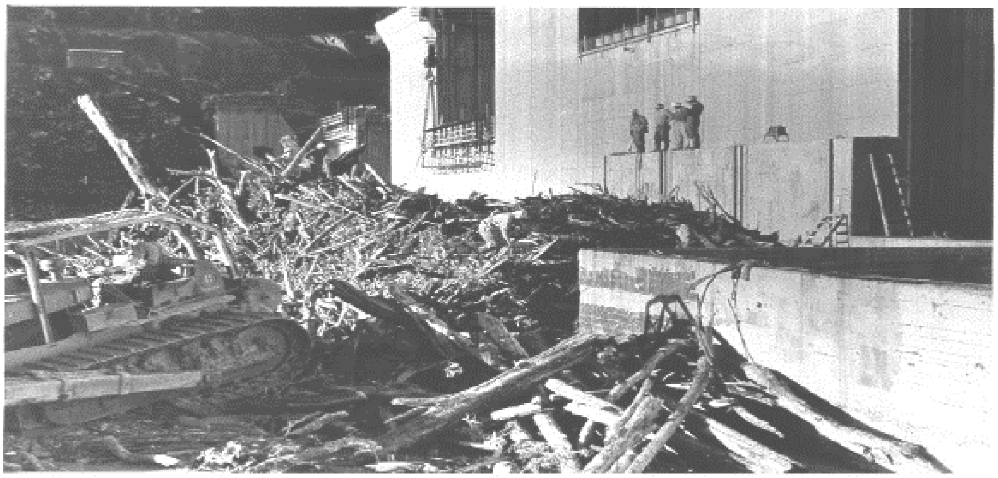

Fig. 2.3
Large floating debris in front of the Catagunya Dam, Australia

Fig. 2.4
Obstructed spillway due to silo bales in Trondelag, Norway
(Photo: L.Lia, NTNU), (Boes et al., 2017)

2.2. CHARACTERISTICS

The characteristics of the floating debris, namely their:

- shape,
- size: length and trunk diameter,
- and density

are important factors to consider in the evaluation of the risk of blockage of reservoir spillways, intakes and bottom outlets.

For example, wood density could be used in determining the threshold of movement for stems within the catchment basin. At spillways with a reservoir approach flow, a higher wood density can increase the blocking probability of an ogee crested spillway equipped with piers (Furlan et al. 2018). The density of trees in Europe typically ranges from 0.4t/m^3 (light wood) to nearly 1t/m^3 waterlogged wood with the average wood density of dry trees in Europe being (0.47 - 0.67 t/m^3) (Chave et al., 2009)

Other factors affecting the risk of blockage are the rate of transport of the floating debris discussed in Section 0, the physical and hydraulic parameters of the respective hydraulic structure which is at risk of blockage as well as the means and rate of removal of the floating debris where such a facility is provided (refer to Section 4). Therefore, accurate assessment of the type and characteristics of the floating debris that could reasonably be expected to arrive at the respective hydraulic structure during a major storm event is indispensable for reliable modelling of its performance and thus establishing its risk and rate of blockage.

The assessment should also give due consideration to the possible effects of the transport of floating debris on their characteristics as explained in Section 2.3.3.

For example, recent physical model testing indicated that a comparatively small amount of floating debris, or just one single log jamming the spillway or the intake/outlet structure due to its relatively small size or poor design, may rapidly recruit other floating debris and lead to an extensive debris accumulation and even result in a full blockage. Therefore, the evaluation of the characteristics of the debris in the drainage basin or the debris accumulations after a flood event must also be based on data on the largest expected log lengths, log diameters, and rootstock dimensions or data on the types and dimensions of other possible large debris such as carcases or man-made debris as discussed in the previous section. The risk of such large debris blocking the respective hydraulic structure will also be affected by the debris material density and their propensity for water logging.

In this connection, the relevant factor influencing the accumulation at bridges and weirs was often found to be the log length (Diehl, 1997; Bezzola et al., 2002; Lange and Bezzola, 2006; Schmocker and Hager, 2011; Hartlieb, 2012). However, recent studies also indicate that in many cases single rootstocks are more likely to cause blockages than single logs, and the maximum blocking probability was observed for a wooden debris cluster containing rootstocks (Pfister et al., 2013, 2015). This is particularly relevant where the respective head over the spillway weir is relatively low compared to the rootstock dimensions. Johansson (1995) and Hartlieb (2012) indicate that single tree generally has the ability to turn into the flow direction and pass the spillway opening without any problem in many situations.

Thus, debris having the same characteristics may pose a different risk of blockage depending on the size and hydraulic characteristics of the respective hydraulic structure. In this respect, some specific design features such as relatively closely-spaced piers, open truss structures, superstructures with open parapets and exposed structural elements like trusses, railings or supply cables and pipes could increase the risk of blockage depending on their relative size.

According to Astrand & Persson (2017) deciduous trees and pines often have deeper roots than spruce and therefore do not fall as easily.

2.3. DEBRIS PRODUCTION, TRANSPORT AND VOLUME

2.3.1. Sources and mechanisms for debris production

Before examining the various techniques used to quantify the floating debris it is worth listing the major debris sources and mechanisms by which debris enter water courses:

- Wind and wave action

On lakes and large rivers waves erode the shoreline causing trees to topple into the water. Structures such as docks can be damaged by waves, and much of the flotsam generated remains in the water. Wind and wave action can also cause the removal of debris from natural storage areas such as bays and coves. Wind throw is a major source of debris input in streams in forested areas and wind has also been known to carry appreciable quantities of sagebrush and tumbleweed into rivers in the western USA.

- Ice Break-up

Moving ice in the spring break-up can increase the undercutting of riverbanks, and trees can be damaged and broken by the force of moving ice. Ice storms can cause tree limbs and sections of trunks to break off and fall into lakes and watercourses.

- Forest Litter

A larger litter input is derived from leaves from forest trees. In temperate regions where the forest is dominated by deciduous trees, forest litter is usually protected by the tree canopy during summer and by a snow layer in the winter, however in early spring trees are without leaves and heavy rains will wash the litter into watercourses.

- Forestry Practices

Forest lands soak up large quantities of water and reduce floods and erosion that bring floating debris to the streams and rivers. If a generous ground cover is maintained during tree harvest and roads are made erosion resistant, forest land can still protect the watershed. The harvest of trees on a reasonable schedule will reduce the number of dead trees that may fall into the streams and rivers. However, poor harvesting strategies can generate large inputs of debris to streams and rivers.

- Debris Jams

Debris jams may release debris downstream when moved in-mass by a large flood flow or when broken down over a long period of time by natural effects such as decomposition.

- Beaver Dams

The quantity of debris brought into streams by beavers is unknown, but may be a substantial proportion of the total debris load in some watersheds.

- Man-made Materials

This includes decaying wooden structures such as piers and wharves, organic and synthetic material from dumps improperly located along water bodies, and general littering of trash and waste. These materials could be transported into reservoirs by flood water or dispersed by the wind.

- Landslides and soil erosion

During floods, it is very common that landslides occur (locally or extended) on the steepest sides of the river valley slopes. When occurring in woody areas, they can bring down into the river significant quantities of wooden debris. On a smaller scale, soil erosion can be triggered by heavy rains and floods and subsequently extract wooden debris into the river.

2.3.2. Debris transport

As discussed in section 2.2 with regards to floating debris hazard evaluation, another important factor affecting the risk of blockage is the rate of transport of the floating debris.

All rivers that discharge into the reservoir may transport floating debris, however, the main sources of floating debris production are thought to be steep tributaries Furthermore, landslides may directly entrain floating debris into the reservoir. For a specific river, the transport of debris to the hydraulic structure which is at risk of blockage depends on:

- volume of available debris;
- velocity and depth of water within the catchment
- characteristics of the flood;
- wind characteristics;
- reservoir area, shape and orientation relative the prevailing wind direction and the parameters of the respective hydraulic structure.

According to Astrand & Persson (2017) the potential for transportation of floating debris from the "source" to the dam facility is primarily dependent on water velocities on the route. They suggest that to assess this, the following questions would need to be answered:

- Is the area upstream a dam site, river stretch, lake or reservoir or a combination of the above?
- If it is a combination, is the shape and direction of the reservoir such that the wind could cause the floating debris to travel towards the facility or is it an irregular shape with bays and headlands where the floating debris may get stuck or delayed?

When dealing with the subject of debris transport it would be important to establish not only the volume but also the rate of transport to the respective spillway or other outlet structure. Thus, for a given volume of available debris the rate of transport will vary depending on the catchment, reservoir, spillway and wind characteristics.

According to guidance produced by the French National Committee on Dams (CFBR, 2013), debris transported on large reservoirs have small probability to reach the dam spillway depending on velocity conditions in the reservoir. When the average velocity on water surface is very small, secondary factors, such as wind or water stream recirculation, might prevail and reroute the debris elsewhere. The design criteria to be taken into account (wind speed, water velocity, debris features) still need to be more precisely explored by the scientific community.

In addition, if the shape of the reservoir is snaky with many turns, it is also probable that many debris will be driven to the external shore of the reservoir bend. Again, criteria still need to be clarified.

However, the flood feedback from the dam operators can bring valuable information to prove this mode of transportation of debris in reservoir.

Establishing the rate of transport would require employing a specialised numerical model. For example, the current commercially available CFD software packages allow amongst other things, modelling of debris waves across reservoirs using floating Lagrangian particles which could be tracked across reservoirs to simulate arrival times under different scenarios. They also could incorporate a wind model, which applies a shear force tangential to the water surface. However, it should be noted though that the reliability of such hydrodynamic modelling is still considered to be relatively low (Boes et al., 2017) and further development in this area would be required.

2.3.3. Debris characteristics after transport in rivers

Transportation of wooden debris through rivers can significantly affect their geometrical characteristic when arriving in the reservoir area depending on the features of the river, flow and source of production. That means:

- Length of stems
- Size of branches
- Density

Steeb (2016) investigated the fragmentation of entire trees down to smaller wood pieces due to fluvial transport, based on measurements after the 2005 flood event in Switzerland for rather steep mountains streams. It was observed that the trees are reduced between 10% and 33% (average value of 20%). The size reduction depends less on the transport distance than on the intensity of the physical degradation processes. The size reduction will be less important for less steep rivers.

The Swiss Committee on Dams report on wooden debris (Boes, 2017) also outlined that:

- Trees might be significantly pealed and loose most of their branches.
- A special attention should be paid to the duration of transportation or stay of wooden debris in the river / reservoir with regard to the type of tree. Some sort of trees will quickly sink while some other will float during weeks or never sink.

In those conditions, the size, shape and type of trees surrounding the reservoir or located close to the shore should be considered to determine the maximum size of debris capable of reaching the dam and spillway.

2.4. ESTIMATING DEBRIS VOLUMES

2.4.1. Volume of available debris

The volume of available debris consists of instream floating debris that is already distributed in the riverbed plus the fresh floating debris entrained during the flood (Bezzola and Hegg, 2008). Trees, or even houses, may fall into the river as a result of changes in channel morphology and due to wind, ice loads, or reduced stability due to old age (Diehl and Bryan, 1993). This debris may lie at the river bed for a comparatively long time until it is mobilized.

During a flood, fresh floating debris may be entrained due to side erosion, bank undercutting, slope failures, landslides, or debris flows. The available fresh floating debris in adjacent river and reservoir areas depends on the timber stock, stand density, forest productivity and maintenance, mortality, insect infestations, forest diseases, and lumbering. The flood discharge determines the degree of side erosion and undercutting, and the rainfall magnitude and intensity may affect the soil saturation and consequently possible landslides.

Three methods to predict the floating debris volume during a flood for a certain drainage basin are presented herein, namely:

1. Empirical methods based on existing data on flood debris transport;
2. Evaluation of the drainage basin; and
3. Evaluation of past flood events.

Method (1) is comparatively simple but exhibits a large uncertainty. Method (2) requires a large work effort but results in a profound understanding of the floating debris potential. Method (3) can be applied if data on past flood debris transport volumes are available.

Note that the exact prediction of the floating debris volume is difficult. Floating debris entrainment and transport are random processes, and a certain scatter of the expected volume must be accepted. Estimations may differ by a factor of 2 or more from the actual volume. Therefore, a sensitivity analysis is always recommended as part of the hazard evaluation.

2.4.2. Empirical methods

Various empirical formulas to estimate the volume of transported floating debris during a flood are available; some of the most recently developed ones are presented in what follows:

Rickenmann (1997) evaluated floods in Switzerland, Japan, and the USA presenting two formulas to estimate the effective driftwood volume as:

$$V_L = 45\ A^{2/3} \qquad (1)$$

$$V_L = 4\ V_W^{2/5} \qquad (2)$$

Where:

V_L = loosely placed driftwood volume [m^3] with a porosity of a ≈ 0.5,

A = drainage basin area [km^2], and

V_W = volume of water [m^3].

The water volume in the above formula is summed up over the entire flood hydrograph using a representative discharge measurement station. The data indicate a comparatively high scatter because neither formula accounts for the drainage basin characteristics or the flood return period.

Assuming that only the forested (subscript F) area adds to the transported driftwood volume during a flood, Rickenmann (1997) also estimated the potential (subscript P) driftwood volume V_{LP} as:

$$V_{LP} = 90\ A_F \quad \text{for } A_F < 100\ km^2 \qquad (3)$$

$$V_{LP} = 40\ L_F^2 \text{ for } L_F < 20\ km \qquad (4)$$

Where A_F = forested part of drainage basin area [km^2] and L_F = forested river length [km].

The data indicate a high scatter and for large drainage basin areas do not follow the overall trend.

Uchiogi et al. (1996) evaluated various flood events in Japan concluding that V_L could be expressed as a function of F = total transported sediment volume during the flood event [m^3] as:

$$V_L = 0.02\ F \qquad (5)$$

They further stated that the relation between the forested area A_F and V_{LP} is:

$$V_{LP} = (10 \text{ to } 1000)\ A_F \qquad \text{for coniferous forest} \qquad (6)$$

$$V_{LP} = (10 \text{ to } 100)\ A_F \qquad \text{for deciduous forest} \qquad (7)$$

Lange & Bezzola (2006) and Waldner et al. (2010) estimated the porosity a of wooden debris accumulating at weirs and trash racks during floods, suggesting that it typically ranges from 0.5 to 0.8, considering:

$$a = (V_L – V_S)/V_L. \qquad (8)$$

where V_L is the volume of loosely placed wood and V_S is the solid volume.

