Assessing Torrential Endangered Areas in Bavaria - Consideration of Log Jams at Culverts and Bridges -

Peter DRESSEL[1], Peter WAGNER[2] and Andreas RIMBOECK[2*]

[1] Engineering consultants aquasoli (Haunertinger Str. 1a, 83313 Siegsdorf, Germany)
[2] Bavarian Environment Agency (Buergermeister-Ulrich-Str. 160, 86179 Augsburg, Germany)
*Corresponding author. E-mail: Andreas.rimboeck@lfu.bayern.de

According to the Bavarian Water Act there is an obligation for the water management authorities to determine torrential endangered areas. In a legal sense these areas are primarily potential flood areas however under consideration of typical torrential characteristics. Especially the involvement of solids has to be regarded. In order to enable a systematic and transparent determination of the design event, a standardized modular approach to assess torrential hazards was developed at the Bavarian Environment Agency. In the approach bedload and woody debris are being considered as two separate components. Bedload is considered as a surcharge added to the design hydrograph (100-year discharge). Problems resulting from woody debris in relevant zones (areas of spatial planning) are individually evaluated during hazard assessment. A method which quantifies the potentially accumulating woody debris in the torrent catchment area was developed for this purpose. On this basis, the dangers for log jams at the particular structures are categorized. Subsequently hydraulic calculation is done with a 2D hydraulic model.

Key words: woody debris, log jam, risk assessment, 2D hydraulic modeling

1. TORRENTIAL ENDANGERED AREAS

Subject to Article 46 of the Bavarian Water Act, water management authorities are obliged to determine torrential endangered areas. They further have to be legally set as regulation by the district office. Torrential endangered areas are floodplains inundated by a 100-year-flood taking into consideration the characteristics of torrents (design event).

In the determination of torrential endangered areas solid materials like bedload and woody debris play a decisive role in the modular system applied. The Bavarian Environment Agency identified resp. developed standardized state-of-the-art methods to deal with these issues.

This paper focuses on the role of woody debris in the procedure of determining torrential endangered areas. Consistent with the practice in flood-endangered areas and floodplains the areas affected by torrential events of high as well as low occurrence probability are displayed in the form of susceptibility maps. Apart from temporarily high discharge, particularly the involvement of solids in the process is regarded as distinctive for torrents.

2. WOODY DEBRIS IN HAZARD ANALYSIS

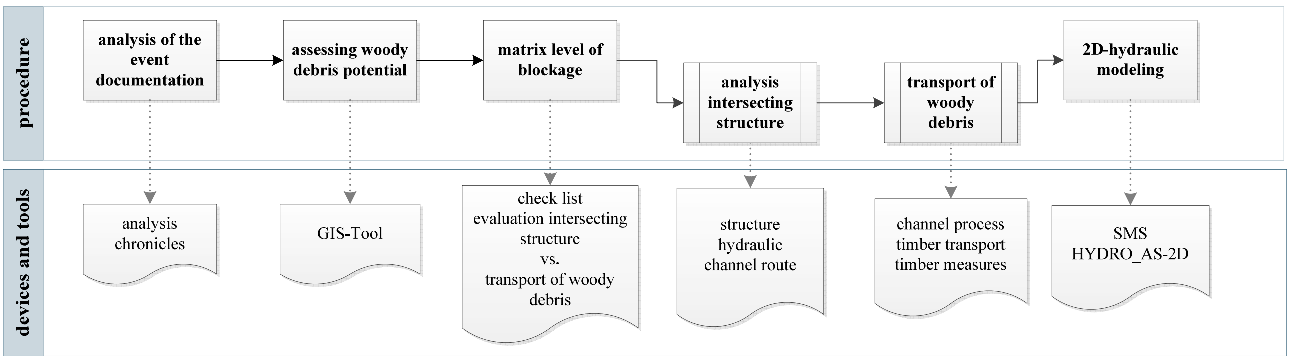

Fig. 1 Overview of the work steps to assess woody debris in torrent endangered areas

Possible hazards due to woody debris are evaluated in line with the hazard analysis of torrential catchments. The term "woody debris" covers all wood being transported in the water during a flood event. At both natural and artificial constrictions this can lead to log jams causing tremendous damage in housing as well as industrial areas. Hereafter the standardized procedure for considering woody debris in hazard analysis is outlined in **Fig. 1**. Following the steps are described in detail.