The above empirical formulas may be used as a simple estimation tool for the wooden debris volume. However, use of such formulas may result in highly different volumes and it is important that they be used with prudence, within their experimental range of validity and for drainage basins presenting similar characteristics. For example, comparison with actual wooden debris volumes observed during the 2005 flood in Switzerland (Schmocker and Weitbrecht, 2012) showed a very high scatter indicating that drainage basins having similar areas different other characteristics could in reality produce highly different wooden debris volumes.

This leads to the conclusion that more data from different types of drainage basins and further research are required to produce reliable methods for estimation of the potential wooden debris volumes produced during storm events with different return periods.

2.4.3. Evaluation of the drainage basin

The evaluation of the drainage basin of a reservoir may result in a more detailed and accurate prediction of the debris volumes. It would normally give due consideration to all important basin characteristics and would typically adopt a method calibrated on the basis of a representative set of real and systematically gathered and analysed data. Two generalized approaches are discussed in what follows. The first approach was developed by the US Army Corps of Engineers Los Angeles District (2000) to estimate the total debris yield for “n-year” flood events in Southern California. In this case, the total debris yield is defined as the total debris outflow (silt, sand, clay, gravel, boulders, and organic materials, including tree trunks, bushes, etc.) from a drainage basin measurable at a specific concentration point for a specified flood event. The second approach, which focuses largely on estimating the volume of woody debris, has been adopted by numerous researches from various different countries. These two methods are discussed in what follows.

2.4.4. Total debris estimation (USACE Approach)

The US Army Corps of Engineers (2000) approach is based on multiple linear regressions between measured unit debris yield and a set of physiographic, hydrologic, and meteorological parameters found to predict the quantity of debris yield in the Southern California watersheds. The predictive equations were developed on a storm-event basis, rather than as an average annual volume. Debris yield data were collected using reservoir survey data and debris basin data obtained from several Federal and local agencies. The largest possible number of observations available was used in the analysis for the Southern California drainage basins. Multiple linear regression analysis was selected as the method to estimate unit debris yield because it is relatively rapid and accurate, and flexible enough to allow extrapolation of results to other watersheds possessing similar geologic, climatic, and vegetative characteristics. In this study, all of the variables, except the non-dimensional fire factor, were log-transformed for the regression analysis.

The group of variables which explained the greatest amount of variance in unit debris yield was selected using common statistical indices. Multiple linear regression analyses indicated that unit debris yield is most highly correlated with the unit peak runoff rate (or the maximum 1-hour precipitation depth), drainage basin relief, contributing area, and fire history. Each of these variables was chosen for its significance in explaining variation in the unit debris yield at the 95 percent confidence level. Many other parameters were considered including maximum rainfall amounts for several durations, total stream length, drainage density, mean bifurcation ratio, hypsometric-analysis index, elongation ratio, transport efficiency factor, and mean channel gradient.

The occurrence of wildfire greatly affects erosion rates in Southern California. Highly flammable woody vegetation, steep slopes, loose sediments, hydrophobic soil conditions caused by wildfire, and dry offshore winds contribute to debris yields up to 35 times that of the watershed in an unburned state (USACE, 2000). Various fire factor curves as a function of drainage area size and years since the last wildfire are presented in the US Army Corps of Engineers report (2000).

Five equations were developed for drainage areas up to 200 mi^2. The equations were developed using Imperial units of measurement, which have not been changed to SI units for this publication. The first equation based on watersheds with drainage areas from 0.1 to 3.0 mi^2 for which peak flow data are not available is:

$$\log D_y = 0.65(\log P) + 0.62(\log RR) + 0.18(\log A) + 0.12(FF) \quad (9)$$

Where D_y = unit debris yield (yd^3/mi^2),

P = maximum 1-hour precipitation (inches times 100),

RR = relief ratio (ft/mi),

A = drainage area (acres), and

FF = non-dimensional fire factor.

The relief ratio is determined by calculating the difference in elevation (feet) between the highest and lowest points in the watershed as measured along the longest stream divided by the length of the longest stream in miles.

The second equation developed for watersheds with drainage areas ranging from 3 to 10 mi^2 for which peak flow data are available and for drainage areas less than 3.0 mi^2 if peak flow data are available is:

$$\log D_y = 0.85(\log Q) + 0.53(\log RR) + 0.04(\log A) + 0.22(FF) \quad (10)$$

Where Q = unit peak runoff ($ft^3/s/mi^2$).

Similarly, equations were developed for watersheds with drainage areas from 10 to 25 mi^2:

$$\log D_y = 0.88(\log Q) + 0.48(\log RR) + 0.06(\log A) + 0.20(FF) \quad (11)$$

From 25 to 50 mi^2:

$$\log D_y = 0.94(\log Q) + 0.32(\log RR) + 0.14(\log A) + 0.17(FF) \quad (12)$$

And from 50 to 200 mi^2:

$$\log D_y = 1.02(\log Q) + 0.23(\log RR) + 0.16(\log A) + 0.13(FF) \quad (13)$$

The US Army Corps of Engineers (2000) approach was developed using data from the San Gabriel Mountains in Southern California for drainage areas less than 200 mi^2. The method is intended for use on watersheds with a Mediterranean climate and a high proportion of their total area in undeveloped, steep, mountainous terrain. It should not be used to predict debris yield resulting from precipitation and runoff events with less than a 5-year recurrence interval, with a 1-hour maximum precipitation less than 0.3 inches/hour or runoff less than 3 $ft^3/s/mi^2$.

For use in areas with different terrain and land use characteristics, application of an Adjustment/Transposition (A-T) factor is recommended to account for differences in geomorphology between watersheds. The development of the A-T factor is presented in Appendix B of the US Army Corps of Engineers report (2000) and is dependent on the availability of flood debris records for the watershed of interest. If flood debris data are not available, the A-T factor is developed from information about geologic structure, soils, channel morphology, and hillside morphology.

2.4.5. Woody debris estimation

Originally, this method focused largely on estimating the volume of woody debris. Its goal was to determine the following two parameters: (1) available wood stock per hectare on the reservoir banks and along the rivers that discharge into the reservoir; and (2) area that may actually add to the wooden debris supply during a flood. The possible wooden debris potential follows from the multiplication of these two parameters. However, the available timber along the reservoir and rivers depends on various factors and may display considerable scatter. General data follow from forest inventories (e.g. National Forest Inventory, Switzerland) or may be acquired from local forest rangers. Various studies have been conducted to establish the wooden debris potential and instream wood along a distinctive river (Gregory et al. (1993); Piégay and Gurnell (1997); Keller and Swanson (1997); Downs and Simon (2001); Kaczka (2003); Kail (2005); WSL (2006); Böhl and Brändli (2007); Lagasse et al. (2010); Soderstrom et al., 2014).

However, the above studies highlighted that a generally valid timber stock based on the drainage basin area alone is impossible to determine. Therefore, a detailed study of the drainage basin characteristics is necessary to reliably predict the potential wooden debris volume. This includes numerous factors such as the degree of forest vegetation, forest condition, streambank slopes, reservoir banks, adjacent hillsides, geology, and flood event processes. Diehl (1997), Bradley et al. (2005) and Lagasse et al. (2010) presented basic procedures to determine the potential of wooden debris production and delivery for a given river section.

Rimböck (2001) and Rimböck and Strobl (2001) determine specific wooden debris input mechanisms (e.g. side erosion, avalanches, landslides, wind-throw, and construction timber) and a defined timber stock for each mechanism separately. The flow depth and flow width as input parameters for the side erosion follow from a hydraulic analysis. The hill slopes determined from aerial views were compared with the critical slopes required to trigger landslides determined by a geological survey. Information on the wood stock per square meter was provided by the forestry administration. The driftwood potential follows as the sum of each hazard process.

Another general concept used to estimate the wooden debris potential for a certain drainage basin was presented by Flussbau AG (2009) and includes the following steps:

1. Determine the specific timber stock along the river and reservoir;
2. Determine the reach-averaged river width for various flood discharges;
3. Determine potential landslide areas;
4. Estimate the probability of side erosion and sliding failure; and
5. Sum the resulting wooden debris potentials.

In this approach, the timber stock is determined at various locations along the reservoir and river by considering test fields with an area of some 100 m^2. Then, the length and diameter at breast height of each tree are determined, resulting in a certain specific timber stock VS' [m^3/m^2] for each section. Possible sliding areas reaching the reservoir or rivers that discharge into the reservoir and their dimensions are estimated using existing hazard maps and geological maps. For the rivers that discharge into the reservoir, the relevant flood discharge is taken as channel-forming discharge and the reach-averaged width for a stable river reach is determined using the methods of Parker (1979) or Yalin (1992). It is assumed that the river will flood this reach-averaged width during the flood event. The reach-averaged width is then compared with the actual river width resulting in a possible rate of side erosion during the flood event. Sections where the existing bank protection prevents side erosion are excluded from the analysis. The total wooden debris volume follows from the obtained specific timber stock and the determined area of possible side erosion and landslides.

2.4.6. Spatial analysis using GIS techniques

Spatial analysis to identify potential floating debris from trees along rivers could be carried out using a combination of filed inspections and ArcGIS. This could allow to find potential risk areas and calculate the number of trees that may fall into the river and become floating debris. This is currently considered to be the most costly, yet most accurate method for assessing the risks posed by large floating debris (Schalko et al.2017a)

Soderstrom et al., (2014) have used GIS techniques for spatial analysis to identify sources of tree debris along the banks of the Pite River in Sweden. Spatial analysis was used to evaluate slope along the river bank, soil type, vegetation type, and inundation areas to determine risk areas in the watershed. Typically, these are areas characterised by both steep river banks (typically slopes of 20-45%) and soil types with instable behaviour (loose sediments and fine materials), ground without forest being excluded from the analysis.

LiDAR scanning was then used in the high-risk areas to classify trees by height and to estimate the number of trees. Where the river banks were accessible, a field survey was conducted to calibrate the LiDAR information. This allowed identification of high-risk areas, where landslides containing large trees could occur, which were not accessible for visual inspection.

Recently, an inventory of potential sources of floating debris has been carried out for the Skallböle Power Plant project (Astrand & Persson, 2017) using ArcGIS based on laser data, flood maps and calculated water velocities available from Ljungan’s contingency planning project. These data, combined with soil maps have been used to identify areas at risk of landslides, erosion and flooding and to quantify the number and height of trees within these areas as shown in **Error! Reference source not found.**.

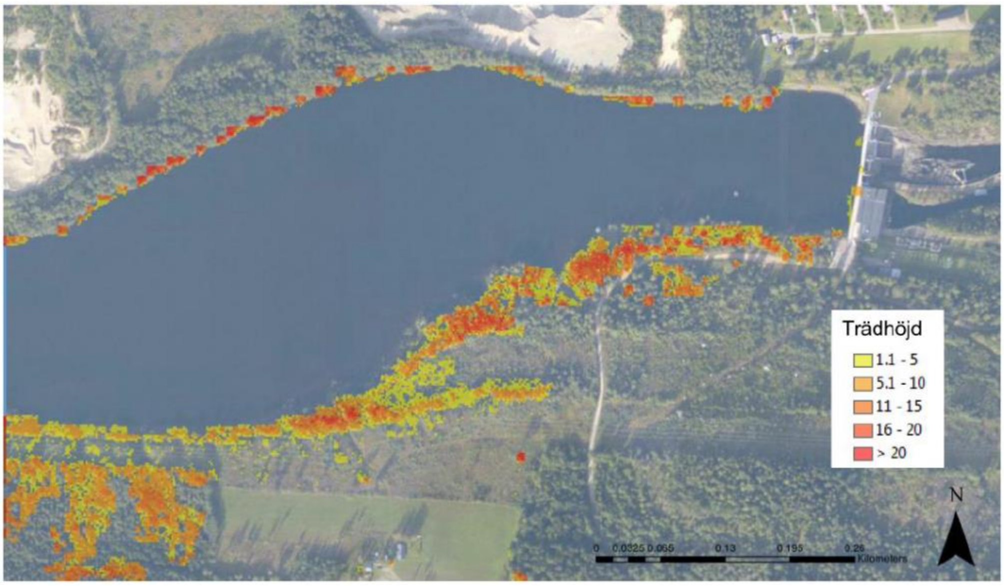

Fig. 2.5
Tree heights in areas with potential for formation of floating debris directly upstream of Skallböle Power Plant

2.4.7. *Evaluation of past flood events*

After a flood, the data on transported wooden debris can be determined and used for future hazard evaluations. The following approaches to quantify the transported wooden debris may be adopted, namely:

- Determine the volume of the transported wooden debris based on the lost forested area along the river and reservoir; or
- Determine the volume of actually deposited wooden debris in the drainage basin and especially in the reservoir and the volume of floating debris discharged downstream of it.

The lost forested area along the rivers and reservoir may be quantified using aerial photos from before and after the flood. If no aerial photos are available, the lost areas can be assessed directly in the field. A timber stock per hectare must be known to finally determine the volume of transported wooden debris down the river and to the reservoir.

However, this method does not allow predicting directly the volume of debris actually transported to the reservoir as some of them may have deposited within the river basin during the storm event. If the volume of wooden debris deposited within the reservoir and the volume of floating debris discharged downstream of it could be established, the wood delivery ratio could be determined which is calculated as the volume of wood deposited in the reservoir and discharged downstream of it divided by the volume of forest lost.

Wooden and other floating debris may accumulate within the reservoir in front of spillways, trash racks, intakes, and gates, or as a wooden debris carpet in the reservoir. The volume of these accumulations can be determined from photos or by direct measurement. If the accumulations are removed, the volume can be derived from the number of truck loads, or if the wooden debris is shredded, from the volume of the wood chips. However, the volume of debris discharged downstream should also be quantified.

This method presents the deficiency of not allowing to predict directly the volume of the transported wooden debris during storm events having a duration, intensity and return period significantly different from those observed.

Also, the lost forested area during a major storm event will have a significant impact on the volume of transported wooden debris during subsequent storm event within the same basin even if they presented exactly the same characteristics.

3. IMPACTS OF FLOATING DEBRIS

3.1. BACKGROUND

The accumulations of floating debris into reservoirs and their transport to spillways, intakes or bottom outlet structures can have significant negative impacts to the operations and functions of a dam. This section explores the potential impact of floating debris within a reservoir. However, it does not provide a comprehensive discussion on the subject of debris impacts to dams but only a literature review on this topic, limited to debris impacts regarding:

- Stability and structural integrity of the dam and its appurtenances, particularly rigid structures;
- Loss of flood storage space;
- Reduced performance of trash racks at intakes, gates, and outlet works for normal and flood operations;
- Reduction of spillway capacity and backwater rise;
- Operational problems related to the removal of debris;
- Downstream effects

For this report, debris impacts will not include discussions regarding ice. Impacts to dams and reservoirs due to ice are discussed in a USACE Engineering Manual (2002). The recently published Bulletin 172, Technical advancements in spillway design has a section devoted to the problems of ice blockage of spillways.

Debris impacts on a reservoir and dam appurtenances is a topic where little background research or information has been compiled. The existing literature that was discovered included design considerations of spillways in areas susceptible to large debris inflows as well as case studies. The most detailed literature is contained within US Federal Highway Administration (FHWA) and US Army Corps of Engineers (USACE) publications. The FHWA publications focus mainly on bridge and culvert debris considerations but also have applications to dam appurtenances.

In addition to the two federal agencies, articles with regard to debris impacts were provided within United States Society on Dams (USSD) and ICOLD conference publications. In 2017 two guidance documents dedicated to the subject of floating debris impacts at reservoirs were produced in Switzerland and Sweden, namely: Methodology for Analysing and Managing Floating Debris at Dams and Reservoirs, Energiforsk, October 2017 and Floating Debris at Reservoir Dam Spillway, Swiss Committee on Dams, November 2017 as referred to in Section 1.2 of this bulletin.

3.2. DEBRIS IMPACTS

3.2.1. Debris Impacts at Reservoirs and Spillways

3.2.1.1. General considerations

Accumulation of debris within reservoirs and around spillways is expected to present operational and most importantly dam safety concerns due to the reduction of spillway capacity and potential structural damage to the dam, gates, and other appurtenance structures It could also cause a loss of reservoir storage and resulting operational problems and may have adverse environmental or flooding impact on the downstream watercourse.

The most typical impact of floating debris at spillways is their reduced discharge capacity, resulting in backwater rise and increased upstream flooded area, increased load on the dam and possible dam overtopping. Such impact may be due to:

- Blockage by large floating debris;
- Increased hydrostatic load and/or dynamic pressure on the dam or any gates due to currents developing underneath the obstructing material which could prevent their successful operation;
- Blockage by relatively small debris of flap gates, underflow gates or other mobile devices, including blockage of their mechanisms;

In addition, large floating debris may cause damage to spillway gates due to dynamic impact;

Also, debris caught against piers increase their size. This concentrates the flow, increasing water depths and velocities thus placing loads on the structures which they have not been designed for.

3.2.1.2. Mechanism of spillway blockage by large floating debris

The spillway blockage by large floating debris has been the focus of most systematic studies carried out to date. It can originate from different causes such as:

- The width of the spillway is not big enough compared to debris length. Godtland and Tesaker (1994) proposed criteria discussed in section 5.2 (spillway width > 80% of wooden length)
- The available vertical clearance between the spillway crest and upper structural elements (bridge, gate lower part when opened) including water depth and air clearance. Again Godtland and Tesaker (1994) proposed a criteria discussed in section 5.2 (vertical clearance > 15-20% of wooden length depending on the spillway width/debris length ratio);
- The approach flow/depth, expressed in term of the Froude number. At Fr>0.15 floating debris have a greater tendency to be drawn down towards the spillway and reduce its discharge capacity as discussed in section 5.2;
- The water depth above the spillway crest. Bénet et al. (2020) and Pfister et al. (2020) proposed criteria of blockage discussed in section 5.1 depending on the ratio water head H_o / tree diameter D_m.

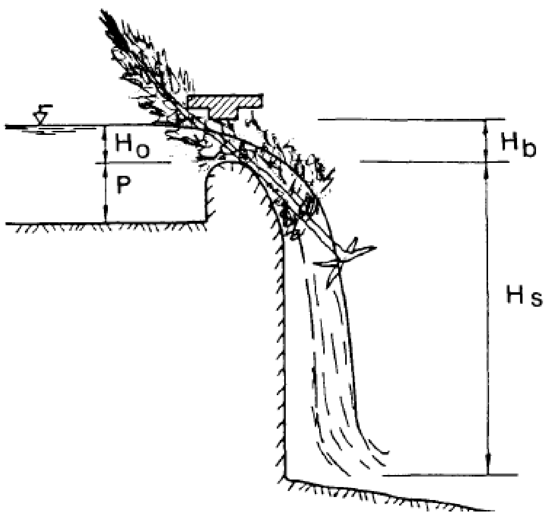

Fig. 3.1
Vertical clearance according to Godtland and Tesasker (1994)

3.2.1.3. Other impacts of blockage

If a large volume of floating debris is accumulated within the reservoir, the loss of storage may become relatively significant. To mitigate the resulting adverse economic impact and reduce the risk of floating debris becoming saturated, thus posing a risk of blockage to any submerged intakes and bottom outlets, regular debris removal would be required.

Besides having a bearing on dam safety, spillway blockage by floating debris could have an environmental impact on the downstream watercourse. In accordance with (Boes et al. 2017), large wood (typically composed by stems longer than 1 m and larger than 0.10 m in diameter – (Furlan et al., 2019) 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. Therefore, from an ecological perspective, it is desirable to leave wood in the water and this could be largely prevented where the spillway may be at risk of blockage during significant flood events which have the potential to generate and transport large volumes of floating debris.

However, the passage of floating debris over the spillway may transfer the risk of blockage to the downstream water course and thus increase the risk of downstream flooding.

Where reservoirs are used for recreation purposes, debris may cause damage to boats.

Floating logs and trees can also damage the upstream slopes of dams.

3.2.2. Debris Impacts at Intakes

The impact of floating debris at intake structures is predominantly an economic impact due to the relatively low hydraulic capacity of these structures compared to the reservoir spillways and thus limited contribution to dam safety.

For example, blockage of hydropower intakes or draw-offs for a water treatment plants entails a loss of power generation and water production respectively as well as a cost associated with the removal of such blockages.

However, blockage of cooling water intakes could be critical and would require contingency measures and emergency procedures to be put in place.

Other impacts on reservoir intakes due to blockage by floating debris include:

- Trash-racks may become overstressed and fail structurally as a result of high unbalanced pressure.
- Vibration of sluices, gates, struts and trash-racks may cause failure of such structures due to material fatigue.

A section of the 1997 USACE publication discusses concerns with vortices at hydropower plant intakes having the potential to pull floating debris into the turbine or onto the trash rack so as to cause rough turbine operations. A run-of-river power plant example is provided where a separation layer on the upstream side of the turbine gave rise to a zone of rotating water. This caused arriving floating debris to be retained some distance from the trash racks. A vertical, radial current potentially could occur in this zone that can develop into a vortex, sucking air and debris from the surface into the intake. This situation can lead to impairing the smooth running of the turbine or possible damage to the turbine. Design considerations and a formula are presented to predict the potential for vortex development to assist in countermeasures to avoid air and debris suction into turbines.

3.2.3. Debris Impacts at Bottom Outlets

The impact of blockage at bottom outlets on dam safety is comparable to that of spillway blockage due to the potential loss of their hydraulic capacity in case of emergency draw-down which, could be critical.

Blockage by floating debris could occur when such debris remain within the water for a sufficiently long period of time to allow them to become saturated and sink thus obstructing and / or impairing the functioning of bottom outlet or its penstock. However, fresh wood usually remains buoyant for several months (Zollinger 1983), which means that withdrawing it twice a year is sufficient. In this connection, wood that has remained in the water for a long time and become waterlogged could go under baffles and gates unless provision is made for regular inspection and cleaning.

Blockage of relatively small size bottom outlets could also be caused by diving birds such as the Cormorant or other diving to quite significant depths of 45m or more. Such birds may be attracted by the high velocity at the inlet to the bottom outlet and may become trapped causing a blockage of this structure. Blockage of fine screens for water offtakes by aquatic fauna such as shrimps can also be an issue.

Similar to reservoir intakes, vibration of sluices, gates, struts and trash-racks due to blockage may cause failure of such structures due to material fatigue.

A more specific issue at bottom outlets is that debris may prevent closure of a gate which in turn may cause scour of the sill due to increased velocities.

The blockage of bottom outlets by sediments is a complex issue related to the reservoir sediment management which is outside of the scope of this Bulletin. It should be mentioned though that during low reservoir levels or periods when sediment arrives to an outlet works or hydropower intake, woody debris can accumulate on grated intakes, impacting reservoir operations. After the woody debris blocks the intake, sediment then deposits behind the accumulated debris, beginning the process of limiting sediment passage during flushing and sluicing, and increasing the potential for eventual burial of the intake (refer to USBR, 2016).

Generally, bottom outlets perform acceptably if they are located at a depth that does not significantly affect the surface velocity [Dath et al., 2007]

3.3. CASE STUDIES

3.3.1. Palagnedra Dam

One of the most studied case histories with regards to spillway clogging is that of Palagnedra Dam in Switzerland. Bruschin et al. (1982) authored a case study of the overtopping of Palagnedra Dam. The reservoir has a drainage area of 140 km^2, and the slopes are very steep. It was found that about 52% of the watershed is afforested with a thin topsoil layer, and there is a weak resistance to erosion on stream banks in the area. Palagnedra is a concrete arch gravity dam. The spillway, an ogee crest on top of the dam with a steep ski-jump chute on its downstream face, was designed with a flood capacity of 450 m^3/s, which had been exceeded without damage on six occasions. A bridge was constructed above the top of the dam, having thirteen openings. A flood on August 7, 1978, from very heavy rainfall, caused overtopping of the dam and excessive damage with 24 lives lost. The very heavy rain eroded large areas of the forest and soil on the northwest flanks of the upper valley.

It was thought that as the initial flood discharge increased, a log jam was created within the watershed area above the reservoir. Then, a first wave was released, and the logs started to obstruct at the narrowest part of the bridge upstream. The flow accelerated in the river bed and produced scouring. A second wave caught most of the floating wood upstream of the bridge, where it became a bore. At this time, the spillway was discharging about 1,000 m^3/s. At the dam, the logs and wooden debris obstructed the spillway. The water continued to rise, and the dam overtopped along the whole length (the peak discharge was estimated at a little less than 2,000 m^3/s into the downstream valley). The case study yielded the following observations:

- There was 25,000 m^3 of debris loading after the event.
- There was 1.8 x 10^6 m^3 of sand & gravel from erosion after the event.

The first analysis on the event concluded the overtopping of the dam was due to a large discharge combined with the debris spillway obstruction. It was felt that additional information could be obtained only through physical and mathematical modelling.

A physical model was developed to get a better understanding of the behaviour of the wood mass that blocked the spillway. The most significant observations were:

- The main flow of water was able to pass over or under logs accumulating upstream of an obstacle.
- When wooden bodies meet an obstacle, they may form a new stack almost immediately. A surge which travels upstream carrying some wooden material is then generated.

The results of the physical test included the following recommendations for re-design of the dam/spillway:

- Raising the abutments by 4 m to prevent overtopping,
- Removal of the top bridge and supporting piers to leave a continuous crest,
- Raising and remodelling of spillway guidewalls to ensure undisturbed discharge of complete runoff, and
- Setting the spillway piers apart at least 12 m to avoid potential build-up of woody debris.

After the incident, the flood spillway was re-designed for a design flood of 2,200 m^3/s. The existing bridge on top of the dam was transformed from a spillway with 13 openings, to an unbroken length of 80 m. The ski jump was modified to accommodate a discharge five times larger than the original design flood, passing up to 3,300 m^3/s without overtopping the dam.

The study concluded that there were many factors needed to be included in the design of the spillway and the general facility layout. These included:

- Hydrological and meteorological environment,
- Historical records of catastrophes and incidents,
- Examination of high sediment yield, and
- Examination of slope stability and top layers in afforested areas.

3.3.2. Sa Teula Dam

Another case study was for the Sa Teula Dam, Sardinia, Italy in December 2004. This event involved a large inflow of floating debris which reduced the flow of water to the galleries, preventing the spillway gates to open. The lack of the gate openings restricted the width of the free overflow spillways, impeding the release of floating debris. The result was an almost complete blockage of the openings, causing the dam to overtop. The large debris load - which caused tree trunks to be trapped between the gate and footbridge - ultimately caused the failure of the gate, and its complete detachment from the dam.

Based on technical documentation [Hartung & Knauss (1976), Gotland & Tesaker (1994), and Bruschin et al. (1982), the following are suggested for a more focused evaluation and minimization of possible blockages:

- Analysis of vegetative typologies and forestry practices in the watershed to understand potential debris loading.

- Pillar spacing on top of the spillway should be at least 80% of the maximum size of the trees moved by the current.
- If not obstructed by superstructure, tangles and single trees may be withheld along the crest until the overflow level reaches 1/6 of the tree length (i.e. the root diameter of the floating trees). Most (debris) tangles will pass the crest without superstructure when the overflow depth reaches 10-15% of the height of trees forming the tangle; where a superstructure is present, with pillar distance according to the preceding bullet, most tangles will pass when the overflow height reaches 15-20% of the tree length.
- Wind and waves normally contribute little to the total anchor force unless the flow is very slow or the wind and waves are of extraordinary strength.
- Open conduits are unlikely to become seriously clogged. In closed conduits, clogging can be avoided if three conditions are adhered to, i.e. a) smooth walls, b) no contractions or obstructions, and c) no sharp bends.
- Gates should be installed in order to form a concentrated jet-flow in the center of the intake. Lift gates should be avoided unless there are a large number of openings due to the danger of trees being drawn below their lower edge during closure. Drum, sector and flap gates should be used if possible, to avoid the clogging problem.
- Model tests and physical models are indispensable tools in the design of spillways exposed to large amounts of floating debris.