2.1 ANALSYING THE EVENT DOCUMENTATION

Initially an evaluation whether woody debris played a role in past events and whether it lead to problems has to be carried out. Further it has to be examined if the problem is still relevant or if any further hazards have to be considered. Only if the preliminary works show indications for an endangerment by woody debris, it has to be considered in the following.

2.2 ASSESSING WOODY DEBRIS POTENTIAL

2.2.1 Status quo

So far the quantity of woody debris was either calculated using empirical formulas or estimated by experts in the course of a field survey of the catchment. Whereas the first holds major uncertainties, the latter is time consuming. Other methods such as the "Aerial photograph-based procedure for the estimation of woody debris potential in torrential catchments" developed by [Rimböck 2001] have to be adapted due to technical innovations.

Now, an extensive data base is available which can be used to quantify woody debris potential. Among the data are hazard susceptibility maps, maps on potential geological hazards, forest data and slope inclinations. They are all digitally available and can be displayed in a GIS.

A new approach is represented by a GIS-tool invented by the Bavarian Agency Administration using the data stock systemically to provide a first estimation. This should be verified or falsified in the following (obligatory) field survey.

2.2.2 Quantification of woody debris potential

Initially the quantification of woody debris potential is achieved using a specifically programmed GIS-tool and finishing with an Excel-spreadsheet. The approach developed for this purpose is depicted in **Fig. 2**. The required workflow consists of the following steps which are commented on below [Meyer & Rimböck 2014].

(a) Collection of input data
(b) Automated GIS-based data processing using the woody-debris-tool
(c) Calculation of woody debris potential using the Excel-spreadsheet

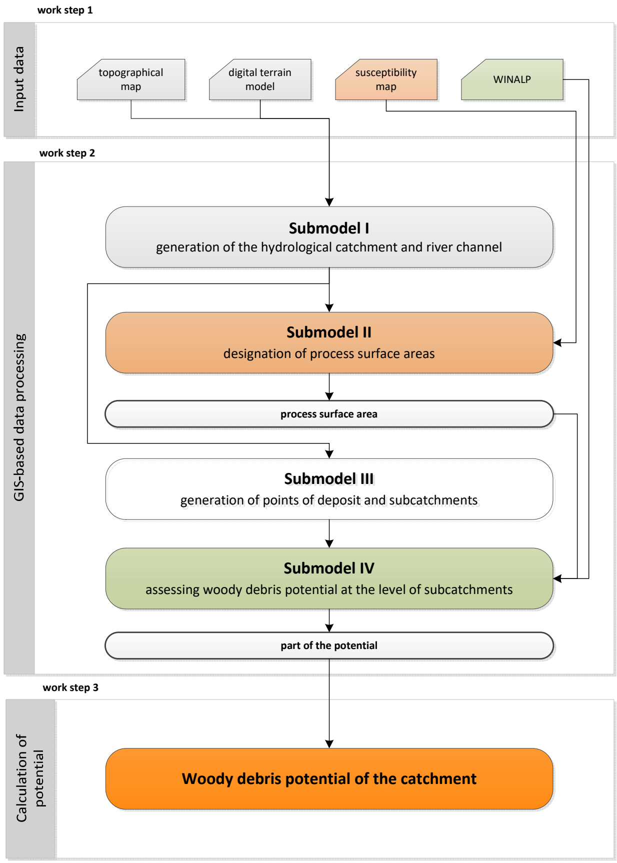

Fig. 2 Basic concept of GIS-based estimation of the amount of woody debris: Delineation of input data, model parts and intermediate and final results