4. MITIGATING IMPACTS OF FLOATING DEBRIS

4.1. BACKGROUND

Mitigation measures to reduce the potential impacts of floating debris on dam safety can be classified into three broad areas: measures taken within the catchment area, retention and removal of debris within the reservoir and passage of debris through the spillway. Besides, additional operational, maintenance and contingency measures would normally be considered in conjunction with any of the above main mitigation measures.

4.2. MEASURES TAKEN WITHIN THE CATCHMENT

The impacts of floating debris on dam safety would be ideally mitigated at the source, namely through the proper maintenance and management of the areas upstream of the dam to reduce the inflow of floating debris to the reservoirs. However, this is normally difficult, technically complex and expensive as it would also need to meet the inherent ecology and various other requirements. Thus, it requires the cooperation of many parties and entities, which have diverse interests, possibly across different jurisdictional boundaries, particularly when the catchment area is large, as with many dam projects.

In catchment management, the emphasis is to promote good practices in land management by taking preventive forest protection measures and coordinating and controlling construction activities, timber harvesting practices, and mining operations in the catchment areas, such as:

- Clear trees prone to falling
- Constructing debris dams upstream of reservoir, and periodic removal of accumulated debris.
- Coordinating and minimizing strip clearing of the forests.
- Carry out deforestation measures within an edge zone adjacent to water courses and the reservoir
- Providing adequate drainage and/or reinforcement of slopes to prevent soil erosion and potential landslides which carry vegetation to streams leading to the reservoir.
- Rapid re-planting and land treatment in logged and mined areas to prevent excessive erosion
- Creating timber barriers downstream of logged areas to prevent movement of downed timber downstream
- Providing a no-construction buffer zone along streams and the reservoir proper
- Siting temporary holding yards for harvested logs and any buildings outside of the 100-year floodplain at a minimum, if the watersheds are being logged for timber or are inhabited
- Working with the forestry companies and/or respective jurisdictional governments to implement forest conservation measures and zoning plans to reduce the potential of human-generated debris on the watersheds
- Control man-made features that could affect potential landslides such as discharges from pipes or surface run-off from roads or other impermeable areas
- Carry out regular clearing of the reservoir from floating peat, fallen trees, log jams etc.

Because clearing of land within the reservoir area is one of the integral construction activities for reservoir projects, good planning and execution are also essential for the reduction of potential floating debris problems for plant operations in the future.

Many of the issues with floating debris could be prevented if there is a comprehensive and effective reservoir clearing program. In addition, much of the negotiation with landowners and forestry companies to maintain good catchment management practices could also be formulated at the beginning of the project.

In general, for reservoir clearing, a forest consultant should be engaged to:

- evaluate the effects of natural clearing agents like ice (in cold regions) and waves
- conduct a detailed characterization of the forest stands in the reservoir for timber utilization
- conduct a general characterization of the forest stands in the entire watershed area to minimize the generation of floating debris

Flooding in the reservoir and tributaries kills trees, thus creating floating debris. Therefore, the clearing objective is to have a minimum of 1.5-m clearance of all timber below the minimum drawdown level and up to the maximum reservoir water level.

In cold regions, ice is a very good natural tree clearing agent. Ice forms in the winter time during high reservoir water level periods. In an inundated forest, ice tends to fuse around the tree trunks. When the reservoir level drops, the trees act as columns supporting the ice field. If the ice is thick and if the reservoir water level drops quickly, the weight of the ice would break the trees by compression, thus creating floating debris in the reservoir. Therefore, it is essential that the clearing of the forest in the reservoir should be done in such a way to adhere to the 1.5-m clearance limit with no trees in the reservoir, particularly in cold regions.

To minimize the generation of floating debris in a catchment which has been logged, it is important to have a detailed characterization of the forest stands in the reservoir area including;

- unburned debris from cleared sites,
- debris from old burned sites, and
- debris left by the natural clearing agents, like ice, wind, or forest fires.

Notwithstanding the benefits provided by effective maintenance and management of the reservoir catchments, it should be noted that any large systems within the catchment providing effective retention of floating debris could also pose a risk of sudden release of the water and debris impounded behind them in case of their sudden collapse. This would have an adverse effect on dams located further downstream and could happen if such structures have not been designed for the storm event considered in the design of these dams.

It should be also recognised that, despite any forest maintenance and management and the provision of wood retention measures, the occurrence of large wood debris at reservoirs in some cases cannot be ruled out.

Fig. 4.1 The U.S. Army Corps of Engineers (USACE, 1997) reviewed and discussed many of the debris retention structures in the USA and Europe. The report provides an example of an effective design to capture floating debris in Southern Germany called “treibholzfang”. The device is a downstream pointing V-device made of posts anchored to the river bed at spacing matching the minimum length of the floating debris to be captured. This arrangement is effective and also creates minimum backwater effects. The only drawbacks are its high initial cost and that it requires a maintenance program to remove the captured debris on a regular basis. Fig. 4.1 through to

show the arrangements and design, taken from this publication.

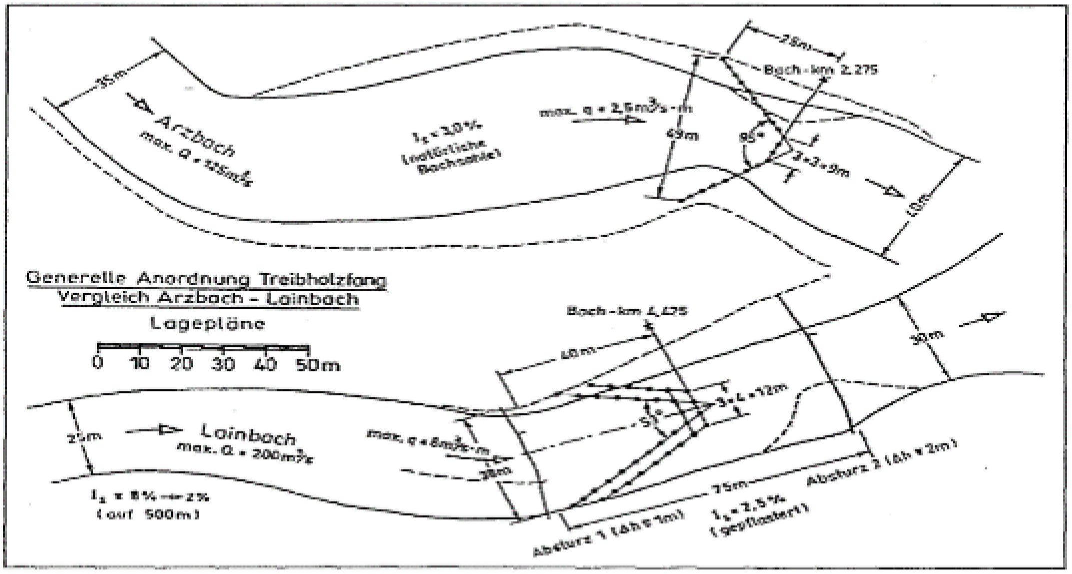

Fig. 4.2
General arrangement of the “Treibholzfang” device

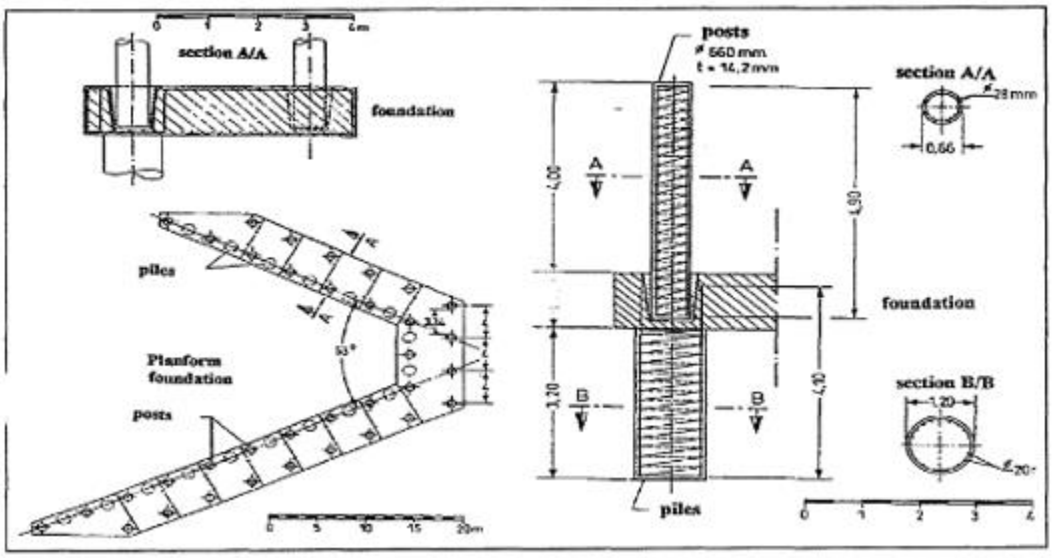

Fig. 4.3
Construction detail of the “Treibholzfang” device (modified from Knauss 1985)

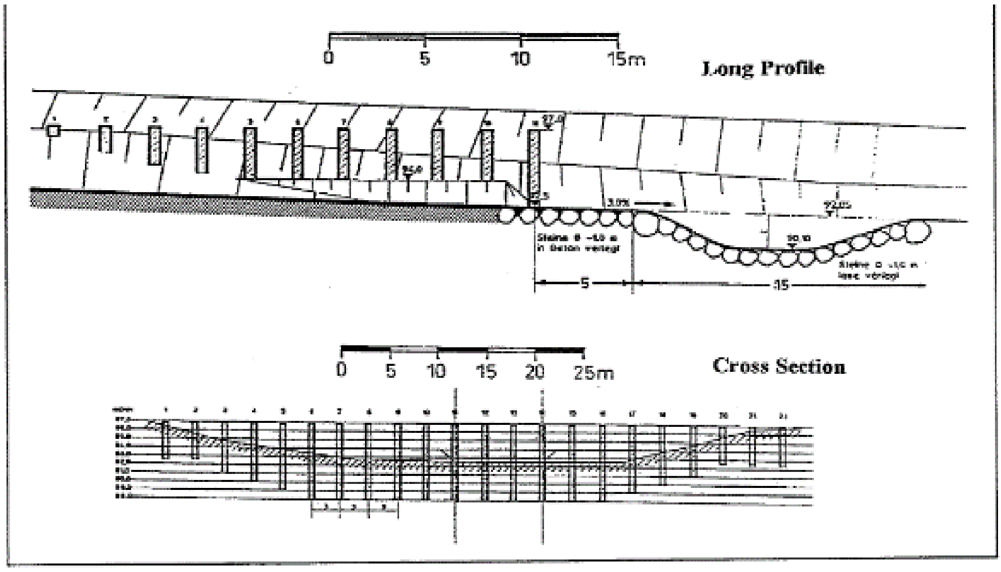

Fig. 4.4
Design plan of the “Treibholzfang” device

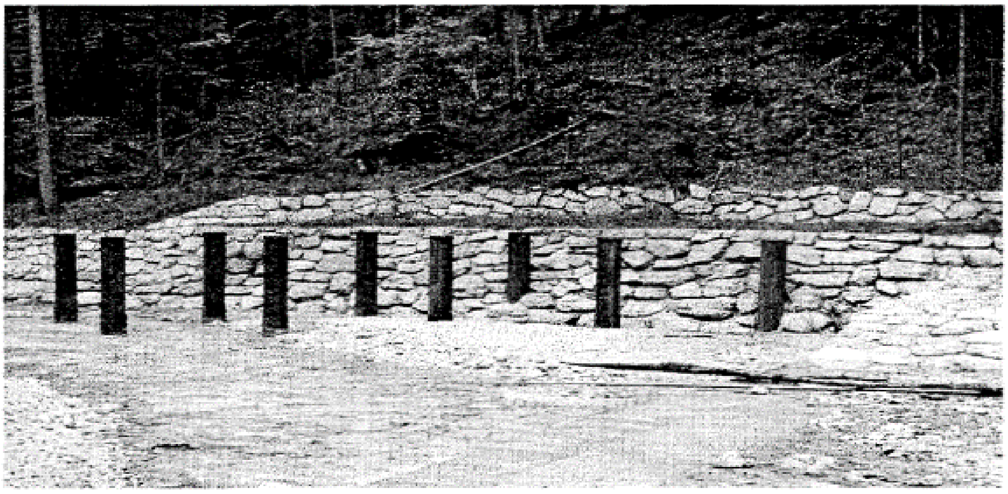

Fig. 4.5
“Treibholzfang” device on River Lainback (viewed downstream)

Fig. 4.6
“Treibholzfang” device on River Lainback (viewed upstream)
Source: United States Army Corps of Engineers (1997)

Fig. 4.7 Another device employed in Switzerland, developed at the Swiss Federal Institute of Technology, Zurich, for steep Alps mountain streams with large quantities of debris and sediment, is a small retention basin with slanting grilled weirs and box-type trash racks at the outlet as shown in

.