2.2.3 Input data

The first step is the compilation of input data. The following data is used in the GIS-analysis:

- Topographic map (scale 1:25'000): Definition of a coarse frame of the catchment boundaries and the basin drainage point
- Digital elevation model (DEM) with a resolution of 5 x 5 m
- "Susceptibility map geological risks" of the Bavarian Alps (scale = 1:25'000): provides information on areas endangered by landslides
- WINALP-map [Reger and Ewald 2011], (scale = 1:25'000): provides information on forest types within the torrential catchments; growing stocks of wood are assigned to the different forest types based on physical inventory data

2.2.4 GIS-based data processing

The GIS-tool automatically identifies the woody debris potential for each partial catchment (in general for each 1000 m of channel length) based on the design event. The automatic data processing is carried out in the following 4 steps resp. submodels:

Submodel I – identification of the hydrological catchment and river channel

Based on topographic maps the relevant area is roughly located and the basin drainage point is defined. The basin drainage point is the position where discharge from the catchment is fed into the 2D hydraulic model. The 2D hydraulic model usually covers building areas or land that is potentially suitable for housing and/or economic activities.

In the second step, the hydrological catchment is automatically identified on the basis of the digital elevation model (DEM), the rough catchment boundaries and the basin drainage point.

Further the stretch of river relevant for woody debris transport is identified. For this purpose only those stretches are considered where woody debris transport is possible. **Fig. 3** shows the result of the analysis by *Submodel I*.

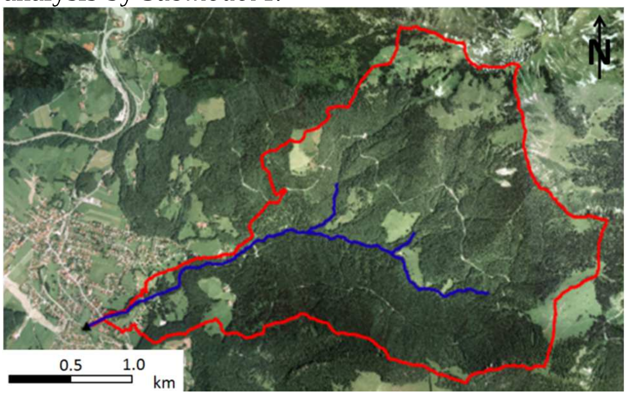

Fig. 3 Hydrological catchment (red) and river stretches relevant for woody-debris-transport (blue). The black triangle marks the previously defined basin drainage point

Submodel II – determination of process areas

The areas from which woody debris can be brought into the channel in case of an event are identified as process surface areas. In *Submodel II* these areas are disclosed by blending and analysing extensive geospatial data covering all topics relevant for woody debris transport.

Therefore the following important processes according to [Rickli and Bucher 2006] are considered, which have been implemented into the woody debris GIS-tool. Each can optionally be deactivated if not appropriate for a particular location.

a) Erosion of forest covered riverbanks
b) Bank erosion
c) Landslide
d) Windthrow

Erosion of forest covered riverbanks: This process is restricted to a narrow zone accompanying the riverbanks. The corresponding process areas are generated using a buffer representing the channel width at flood discharge. The flood channel width is set to 10 m as default. It can be adjusted manually if further information is available from hydraulic simulations.

Bank erosion: Areas where bank erosion is possible are normally part of the default flood channel width of 10 m (see above). Bank erosion zones beyond this extent have to be added manually (cp. **Fig. 5**). In these cases the model doubles the buffer width and a 20 m width is regarded.

Landslide and debris flow: The areas affected by landslides and debris flows mapped in the susceptibility maps of the Bavarian Alps constitute the basis for the identification of landslide-related process-areas. The woody debris GIS-tool selects those landslide and debris flow deposits reaching the channel sections as relevant for woody debris transport.