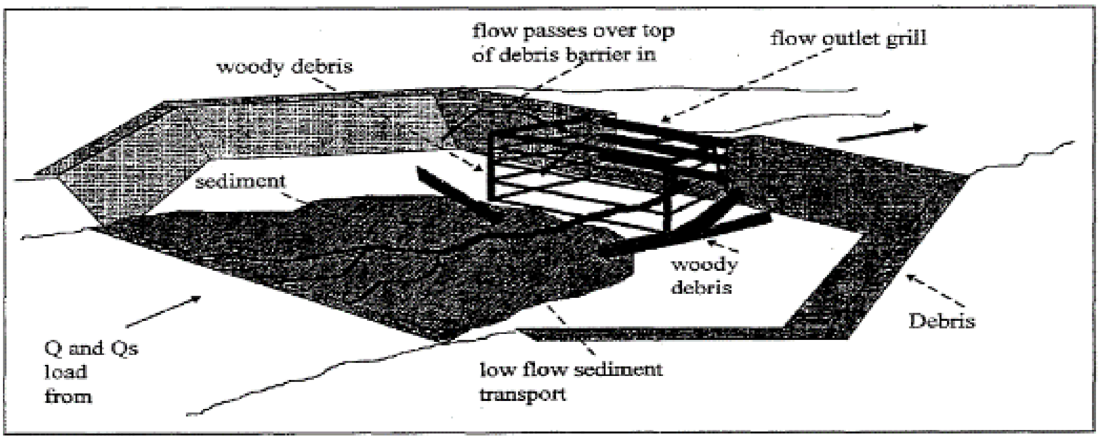

Fig. 4.8
Debris retention basin with debris protection device

Fig. 4.9 A large wood retention system of recent design, using a combination of large wood and trash cable racks installed on the Chiene river, Canton Bern is shown in
(Photo: Emch + Berger AG), Boes et al. (2017).

Fig. 4.10
Large wood and trash cable racks installed on the Chiene river, Canton Bern
(Photo: Emch + Berger AG), Boes et al. (2017)

4.3. RETENTION AND REMOVAL WITHIN THE RESERVOIR

4.3.1. General

Debris retention and removal within the reservoir could be considered where measures within the catchment or measures to pass debris through the spillway are impractical or not possible to implement or passage of debris is not permitted for ecological or safety reasons considering the downstream river reaches. Such measures would also normally be considered where the expected volume of the floating debris entering the reservoir is not too high to be removed at a reasonable cost.

Such systems are aimed at preventing the blockage and damage of the reservoir spillway and any appurtenant mechanical equipment.

Since large wood retention systems could pose a risk of sudden release of the water and debris impounded behind them in case of their collapse, they should be designed to withstand the maximum possible debris, hydrostatic and other loads imposed on them and their supporting structures considering a full blockage scenario.

4.3.2. Debris retention

4.3.2.1. Wood racks

Large wood racks are the most common debris retention system. They should normally be positioned upstream of the spillway inlet where sufficient water depths exist such that the flow could still pass under the rack in the event it became completely blocked. Under such circumstances, the velocity under the rack shall not exceed 1 m/s (Boes et al.). This would promote efficient retention, whereby floating debris are retained in the form of a loose floating single layer carpet, rather than being pulled down, and would thus largely reduce the additional head loss due to the blockage.

Where necessary, the racks could be positioned at an angle of 15-30dge to the vertical (Hartlieb, 2015) or further upstream where greater depths under the debris carpet could be achieved thus reducing further the backwater level rise. In the latter case, the access arrangements for removal of the accumulated debris would become more onerous.

The clear spacing between the racks should be as large as possible, while ensuring that it retains large wood exceeding the width of the narrowest part of the spillway. According to a study carried out by Lange & Bezzola (2006), wood with a length of $L \geq 1.5 \cdot s$ can be retained at a rack with a clear bar spacing of s.

The wood rack shall be positioned sufficiently but not too far upstream of the spillways structure, so that any floating debris passing between the racks remain aligned with the flow and do not block the spillway structure.

Wood racks could take various forms and shapes.

An example of a large wood rack installed in front of a concrete dam spillway at the Thurnberg reservoir at RiverKamp in Austria is shown below on **Error! Reference source not found.**.

Fig. 4.8
Large wood rack at the Thurnberg reservoir at RiverKamp in Austria
(Photo: Federal Ministry of Agriculture, Forestry, Environment and Water Management Austria), Boes et al. (2017).

Bénet et al. (2020) undertook systematic and parametric tests on physical models. It was showed that a simple rack made of vertical bars placed upstream of spillway peers could prevent from any loss of discharge capacity under given conditions. Fig. 5.3 shows the layout of a vertical rack made of bars located at 0,5b upstream the spillway (b is spillway width not respecting the Godtland and Tesaker criteria: b < 80% of debris length).

Instead of a rack placed closely in front of the spillway inlet Hartlieb and Overhoff (2006) installed ten vertical rack pillars arranged in a semicircle, far away from the inlet to the spillway of the Grüntensee dam (Bavaria, Germany). The clearance distance between the pillars is around 1.6 m (approximately the width of the narrowest part of the dam spillway) – refer to **Error! Reference source not found.**4.9.

Fig. 4.9
Vertical rack pillars at the inlet to the spillway of the Grüntensee dam (Bavaria, Germany), Boes et al. (2017)

Fig. 4.10 A log collection structure based on the 'treibholzfang' system, developed to capture debris in river channels, has been installed on the low-level spillway at South Para Dam in South Australia (refer to

4.10).

Fig. 4.11
A log collection structure on South Para Dam in South Australia

Fig. 4.12 Another variation of the concept of wood racks is the provision of debris retention posts, installed in one or several rows, as provided at the Lee Green reservoir in the UK (refer to

4.11).

Fig. 4.13
Debris posts arrangement at the Lee Green Reservoir in the UK

Fig. 4.14 Following severe floods in 2002, the spillway of the Znojmo Dam on the river Dye in southern Moravia was almost entirely blocked by floating debris. Following this, a steel wood rack frame was installed upstream of the spillway as illustrated on

4.12.

Fig. 4.15
Steel ‘wood’ rack frame at the Znojmo Dam in Moravia

Fig. 4.16 An alternative wood rack structure studied by Yang and Stenstrom (2011) is the debris visor. It is designed to be arc-shaped, the curvature of which is dependent on the channel-like reservoir topography in front of the spillway, refer to 4.13.

Fig. 4.17
Debris Visor in physical model

The visor consists of a number of supporting piers of triangle-shaped slabs that are oriented in such a way that they approximately follow the main flow direction. The visor stretches over the whole water passage.

One important feature of the visor is that its net flow area is larger than that of the spillway openings.

Tests showed that the tree density plays a role in the debris behaviour. Those trees having low density get stuck crossways and stay in the surface water. The flow has a tendency to push up the trees along the sloping piers. Tree with higher density approach the visor obliquely in the water and often get caught in the lower part of the visor. The root system of the trees does make a difference to the test results. In the model, roots of some trees weight more than the trunk per length meter. As a result, some trees, especially those with a specific density just below 1.0, can float almost vertically when approaching the visor. Their roots may touch the reservoir bottom. In relation to the tree length tested, the water upstream of the visor is shallow. Those trees get stuck in the visor more or less in the flow direction.

In the beginning of the tests, some solitary trees pass the visor. Those trees can often pass the spillway as they follow the main flow direction after the visor. When many trees are intercepted, the clogging results in certain water level difference across the visor and the flow has also a tendency to drag down the trees. Depending on the density distribution, the intercepted trees may cover the whole visor height in the water. The head losses across the visor can be significant, although less than some of the other forms of debris passage that were modelled.

This and other papers (ICOLD 2009, Q91 R4) outline model studies and optimize designs for debris visors, the use of debris visors to protect debris build up on spillways is not understood to be widespread.

A similar, though somewhat reduced, effect to that produced by wood racks and debris visors, can be achieved by providing the spillway with piers which noses protrude into the reservoir. In some cases, this would allow the floating carpet of stems to be kept away of the weir crest and thus the discharge capacity may not be affected.

Laboratory tests were carried out in the Laboratory of Hydraulic Constructions (LCH) at the EPFL, Switzerland to evaluate the blockage at an ogee crested spillway equipped with piers by artificial stems. They indicated that where stems block the spillway perpendicular to the flow direction (bridging between two piers) a floating carpet of stems develop which prevents the large wood to reach the weir crest, thus not increasing the reservoir water level upstream of the weir. However, where stems were aligned parallel to the flow direction a condensed wood jam could develop causing an increase of the reservoir water level (Furlan et al, 2019).

The test also indicated that the firsts stems that block at the weir tend to determine the shape and composition of the jam, thus becoming key elements that control the blockage process. The movement of stems for a reservoir flow approach was observed to be erratic with stems tending to align to the flow direction close to the weir. Stems were also observed to move above each other in several vertical layers which influenced the blockage process (Furlan et al., 2019).

4.3.2.2. Skimming baffles

Where the spillway structure is to be protected against the passage of very small debris, skimming baffles could present a pragmatic alternative to wood racks having reduced spacing. Where water levels are subject to high fluctuations such skimming walls should be designed as floating baffles.

Skimming baffles should be sufficiently submerged with due consideration of the velocity of flow under the baffle. As a minimum, a depth of 1m below the water surface should be provided in accordance with the Swiss Committee on Dams report (Boes et al., 2017).

A disadvantage of such an arrangement is that any waterlogged debris may still pass under the baffle and block the spillway. Therefore, such a solution should be implemented in conjunction with a strategy for regular removal of floating debris accumulated within the reservoir as well as with suitable access and means of regular removal of debris retained in front of the baffles.

Fig. 4.14 A partially baffled arrangement has been provided in front of the Piano Key Weir installed on the crest of the Black Esk reservoir shaft overflow structure, refer to

4.14.

Fig. 4.15
Black Esk PKW, UK - Belmouth Shaft Overflow Raising (Source: Black & Veatch Ltd.)

4.3.2.3. Floating booms

Fig. 4.15 Floating barriers or 'booms' could be used to retain or divert floating debris to a dedicated passage area thus protecting the reservoir spillway and any intakes from blockage. A typical floating boom installation is shown on 4.15.

Fig. 4.16
Typical Floating Boom Installation

The design of the boom needs to take into account the type and quantity of the debris likely to be captured and must be part of an integrated plan for the management of the debris.

The main factors to be considered in the estimation of debris boom loads are:

- Maximum and minimum water levels

- Extent of the debris mat and average thickness
- Flood water levels
- Reservoir inflows and outflows during normal and storm conditions
- Water speed and direction
- Wind speed and directions
- Extent of the ice mat and thickness
- Combinations of flood and wind conditions
- Wave heights
- Boom span and geometry

The actual loads and the load combinations selected will depend on the importance of the structures, the hazard that they pose, and as a result, on the level of protection required.

There are two major elements contributing to the forces acting on a debris boom, wind and water. The debris boom and debris mat are at the interface between air and water and are acted on by forces of inertia and the viscosity of the fluids.

A detailed evaluation of the derivation of boom loads is beyond the scope of this Bulletin, however there are a significant range of publications dealing with loads on debris booms. One of the more comprehensive publications is “The design of Ice Booms” by Foltyn and Tothill (1996). Perham (1988) provides an overview of the problems of controlling debris and the USACE Engineering Manual 1102-2-1612, “Ice Engineering” (2002) gives a comprehensive account of the theory and practice of control measures.

Even though floating booms are a cost efficient and relatively easy to install debris mitigation measure, they represent a less robust solution than wood racks and are prone to failure if undersized or subjected to extreme and unexpected loads. As a result, the risk of blockage of the reservoir spillway due to the sudden release of large volume of debris may further increase.

Fig. 4.17 Floating booms 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 as illustrated on

4.16.

Fig. 4.18
Floating rack (Photo: H. Czerny, Federal Ministry of Agriculture, Forestry, Environment and Water Management, Austria), Boes et al. (2017)

The report of the Swiss Committee on Dams on Floating Debris at Reservoir Dam Spillways (Boes et al., 2017) highlights some of the main risks and deficiencies presented by floating barriers including:

- Large Wood (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;
- Ice drifts could damage or destroy them;
- Barriers chain may be left hanging in the air at very low reservoir levels which may result in their failure.

It also provides feedback from experience with the application of LW barriers on Lake Thun, Lake Brienz and Lake Biel in Switzerland as follows:

- 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 conclusion the report states 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, including the failure at the Montsalvens reservoir in Switzerland in 2015.

This conclusion is also corroborated by Bradley et al. (2005) suggest that floating barriers are only suitable as a measure for ‘small’ and ‘medium’ LW debris dimensions and volumes.

In the same spirit, S Astrand & F Persson (2017), reiterate the risk posed by floating booms/chains breaking due to the forces acting on them potentially exceeding those they have been designed for thus generating a sudden release of debris. They also state in the case of floating booms, it has been identified as part of DSIG projects that it is very difficult to design them for extreme conditions and be able to rely on them to operate in a real situation. Therefore, knowledge in this area still needs to be improved in order to be able to reliably design floating booms with regard to dynamic loads.

4.3.2.4. Intake trash racks

The conventional way to manage the inflow of floating debris at reservoir intakes is to use trash-racks with scrapers which remove the captured debris continuously and place the debris onto designated areas on the dam proper. However, this method can only handle relatively small and occasional debris quantities, not debris accompanying design flood events which could endanger the safety of the dams by hindering spillway gate operations.

Similar to the design of wood racks, the blockage of intake trash racks could be mitigated by providing ample trash rake submerged areas in order to reduce velocities and prevent debris from being drown down and obstructing the lower parts of the rack.

Also, arrangements could be made for providing differential head measurement across the trash racks or flow measurement within the inlet/bottom outlet pipe so that any blockages are identified and cleared in due time.

Trash screens should normally be designed to withstand the loading resulting from full blockage. However, in some cases, where access to the trash screens is difficult, it may be preferable for these to be designed to collapse under a certain head preventing the full blockage of the intake or bottom outlet and avoiding the need to use to divers to clean them.

Alternatively, the risk of blockage of trash screens may be mitigated via the provision of by-passes.

The CIRIA C786 Culvert, screen and outfall manual (Benn et al., 2019) sets out good practice for the design, assessment, management and operation of debris and security screens upstream of culverts in England and Wales some of which is also applicable to trash racks at intakes.

4.3.3. Debris removal

Debris removal is a measure that may only be relied upon when there is very low potential for debris reaching the spillway structure and where a full blockage of the spillway or intake structure would not pose a risk to the safety of the dam.

Fig. 4.17 Removing debris during a flood event would normally require the installation of or access to heavy machinery, including boats, excavators, automated trashrack equipment etc. However, removing large wood blocking a spillway during a flood event is likely to be very difficult due to the high velocity, draw-down and wedging effects. Therefore, in most cases debris should be prevented from reaching the spillway and should be retained in areas of low velocity for ease of their removal during a flood event if necessary. Large amounts of debris are only possible to remove after the flood event. The removal of floating debris with excavators is illustrated on

below.

Fig. 4.18
Removal of floating debris with excavators at the Yarzagyo dam, during the 2015 flood in Myanmar
(Photo: M. Wieland), (Boes et al., 2017)

Since floating debris normally remain buoyant for several months, removing them twice a year would be sufficient to prevent them from reaching the spillway or sinking and obstructing bottom outlets or submerged intakes.

4.4. PASSAGE OR DIVERSION OF DEBRIS THROUGH THE SPILLWAY

4.4.1. Debris passage

For dams in areas which are prone to heavy floating debris loads, characterisation of the floating debris should be incorporated in the design phase of the project. The spillway structure should then be designed or modified with reference to the criteria for assessment of the likelihood of blockage provided in Section 5.2, in particular:

- The weir bays of the spillway structure should be large and tall enough or;
- There is a free spillway structure (without superstructure) which is wide enough and;
- The approach velocity and depth and any bottom outlets operating during the design storm event would not cause debris to be pulled down to the weir crest and obstructing it.

Furthermore, the Swiss Committee on Dams report (Boes et al., 2017) provides guidance on the possible adjustments and mitigation measures including:

- Removal of pillars, bridge structures and regulating structures where possible to increase clearance;
- Design foot bridges such that they can be quickly removed or washed-away in an emergency
- Avoid/replace regulating structure generating undercurrents (vertically lifted/lowered gates) and use overflowable regulating structures such as flap gates and inflatable weirs or drum/sector gates which are less susceptible to obstruction;
- Locate drive shafts outside of the area of impact by large floating debris or protect obstruction prone components with casings
- Relocate any coarse rakes positioned directly on the crest further upstream where velocities are lower;
- The design of the inlet structures facilitates the passage (round shapes, trumpet shaped inlets, rounded pillar heads etc.)
- Free-standing pillar in front of the dam spillway to re-orientate trunks floating transversely to the flow direction as long as they are located sufficiently upstream of the spillway (Boes et al.). Normally, a circular cylindrical pillar is advisable for cost and construction method reasons (Waller et al. 1996)
- Footbridges should be built so that they can be quickly removed or washed away in an emergency

Due consideration should also be given to the potential for damage of spillway chutes and energy dissipators by floating debris, especially where baffle blocks or other protrusions are present.

4.4.2. Debris diversion

Debris diversion structures can also be used to guide floating debris to the spillways for discharge. Such a structure was incorporated in the Cowlitz Falls Hydro Project in the State of Washington, U.S.A. The structure is an upstream pointing V-shape floating barrier device which incorporates positive displacement buoyancy chambers above the waterline, with submerged eductor chambers below the normal water line. The chambers are filled with water at low flow conditions so that the structure will float at the waterline. At high flows, water is sucked out of the educator chambers to increase the buoyancy. This device is attached to the portion of the dam where the power intakes are located, to guide the floating debris to the spillway bays which are situated on both sides of the power intakes.

Fig. 4.18 shows a sketch of this structure, together with photos with the device attached to the dam in the hydraulic model during testing, taken from Western Canada Hydraulic Laboratories Limited (WCHL, 1989) – see

4.18.

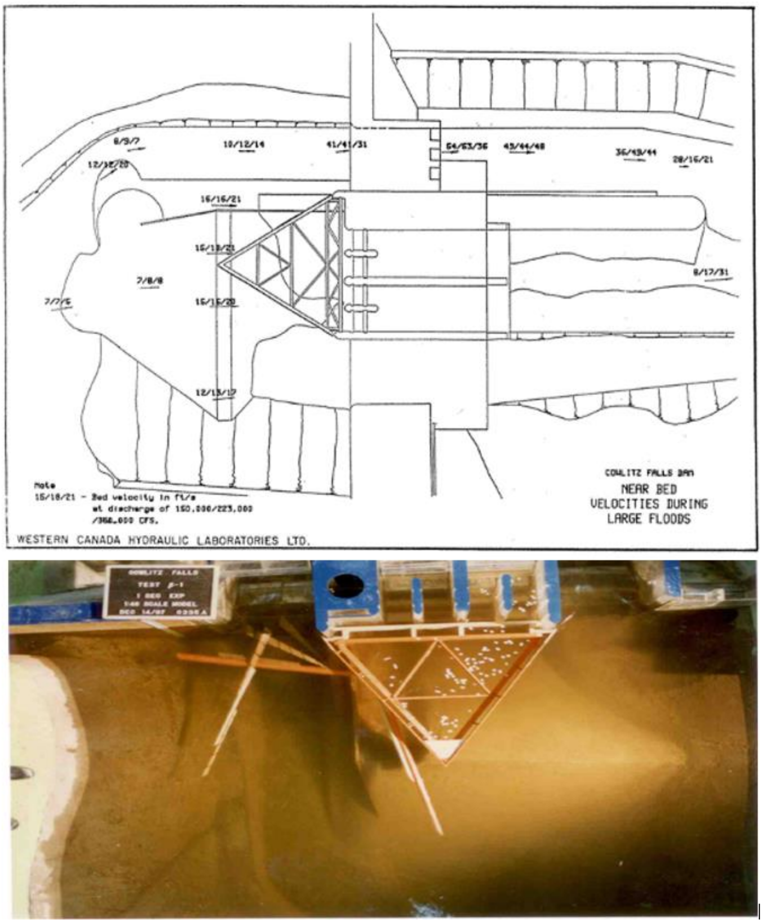

Fig. 4.19
General layout of the dam showing the debris diversion structure and physical model
showing the passage of logs through the spillway bay
Source: Western Canada Hydraulic Laboratories Limited (1989).

4.4.3. Debris by-pass spillways

Fig. 4.19 Debris by-pass spillways could be provided where it is not practical to modify the existing spillway to allow passage of floating debris. Such spillways should be designed in accordance with the principles and guidance provided in Section 5.2. Failure to do so could result in a failure to achieve their intended performance. This is highlighted in a paper by Yang and Stenstrom (2011) describing the model studies of a by-pass spillway structure aimed at mitigating the potential clogging of the existing spillway measures under consideration refer to

4.19.

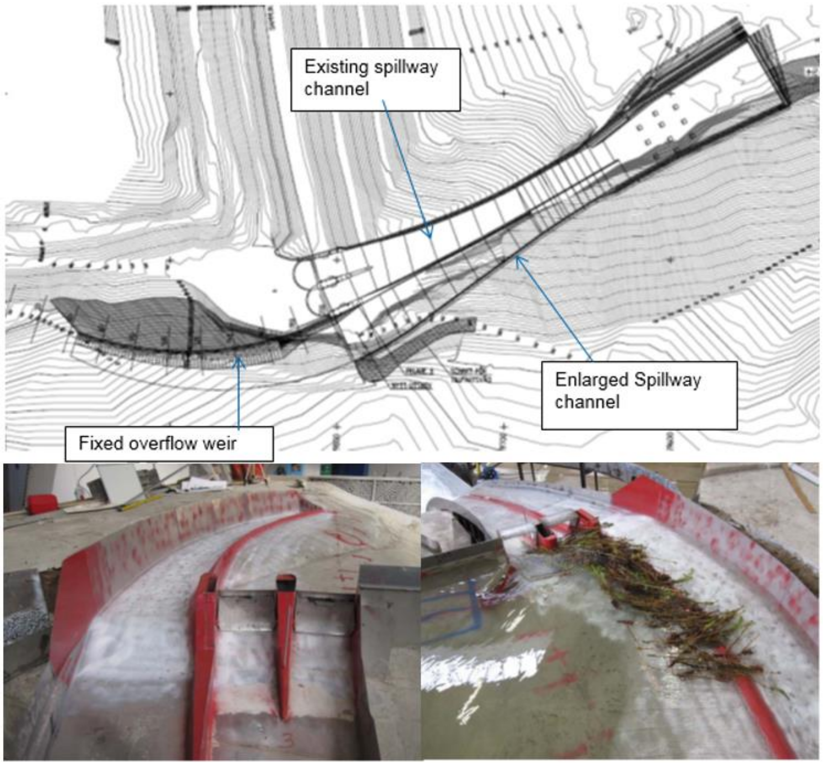

Fig. 4.20
General layout of the existing and proposed by-pass spillway and physical model showing the clogging of the by-pass weir

The model runs have showed that with the first trees clumped together in the right spillway opening, trees also started to get wedged on the by-pass weir immediately upstream of the spillway. As a result, a jam of floating trees was formed and developed further upstream along the weir and it has been found that even with a reasonable water level rise, it was almost impossible to lift a long jam of tightly knitted trees over the weir.

4.5. OPERATIONAL MEASURES AND CONTINGENCY PLANNING

A range of operational measures could also be undertaken to provide partial or full mitigation to the risk of spillway blockage.

Flap valves, tipping gates or pneumatic gates could be useful in facilitating the free passage of floating debris while delivering the benefits associated with gated spillways.

Experience also indicates that a single surface spillway opening is more likely to allow trees to pass than if several surface spillway openings are adjacent to each other [Johanson, 2010]. This can be explained by the fact that, in the case of a single surface spillway opening, the acceleration towards the opening rotates the tree in the direction of flow (Astrand & Persson, 2017).

Also, in accordance with (Astrand & Persson, 2017), the discharge of floating debris could be efficiently managed through opening of the spillway gates at the same time, to reduce the impact of increased surface water velocity. If the flow field's epicenter is restricted deeper down in the reservoir, this would create favourable conditions that would keep floating debris at the surface of the reservoir. This limits the phenomenon of drawdown of the floating debris. The measure is limited to a given level of gate opening.

If flooded areas are deemed to be a significant source of floating debris, lowering of the reservoir water level can be a suitable measure to prevent the occurrence of floating debris (Astrand & Persson, 2017).

The Swiss Committee on Dams report (Boes et al., 2017) also provides guidance on operational measures, as follows:

- 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;
- 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, it is stated that: In extreme cases, most of the weir bays would usually be needed, and asymmetric operation is therefore no longer possible

However, the report states that apart from Hartlieb (2015), there are generally no systematic investigations on weir spillway control, and the effectiveness of measures is therefore not conclusively proven.

Contingency planning measures could be taken where additional corrective measures to manage the risk of blockage by floating debris may be required. These could involve providing machinery for the short and long term. The planning consists of contracting maintenance or setting up one's own. The type of machinery is determined by the corrective measures to be taken. In addition, suitable placement, axle weights, etc. must be evaluated when choosing the machinery (Astrand & Persson, 2017).

The UK Guide to drawdown capacity for reservoir safety and emergency planning (Courtnadge et al., 2017) discusses amongst other things options for mitigating the risks where the existing drawdown capacity typically provided by bottom outlets is judged to be insufficient. These options, which could also be considered to mitigate the risk of blockage of bottom outlets by waterlogged floating debris or silt include:

- Installation of drawdown facilities which avoids works at the base of the dam, such as syphons or penstock installed close to the spillway crest;
- Increased frequency and/or quality of surveillance allowing early detection of blockages;
- Emergency planning on-site including the provision for pumps or siphons to be on standby so that they can be quickly mobilized or planning a means of controlled breach of low height section of the dam

In order to ensure that draw-down facilities could be operated reliably in an emergency, the Guide recommends that reliable access to the site to maintain and activate drawdown facilities is maintained at all times and that valves and gates on all drawdown facilities are regularly exercised under full head conditions, with the full discharge being released at regular 6-monthly intervals.

5. EVALUATION AND MANAGEMENT OF THE RISK OF BLOCKAGE

This Bulletin deals with the evaluation and management of the risk of blockage mainly of reservoir spillways which has been the primary focus of any past and more recent research and guidance provided. This is due to its more significant impact on dam safety compared to the risk of blockage of submerged intakes and bottom outlets which has received less attention in the past and is only briefly discussed here.

The risk of blockage of reservoir spillways is a function of the probability of blockage and severity of the associated consequences.

The probability of blockage is typically defined as the probability of single trunks blocking the spillway but could also allow for the presence of tree rootstocks, branches and clustering (Boes et al., 2017).

The severity of the consequences of a blockage would depend on the type of dam (concrete or embankment dam) and impact of its overtopping, the static and dynamic impact on the weir structure and any associated gates or other equipment, the rate of transport and attenuation of the floating debris and flood hydrographs, the availability, reliability and capacity of any debris removal systems and access routes, the vulnerability of any downstream assets or communities to flooding, the environmental impact of retaining floating debris on the downstream watercourse etc.

5.1. PROBABILITY OF BLOCKAGE

Free overflows normally present a lower probability of blockage than regulated dam spillways under identical conditions. On the other hand, vertically lifted/lowered gates create undercurrents which increase the probability of blockage as opposed to overflowing regulated structures such as flaps, drum and sector weir or inflatable weirs which are less susceptible to obstructions (Boes et al., 2017).

The available methods for estimation of the probability of blockage of dam spillways are based on physical model tests which are normally focussed on one particular structure and use a limited number of types and configurations of large wood debris and therefore are not necessarily generally applicable (Boes et al., 2017). Furthermore, there is no systematic research on the probability of blockage due to large floating objects such as silo bales, boats, cars etc.

Hartlieb (2015) investigated the obstruction risk at dam spillways with segment gates and presented the following formula to determine the blocking probability of a weir bay due to single trunks P:

$$P = (H_t/L_p - 0.96)*0.73 \quad (14)$$

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

Similarly, Lange & Bezzola (2006) proposed empirically derived equations for establishing the blocking probability of river bridges PL due to single trunks as a function of the trunk length L and width of the bridge cross-section B as follows:

$$P_L=0 \quad \text{for } L/B<0.5 \quad (15)$$

$$P_L=0.133\ L/B - 0.066 \text{ for } L/B >=0.5 \quad (16)$$

The above formula could be used with prudence for the evaluation of the blocking probability of dam spillways with bridge superstructures in the absence of specific research on such structures at reservoirs.

Naturally, the blocking probability associated with trunks with branches and/or rootstocks or clusters of trunks would be expected to increase as it would increase the overall size of the floating debris.