Windthrow: Storm events can cause the input of woody debris into the channel from the adjoining slopes up to a distance of one tree-length [Handschin and Duss 1997]. At steep slopes logs from a distance of up to two tree-lengths can reach the channel. The identification of the affected areas is achieved automatically by generating slope angle classes based on the DEM.

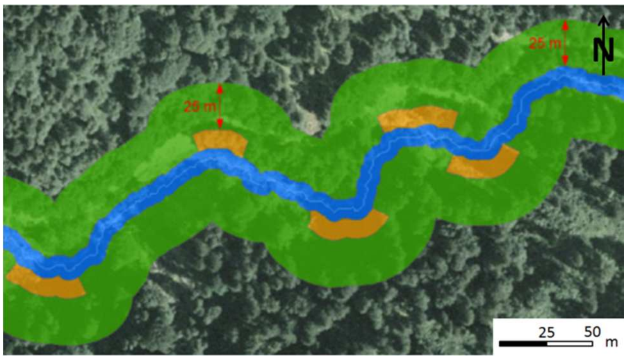

Fig. 4 Identification of process-relevant areas: Windthrow-affected areas with a distance of one tree-length from the channel are depicted in green. The areas related to erosion of forest covered riverbanks are shown in blue. Bank erosion related-areas are plotted in orange. In this example, no landslide reaches the channel

Submodel III – generation of potential woody debris deposits and subcatchments

In order to model transport and deposition of woody debris, *Submodel III* automatically creates deposition points at intervals of 1.000 m along the channel section relevant for woody debris transport (cp. **Fig. 5**). It is additionally possible to choose known constrictions or deposition zones manually. These points are subsequently used for the identification of subcatchments.

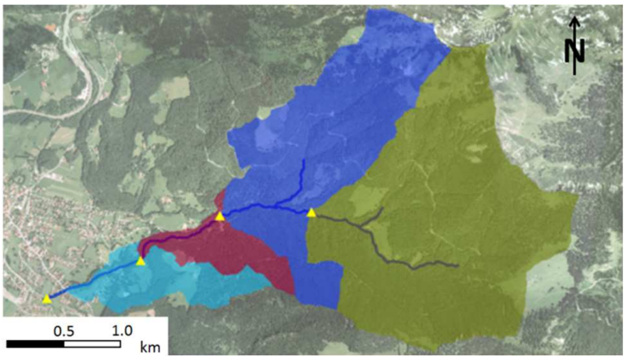

Fig. 5 Generating the subcatchments based on the deposition points (yellow point symbols)

Submodel IV – assessing woody debris potential for the subcatchments

Submodel IV (cp. **Fig. 6**) assigns the process-related areas from *Submodel II* to each subcatchment derived in *Submodel III*. Eventually the relevant areas are multiplied with the corresponding stock-of-wood data from the WINALP-dataset. As a final result the GIS-woody-debris-tool provides a dbf-file for each subcatchment. The file contains the woody debris potentials of each input process and can be directly calculation.

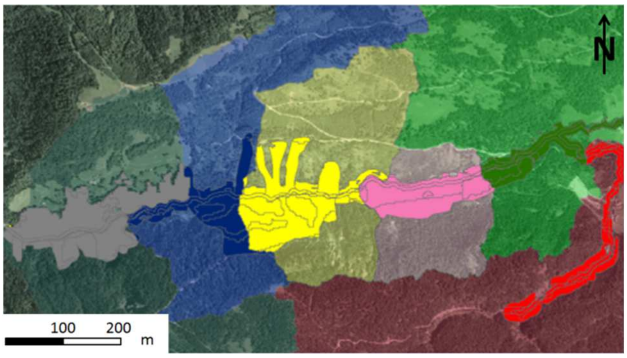

Fig. 6 Clipping the process-related areas from the designated subcatchments

2.2.5 Excel-spreadsheet for estimating the woody debris potential

The scoring sheet templates contain the woody debris potentials of each subcatchment. These potentials calculated using the GIS-tool are multiplied in the Excel-spreadsheet with process- and region-specific reduction factors. In order not to overestimate the quantity of wood being mobilized and transported, all processes involved are weighted by an appropriate factor.