Similarly, stiff, dead spruces were found to present a higher probability of blockage than flexible green spruces, beeches and maples (Hartlieb, 2012).

Various authors also attempted to establish the required minimum flow depth to ensure safe passage over dam spillways. Thus, according to Zollinger (1983), the following minimum relative flow depths 'H/d' are required for the transport of trunks with relative lengths up to twelve times their diameters 'd', i.e. for $L/d < 12$, at overflow sections:

$H/d = 1.5$ for single trunks; and $H/d = 3 \dots 6$ for relatively loose large wood clusters, where: H – energy head relative to the weir crest, d – large wood trunk diameter.

However, blockage due to insufficient flow depth over the dam spillways is normally temporary, until the water depth increases sufficiently and therefore is not the main criterion governing the probability of blockage. Notwithstanding this, some structures which are typically designed to operate at relatively low head, such as labyrinth or piano key weirs, as well some auxiliary weirs set at a higher level, would normally present a higher risk of blockage.

Pfister et al. (2013, 2015) present an analysis of the blocking probability at piano key weirs (PKW) subjected to individual trunks (without branches and roots) and conclude that the diameter of a trunk is greater than the overflow depth, the PKW will be blocked. The blocking probability is predicted to reduce to 50% where the trunk diameter equals the critical depth on the weir crest. However, due to the complex crest geometry, there is a likelihood that the probability of blockage by trees with large branches and rootstocks could be higher compared to the conventional overflow structures.

Feedback from operators of hydropower plants in Switzerland also indicates that a higher probability of blockage could be expected at bellmouth spillways which reportedly present more problems in this respect.

It could be seen that the probability of blockage estimation is heavily dependent on the accurate estimate of the maximum expected trunk lengths, diameters, rootstock diameters and other parameters and debris configurations involved. This estimate is though subject to a relatively high degree of uncertainty.

In this respect, the expected tree length H_t can be estimated in the field on the basis of the prevailing forest stand (Boes et al., 2017). Alternatively, observed tree lengths in past floods can be taken as a reference (Bezzola & Hegg, 2007, 2008).

According to Zollinger (1983), large wood debris may be exposed to enormous forces during entrainment. Trunks could thus be quickly debranched when travelling down steep mountain streams after a few meters, peeled, and usually broken down into 1 - 5 m long pieces (Boes et al., 2017).

However, this may not always be the case, in particular where trees enter reservoirs as a result of nearby landslides and/or reservoir bank erosion in which case they may not be much reduced in size and may retain most of their branches and rootstocks.

Furthermore, the probability of blockage could be affected by the Froude number directly upstream of the spillway affecting the potential for floating debris to be pulled down to the spillways crest and becoming stuck as opposed to floating on the surface as a loose single layer mat.

Large scale hydraulic model tests for floating debris jams at spillways were systematically performed at the Laboratory of Hydraulic and Water Resources Engineering (VAO) of the Technische Universität München as part of an extensive research project of the Dam Safety Interest Group of CEATI.

The tests have shown that there is a correlation between the behaviour of the floating debris and the Froude number as follows: (Hartlieb, 2015)

- $Fr = v/\sqrt{(g \ x \ \mathrm{h})}$, where h = D+H - average depth of the approach flow (refer to Figure 5.1) , where v - average surface velocity at h,
- Fr <0.15 causes a sparse mat of trees to form
- Fr> 0.30 the floating debris have a greater tendency to be drawn down towards the spillway threshold and reduce the discharge capacity.
- Fr=0.15-0.30 in this interval the density of the trees is the governing factor for weather the trees are drawn down or not.
- The density of the trees for these Fr values are between 800kg/m^3 and 975kg/m^3.

Thus, the test allowed to establish that the critical Froude number at which natural debris logs start to plunge under others and dangerous multi-layer bodies occur is Fr=0.15.

The tests indicate that the average velocity and Froude number of the approach flow have got a smaller influence on the probability of blockage than the debris length, stiffness and length of branches. Instead, they predominantly affect the reduction of the spillway discharge capacity. Thus, for higher Froude numbers, F > 0.30, multi-layer debris bodies with high compactness form, causing high relative backwater effects, i.e. > 12% increase of the head over the weir. For lower Froude numbers F < 0.15, loose single-layer floating carpets with low compactness form, causing < 6% increase (Hartlieb, 2017).

The definition of the approach velocity and Froude number are shown on Figure 5.1 below:

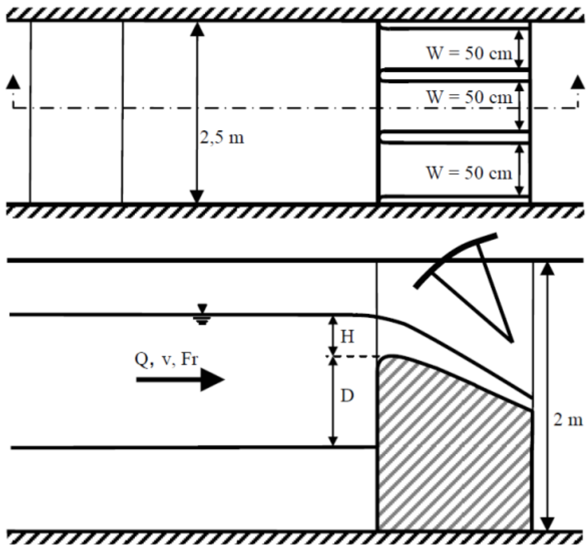

Fig. 5.1
Layout and section of the spillway model (Hartlieb, 2015)

It should be noted that the location at which the Froude number applies should be as close as possible to the spillway structure, while being clear of the effects of draw-down, typically at a distance of approximately 2H upstream of it.

Generally, the density of trees depends on their type, age and season, and residence time in water. Tests have shown that debarked pine trunks, after approximately 5 months in water, in effect reached the limit of their ability to float at 940kg/m^3 (Astrand & Persson, 2017).

Physical model testing carried out in the Laboratory of Hydraulic Constructions at EPFL, Switzerland studied the effect of blockage by artificial stems at an ogee crested spillway equipped with piers on the head increase at a reservoir (Furlan et al., 2018). The studies concluded that an increasing head tends to decrease the blocking probability but not linearly. Since the increase of reservoir head is a reflection of the spillway blockage, the studies also provide useful insight into the factors affecting the probability of blockage including the alignment, composition and volume of the blocked large wood as well as the jam shape. In particular, it was found that similar blocked volumes of stems had different effects on the head increase in the reservoir and were dependent on whether stems were in contact or not with the spillway crest.

When doing model tests, it is very important to repeat the tests sufficiently several times in order to obtain the correct probability of the blocking process of stems at spillways (Furlan et al. 2018, Furlan, 2019). Depending on the used composition of driftwood, i.e. number of stems involved, often up to 30 repetitions are required in the model tests to assess the blockage probability correctly in the case of a few individual stems only. The higher the number of stems is, the less test repetitions are required.

5.2. CRITERIA FOR ASSESSMENT OF THE LIKELIHOOD OF BLOCKAGE

Given the relatively high uncertainty in estimating the probability of blockage, the previously discussed methods could be used as an indicator of the likelihood of a blockage occurring, rather than as a means of accurately quantifying the actual probability of blockage for the purpose of estimating the joint probability of flood and spillway blockage events. Since it is not practically possible to determine the maximum percentage of blockage of a spillway structure, the available methods could be used to conservatively predict the likelihood of full blockage occurring. They could also allow adopting a risk-based approach, whereby considering that no blockage would occur when the predicted probability is relatively low.

The likelihood of blockage could also be assessed against any general criteria and recommendations for minimum spillway clearance widths and heights. Such recommendations are provided in some countries based on hydraulic model testing and/or operational experience.

For example, in Norway and Switzerland the following recommendations are made, based on the results of model experiments (Godtland & Tesaker 1994), to avoid dam spillway obstructions by trees and other large floating debris:

$$L_p \geq 0.8H_t \tag{17}$$

$$H_b \geq 0.15H_t \text{ for } L_p \geq 1.1H_t \tag{18}$$

$$H_b \geq 0.2H_t \text{ for } L_p \leq 1.1H_t \tag{19}$$

Where L_p is the minimum clearance width, H_b is the minimum clearance height of the individual dam spillway openings and H_t is the expected tree length.

In this respect, observations have revealed that tree trunks in mountain rivers and streams that are transported by floods are rapidly reduced to maximum lengths of about 10m. However, this may not necessarily be the case for the lower river reaches characterised by much lower velocities. On this basis, according to the basic documentation on dam safety of the Swiss Federal Office of Energy (SFOE) in 2016 (Boes et al., 2017), a spillway width of 10m would normally be considered sufficient in mountainous regions, while widths greater than 10m would be required at major rivers in the plains. An earlier version of this guidance also stipulates that 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).

According to the guidance produced by the French National Committee on Dams (CFBR, 2013), dam spillways are also prone to obstruction where the critical depth (typically occurring in the vicinity of the weir crest is less than 0.5m. In addition, for newly built structures, the recommended minimum clear width of weir bay increases from 4m (at altitude > 1800m above sea level) to 15m (at altitude < 600m).

This reflects the general trend for reduction of the size of the large wood with increasing altitude and while highlighting a trend for an increased blockage risk at lower altitudes, it is not directly applicable to other countries due to the different climate conditions affecting tree growth.

For circular spillway cross-sections, as for morning glory spillways, the minimum actual or equivalent diameter (for non-circular section) should be 5m (Boes et al., 2017).

Overall, the Swiss Committee on Dams report concludes that the database for determining the minimum required weir bay opening dimensions is considered to be very modest and the above safety criteria should be used with prudence while making conservative assumptions on the maximum expected tree lengths.

5.3. PROBABILITY OF PARTIAL BLOCKAGE

Some reservoir owners may be reluctant to take measures to manage the risk of full dam spillway blockage which they may consider unrealistically conservative, based on their operational experience. Therefore, attempts could be made to quantify the implications of a partial spillway blockage to aid the reservoir risk assessment. This could be done via numerical of physical modelling of spillways obstructions with various degrees of accuracy and representativeness of the actual expected type, size and rate of transport of the floating debris to the spillways structure.

In its simplest form, such simulation could model the effect of various percentages of spillway blockage in an attempt to inform the reservoir owners on the associated reservoir risks.

Such an approach to managing the reservoir risks due to spillway blockage could be quite misleading though as it would not provide any indication on the actual likelihood, let alone the probability, of a given percentage of blockage materialising during the design storm event.

In this connection, model tests and operational experience indicate that once a partial blockage of a spillway by a large floating debris occurred, this would start retaining smaller branches leaves and other debris and would have the potential to form a complete blockage. How fast this may occur, and the extent of the blockage, would depend on the volume of floating debris entering the reservoir, their accumulation and rate of transport to the spillway, the availability and capacity of any systems for removal of floating debris etc.

5.4. SEVERITY OF IMPACT OF BLOCKAGE ON SPILLWAY DISCHARGE CAPACITY AND DAM SAFETY

The impact of blockage by debris on spillway capacity is a major issue regarding dam safety. Its severity can be assessed in terms of:

- Reservoir level increase
- Loss of spillway discharge capacity

The loss of discharge capacity, like the probability of blockage, depends on many parameters, especially the geometrical features of the spillway (gates, bridges and piers), its hydraulic flow features (head, upstream depth etc.) and the floating debris characteristics (trunk length, diameter and density) as discussed in Section 5.1.

There is no generally applicable value for the loss of discharge capacity in case of debris blockage, therefore, it has to be assessed for each project configuration.

Based on physical models carried out for specific project configuration (no parametrical tests on geometry), Yang (2015) mentioned a water head increase between 16 and 27% while Hartlieb (2015) quoted a water head increase from 20 to 30%. This water head increase corresponds to a loss of discharge capacity between approximately 20 and 33%. The guidance produced by the French National Committee on Dams (CFBR, 2013) proposes a value of 30% by default.

For studying the effect of extreme driftwood volume instantaneously arriving at a standard ogee crest spillway without piers (Fig. 5.2) on the head increase in a reservoir, systematic model test were performed at the Laboratory of Hydraulic Constructions at EPFL, Switzerland (Bénet et al. 2020, Pfister et al., 2020) resulting in the following practical recommendations:

- The tests for the standard ogee crest revealed a blockage if $b/L_M < 0.77$ and thus confirming Godtland and Tesaker's criterium (1994) where b is the width of the ogee crest and L_M the maximum length of the trunks in the large driftwood volume
- Without countermeasures and for a full blockage, the discharge coefficient of the ogee crest was reduced to a relatively constant mean value of C_d= 0.38. This was independent of the (up to the design discharge), of the relative bay width (for $b/L_M \leq 0.77$), and of the driftwood volume (for extreme volumes). With regard to the variation in the test data, a reduced discharge coefficient of C_d= 0.36 is recommended for spillway discharge assessment in practice.

Fig. 5.2
Trees of an extreme driftwood volume blocked on spillway crest without piers and for a low reservoir head (Pfister et al., 2020)

In addition, recent research gives more information about the loss of spillway discharge capacity to be taken into account when considering piers, racks and gates, as described hereafter.

However, as mentioned in Section 5.3, once a partial blockage of a spillway by a large floating debris occurs, in some cases, this could progressively lead to a complete blockage. Therefore, where such a likelihood exists, a detailed project specific analysis of the possible loss of spillway capacity or water head increase and associated impact on dam safety could be carried out. Alternatively, the severity of the consequences of blockage could be established conservatively based on assumed full blockage.