Among the crucial factors for a reduction is that not the whole woody debris potential gets mobilized and delivered into the channel during one event. The reduction factor considers the geological, geomorphologic, topographic and silvicultural conditions within the catchment. Further not every process-related area (e.g. landslides or bank erosion) will be activated during a single event. Due to remaining uncertainties in choosing the reduction factors it is recommended to examine three different scenarios of frequent, average and rare occurrence.

In the last step the probability for transport resp. deposition is considered: Only a certain percentage of the woody debris is transported from one subcatchment to the next one downstream (default setting: 80 %). The rest is either deposited within the subcatchment or disintegrated into smaller pieces so it no longer represents a hazard.

The weighting factors hold enormous degrees of uncertainty leading to the result only being an indication. Only woody debris of natural origin finds its way into the model described. Man-made sources of woody debris like timber yards or forest residues disposed of into the channel have to be added manually into the model.

2.3 EVALUATION OF EVENT DOCUMENTATION

The documentation of events gives hints whether the regarded bridge is prone to log jams or not. If log jams have been observed previously and neither the bridge's construction has been changed nor any wood retention measures have been built since, blockage has to be considered at the regarded location. The level of blockage is to be determined using the matrix described in *chapter 2.4*. A minimum level of blockage of 25 % is to be applied in these cases.

If the event documentation can be considered as complete and comprises at least 2 events in the range of a design event and no log jams have been recorded, the risk of the bridge being blocked by woody debris can be considered as negligible.

In cases when no log jams are recorded at a certain bridge or culvert, but it is uncertain how far the event documentation can be trusted, the matrix described in *chapter 2.4* is to be applied without limitations.

2.4 MATRIX LEVEL OF BLOCKAGE

The specific woody debris load determined by the GIS-tool does not allow drawing conclusions on the probability of a log jam on its own. Thus both aspects – woody debris transport and the characteristics of the intersecting structures – have to be rated.

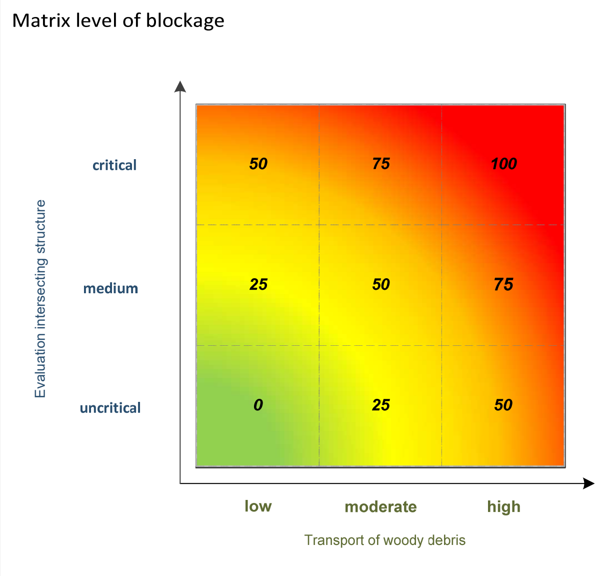

Fig. 8 Matrix level of blockage for 2D hydraulic modeling: Combination between evaluation intersecting structures (y-axis) and transport of woody debris (x-axis)

Assessing the interaction of these aspects by means of a matrix designed for this purpose allows determining the grade of closure needed for subsequent 2D hydraulic simulation. The grade of closure characterizes the decrease of the bridge's cross section.

2.4.1 ANALYSING INTERSECTING STRUCTURES

structure	Disposition at modeling sector	bridge with greater/similar log jam risk above		first bridge in the model space
	inner width B	$B > b_W$	$B = b_W$	$B < b_W$
	typ of bridge	bridge with plate		arch bridge, girder bridge, framework bridge
	bridge pier	no pillar		one/more pillar(s)
	supply line(s)	none		below design level
hydraulic	freeboard Fb	≥ 1.0 m	1.0 – 0.5 m	≤ 0.5 m
	relative depth of flow h/H	< 0.5	0.5 ≤ 0.75	0.75 ≤ 1
	froude-number Fr	< 1		≥ 1
channel-route	free surface-width b_W upstream$_O$	$b_{WO} < B$	$b_{WO} = B$	$b_{WO} > B$
	downstream$_U$	$b_{WU} = B$	$b_{WU} > B$	$b_{WU} < B$
	channel bottom structure upstream	slick, fastened		raw, unsurfaced
	downstream	slick, fastened		raw, unsurfaced
evaluation - structure		**UNCRITICAL**	**MEDIUM**	**CRITICAL**

Fig. 9 Evaluation intersecting structure

In the course of hazard assessment, the intersecting structure has to be classified concerning the risk for a potential log jam. The following three aspects have to be considered (cp. **Fig. 9**):

- intersecting structure
- hydraulics
- channel route

2.4.1.1 Intersecting structure

In most cases, the first bridge within the hydraulic model poses the highest risk for being jammed by woody debris compared to bridges further downstream [Gschnitzer et al. 2014]. Corners, rims, sharp bends and structural elements protruding into the stream channel increase the risk of log jams at constructions. The same applies to pipes protruding into the channel section on the upstream-facing side of the bridge.

2.4.1.2 hydraulics

A first hydraulic simulation is done with the design hydrograph (100-year discharge) including bedload surcharge. This calculation provides important data for evaluation of the risk of log jams. Apart from the degree of freeboard, relative flow depth and the Froude number have to be categorized as well (cp. **Fig. 9**). Knowledge of the freeboard during a 100-year event can be considered as a key element in hazard evaluation. A freeboard of less than 0.5 m is to be considered as critical. Furthermore relative flow depth and Froude number obtained in the 2D hydraulic simulation provide valuable information and have to be classified into one of the three classes uncritical, moderate or critical.

2.4.1.3 Channel route

A continuous stream channel near the culvert reduces the probability of woody debris getting stuck and thus causing a log jam. On the contrary expansion or narrowing of the channel section as well as drops in the channel increase the probability of log jams due to the varying flow conditions and hydraulic framework conditions.

2.4.2 TRANSPORT OF WOODY DEBRIS

In order to assess woody debris transport a representative stretch of about 1 km upstream of the intersecting structure can be taken as reference for estimating timber sizes. For hazard analysis a log length (L) corresponding to the minimum channel width along the representative stretch (b_{wo}) can be chosen as reference value [Stetter 2015]:

$$L \cong b_{wo} \qquad (1a)$$

Furthermore the following aspects have to be evaluated (cp. **Fig. 10**):

- channel (flow) process
- wood transport
- wood dimensions

2.4.2.1 Channel process

The category channel process evaluates process type, disposition and the relevant framework conditions for woody debris transport. For this purpose, the supposed flow process in the torrent is essential. Discharges featuring strong turbulences lead to frequent collisions of woody debris with the channel bed and the channel banks. This increases the probable occurrence of log jams. The classification of process type is hierarchically arranged as follows: Flood and fluvial sediment transport, hyperconcentrated flow and debris flow.

Another factor covers the classification of the intersecting structure. It is to be classified according to the channel's gradient. Further the bank vegetation has to be assigned to a certain category. The method takes the effects of different habitats into account. Stem-forming bank vegetation tends to trap woody debris, thus holding it back and preventing further transport. Shrub vegetation fulfills this function as well but to a much lesser degree.

2.4.2.2 Wood transport

The parameter wood transport is significantly controlled by the amount of wood being transported, channel routing, channel roughness and course of the longitudinal section. For this purpose, the flow conditions are to be evaluated concerning their homogeneity. Due to frequently changing hydraulic conditions, highly braided channels tend to transport logs with a less critical length compared to stretched channels with nearly constant flow velocities.