5.4.1. Effect of upstream piers and racks

Physical model testing carried out in the Laboratory of Hydraulic Constructions at EPFL, Switzerland (Pfister et al., 2020) studied the effect of blockage by artificial stems at an ogee crested spillway equipped with piers on the head at a reservoir as a function of the length of the overhanging pier nose (protruding into the reservoir (see Fig. 5.3) as well as the effect of racks placed in front of the ogee crest). The results can be summarized as follows (Bénet et al., 2020:

- Overhanging piers reduced the negative effect of driftwood on the rating curve of the ogee crest spillway. The effect of a fully blocked weir on C_d is quasi-absent (reduction less than 5%) if the pier overhang p into the reservoir exceeds $0.35H_R$ (reference head H_R without driftwood).
- Without piers (and gates or a weir bridge, $b=L_M$ is large), no effect of a driftwood blockage on the ogee crest discharge coefficient C_d was observed if the maximum trunk diameter D_M was below $0.35H_R$ that means that all trunks passed.
- A blockage with an individual and sporadic trunk passage was observed for trunk diameters of $0.35H_R$–$0.60H_R$, and a full blockage occurred for diameters exceeding $0.60H_R$.
- A full rack (one bar per pier, respecting the Godtland and Tesaker criterion) positioned 0.5b upstream of the weir front almost removed (discharge coefficient reduction less than 5%) the effect of the driftwood blocked at the rack. A reduced rack with one bar every other pier did not respect the Godtland and Tesaker criterion. Accordingly, wood reached the ogee crest and partially perturbed the discharge capacity so that the discharge coefficient of the standard ogee crest was reduced up to 10%.

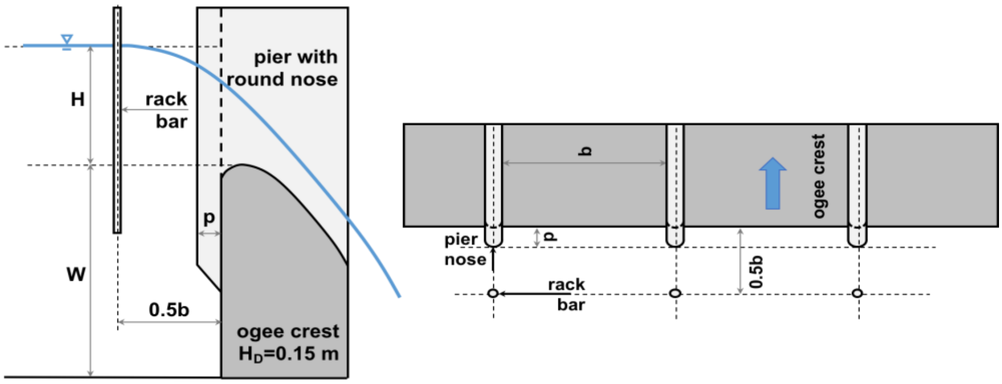

Fig. 5.3
Layout of physical model by Pfister et al. (2020)
Effect of overhanging pier nose or vertical racks

5.4.2. *Effect of Gate index*

Walker (2018) performed series of tests on physical models to assess the reduction of discharge capacity as a function of a parameter called “Gate index”.

Tests were performed in the USBR laboratory on a dam equipped with gated ogee spillways supposed to be representative of USBR spillways.

The Gate index is defined (see Fig. 5.4) as the ratio G_o/Hr where:

G_o = vertical orifice opening

H_r = Head above ogee crest in reservoir

As shown in Fig. 5.5, at small gate index values (small gate opening relative to reservoir head, indicating that the open orifice is considerably below the water surface elevation) debris impacts were minimal, typically smaller than 10% for Gate index smaller than 0,7.

However, at high gate index values where the spillway gates are out of the water, the maximum impact was a discharge reduction of 25% for “natural” jam.

In addition to the natural jam that formed in the model due to physical processes, the debris was manually condensed to form an "artificial" jam where the much higher debris density can provide a conservative upper limit to the impacts that spillway debris can create. In these conditions, the maximum impact from the artificial jam to the water surface elevation was a discharge capacity reduction of 40%.

Fig. 5.4
Gate index by Walker et al. (2018)

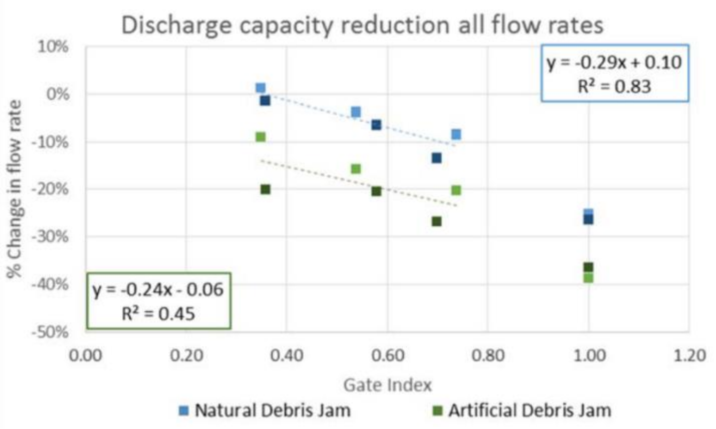

Fig. 5.5
Discharge capacity reduction according to gate index by Walker et al. (2018)

5.5. HAZARD ASSESSMENT DIAGRAM AND RISK MANAGEMENT

The report of the Swiss Committee on Dams on the State of Floating Debris Issues at Dam Spillways recommends the use of the following hazard assessment procedure when examining an existing dam spillway and/or building a new one (Boes et al., 2017):

1. Collecting/determining basic information on the dam spillway (type, dimension, etc.) as well as determining the impact (flood load cases, 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 large wood or not;
5. Development of measures to reduce the risks for the dam

This is illustrated on the below Fig. 5.6 (Boes et al., 2017)

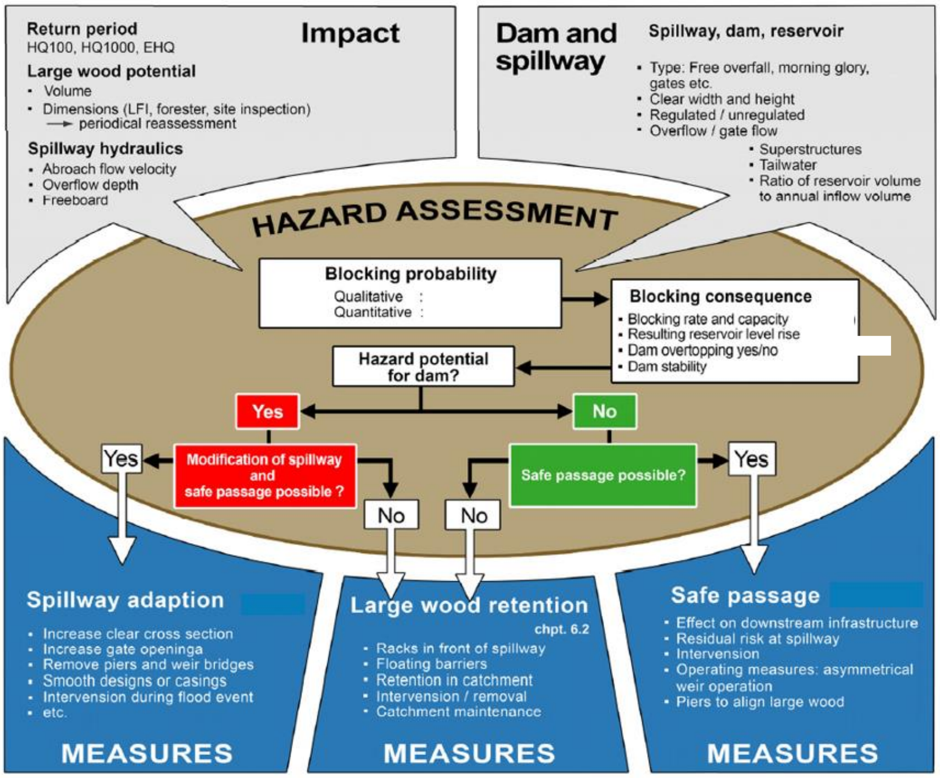

Fig. 5.6
Hazard Assessment Diagram (Boes et. al., 2017)

In some cases, an efficient strategy of managing the risk of spillway blockage may be based on the acceptance of the consequences of temporary partial or complete spillway blockage and providing suitable means of removal, possibly combined with partial retention, of large debris during the flood event. This may be used at reservoirs where the large wood volume potential is relatively low and where the available storage area has got the potential to reduce the rate of transport of large wood to the spillway and/or where auxiliary spillways allowing safe passage are provided. Also, this strategy could be applied at reservoirs where short duration overtopping may be tolerable such as some concrete or masonry dams.

Adopting such a strategy would require an assessment and detailed physical and/or numerical modelling of the expected maximum size and shape of the large wood, typically based on the size of the trees existing in close proximity to the reservoir, as well as of the expected volume, attenuation and rate of transport of large wood to the spillway. Such an assessment could be based on conservative simplified methods of analysis and operational experience. Alternatively, it could employ a detailed hydrodynamic numerical model allowing amongst other things for the design flood hydrograph, catchment, reservoir and spillway characteristics, direction and speed of prevailing winds and resulting waves etc. as discussed in section 2.3.2.

Should removal of large wood and/or other floating debris during the flood event be included in the strategy for managing the risk of spillway obstruction, the adequacy of debris removal (capacity and time for mobilisation) and reliability of the access to the reservoir for large debris removal equipment during a flood event should also be thoroughly assessed.

However, management of floating debris stuck in the spillways is described as a more uncertain method, as experience shows that dangerous volumes can soon build up, which cannot be managed safely (Astrand & Persson, 2017).

5.6. VULNERABILITY ANALYSIS

A 'Methodology for analysing and managing floating debris at dams and reservoirs' has been developed by Astrand & Persson (2017) providing a systematic approach for use by dam owners to analyse the vulnerability of dam facilities' to floating debris, and to analyse the adoption of appropriate measures taking into consideration the river perspective

The methodology consists of the assessment of three main components;

- Potential for the formation of floating debris - mainly depending on the presence of steep tributaries, erosion, landslides and rockfalls within the catchment as well as on flooding, and high floods and water velocities that carry objects already in or adjacent to the body of water
- Potential for transport of floating debris to the facility - depending on water depths and velocities on the route but also on the reservoir shape and orientation relative to the direction of prevailing winds
- Potential for floating debris to get stuck in the spillway opening and subsequently drawn down to the spillway threshold - depending on the width of the spillway compared to tree lengths as well as the Froude number directly upstream the spillway

The above components are then assessed and assigned 'high', 'some' or 'low' potential of formation, transport and blockage respectively.

On this basis, the combined vulnerability is assessed, and a 'high' vulnerability rating is assigned to structures where all three components have got a high potential of occurrence.

The overall vulnerability assessment is used to identify the facilities to be prioritised for action.

The report provides a procedure for selecting the appropriate measure for a specific dam facility. The decision is made based on the conditions that are present at the facility and the effect that this measure can achieve also from a river perspective. The procedure is illustrated on the below diagram (Fig. 5.7):

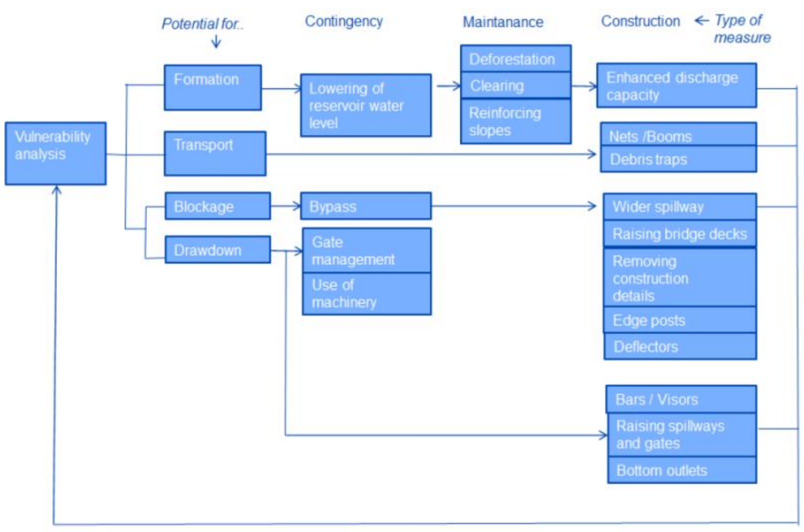

Fig. 5.7
Flow Chart for determining the potential for formation of floating debris (Astrand & Persson, 2017)

5.7. FURTHER WORK

As discussed in the previous sections of this Bulletin, the current methods for evaluation of the production, transport and volume of floating debris, as well as the methods for evaluation and management of the risk of blockage of reservoir spillways by floating debris are subject to a number of uncertainties and limitations. Addressing these in future would be important for understanding better and managing more efficiently the risk posed by blockages by floating debris. Key areas of focus of future research and development in these areas are:

- Improvement of the spatial analysis methods to identify potential floating debris from large wood or from human origins (boats, pontoon, mobile homes etc..) along rivers using a combination of field inspections and ArcGIS in order to address the uncertainties associated with the current empirical and other methods of floating debris volume estimation;
- Expansion of the data base used to determine the minimum required spillway bay opening dimensions through further systematic model testing and prototype experience to include a wide range of topographical, geological, climatic and other geographical conditions.
- Impact of debris on spillway discharge capacity by systematic parametrical tests
- Further enhancement of the numerical models used to simulate the dynamic processes of floating debris transport and obstruction of spillway structures;
- Enhancement of the reliability of designing floating booms with regards to dynamic loads;
- Further research to establish:
    - transportation of debris through rivers and dam reservoirs:
        a. definition of criteria whereby the debris might not reach the dam spillway (small water velocity versus wind forces, external stream lines in river curves, rerouting the debris to the bank).
        b. reduction of size and geometries of debris reaching the dam spillway
    - correlation between the flood characteristics and the volume of floating debris produced (Astrand & Persson, 2017);
    - required flow depths at dam spillways to ensure safe passage of floating debris which are currently little known (Boes et al., 2017);
    - impact of rootstocks having different shapes and configuration on the probability of obstruction of spillways;
    - water velocities required to catch and transport larger volumes of trees; more information in this area could potentially be obtained from available data on timber transport in waterways (Astrand & Persson, 2017);
    - impact of the surface velocity and density on the drawdown of floating debris especially in the range $0.15<Fr<0.3$ (Astrand & Persson, 2017);

Meanwhile, where significant uncertainties are present regarding the amount of large floating debris and the processes of obstructions, hydraulic model tests would remain an indispensable tool for evaluation and management of the risk of blockage (Boes et al., 2017).

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