2.4.2.3 Wood dimensions

Finally woody debris size (length and diameter) as well as local and hydraulic framework conditions affect the risk of jamming. The maximum length of the logs can approximately be estimated taking the minimum channel width upstream of the bridge as a reference. A minimum flow depth (h) of half the logs' diameter (d) is required for woody debris transport to begin [Imhof 2008; Lange & Bezzola 2006].

$$h = \frac{d}{2} \qquad (1b)$$

2.5 2D HYDRAULIC MODELING

The determination of the torrential endangered area is achieved by a 2D hydraulic simulation of a 100-year event using the program Hydro_AS-2D. By default a simulation of the basic scenario without

channel process	typ of process	flood – fluvial sediment transport	debris flood/hyperconcentrated flow	debris flow
	equivalent friction angle	≤ 10 %	10 – 30 %	≥ 30 %
	stream bank vegetation	stem forming growth	shrub vegetation	hardly growth
timber transport	woody debris potential (GIS-Tool)	≤ 20 m³/m²	20 – 40 m³/m²	≥ 40 m³/m²
	alignment	highly curved	slightly curved	streched
	channel roughness	rough		slippy
	long profile	drop structures	stepped	uniform
timber-measures	tree length L	$L \geq b_{WO}$		$L < b_{WO}$
	stem diameter d	$d/2 \geq h$		$d < h/2$
	root plate diameter d_W	$d_W \geq h$		$d_W < h$
evaluation - transport of woody debris		**LOW**	**MODERATE**	**HIGH**

Fig. 10 Classification of woody debris transport

any log jams or sediment accumulation is carried out. A maximum of two further scenarios considering log jams, sediment accumulations or both can be taken into account and simulated. Additional scenarios only should be considered if they most likely occur during a design event.

The level of blockage defined in the previous steps has to be considered appropriately. Depending on the channel course two configurations are to be distinguished. In curved channel courses, the log jam is incorporated into the model by moving the bridge’s outer abutment into the channel bed. In stretched channel courses, the lowest line of structure is lowered by the amount needed to reproduce the level of blockage. The reduced channel section makes it possible to show effects of the log jam on the extent of the flooded area.

The method of determining the level of blockage and the subsequent implementation into the hydraulic model is illustrated in the following case study.

2.5.1 Case study Weisslofer, Reit im Winkl

The bridge at Entfelderstrasse is the third bridge in the local area of Reit im Winkl (Upper Bavaria) crossing the Weisslofer river (see overview in **Fig. 11**). It is thus not regarded as the most critical one in the hazard assessment. Nonetheless, it is still capable of posing problems since there is no woody debris retention and the bridges further upstream did not show a high probability of jamming and thus holding back incoming woody debris. Between the last bridge further upstream and the bridge at Entfelderstrasse the Weisslofer’s outer bank runs along a wooded hillside toe for about 700 m. If bank erosion occurs along this stretch, woody debris is expected to accumulate at the bridge at Entfelderstrasse.

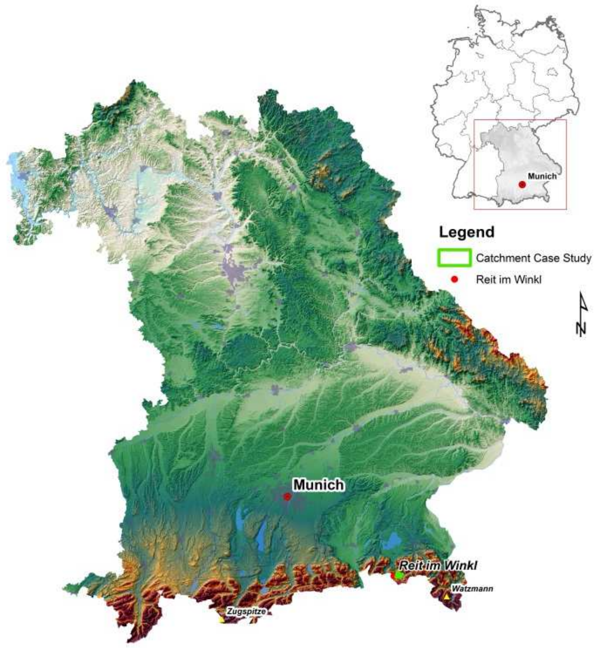

Fig. 11 Relief map of Bavaria and general map of Germany. The case study catchment of the Weisslofer near Reit im Winkl, Upper Bavaria, is highlighted by a green frame.

Due to the bridge’s dimensions and constructive design it is regarded as a critical structure, especially as the flow depth exceeds the clearance height. Further aspects are: rough and unsurfaced channel bottom, structures upstream and downstream of the bridge. Furthermore the free surface width of the channel is wider than the bridge’s inner width (see **Fig. 12**).

Fig. 12 Bridge at Entfelderstrasse

The longitudinal section of the channel is stepped, the channel route can be classified as slightly curved. The log diameters are less than the flow depth and the maximum tree length is smaller than the upstream channel width. This classifies the woody debris transport at the bridge’s location as moderate.

The evaluation of the structure and the assessment of a moderate wood transport plotted into the matrix results in a blockage level of 75 %.

2.5.2 Results

The first hydraulic simulation run considers the basic scenario without log jams or other scenarios (**Fig. 13**). The results show minor flooding near the bridge at Entfelderstrasse mostly affecting lawns and agricultural land. At the adjacent bridge where the Weisslofer is crossed by the Alpenstrasse, the simulation results show an overtopping of the banks resulting in major inundations along the Alpenstrasse. The overflowing affects settled land to a large extent even in the scenario with an unblocked bridge at Alpenstrasse.

Fig. 13 Simulation result for the default scenario without any log jams or sediment accumulations. The Entfelderstrasse bridge's position is marked with a *green* dot. The bridge at Alpenstrasse is marked with a *red* dot

The second scenario (see **Fig. 14**) takes into account the log jam at the bridge at Entfelderstrasse. Compared to the default scenario, the river overtops near the Entfelderstrasse bridge. This results in an additional inundation of major settled areas east of the Entfelderstrasse. However, the log jam at the bridge at Entfelderstrasse does not affect the extent of the inundated areas along the Alpenstrasse.

Fig. 14 Simulation result for the scenario considering a log jam at the bridge at Entfelderstrasse. The Entfelderstrasse bridge's position is marked with a *green* dot. The bridge at Alpenstrasse is marked with a *red* dot

3. CONCLUSION

The torrential endangered area determined by 2D hydraulic simulation displays the range of most probable scenarios of the design event. This systematic approach enables a reproducible determination and consideration of possible log jams and a comparability of obtained results is achieved.

First assessments of the proposed procedure show that the approach to calculate the level of blockage at intersecting structures is feasible to document the susceptibility for blockages through woody debris at bridges or culverts.

REFERENCES

Gschnitzer, T., Gems, B., and Aufleger, M. (2014): Laborversuche zu Schwemmholztransport und einhergehenden Brückenverklausungen und Erstellung eines Leitfadens zur Berücksichtigung dieser Phänomene in der Gefahrenzonenplanung. Innsbruck.

Handschin, W. and Duss, H. (1997): Holzprobleme an Wildbächen, 1. Phase. Literaturstudium und Prozessanalyse, Altdorf, den 13. Oktober 1997.

Imhof, M. (2008): Verklausung von Schwemmholz an Brücken.

Einfluss der Abflussverhältnisse. Zürich: ETH.
Lange, D., and Bezzola, G. (2006): Schwemmholz: Probleme und Lösungsansätze. Zürich: Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie. Zürich.
Meyer, J. and Rimböck, A. (2014): GIS-basierter Ansatz zur Abschätzung des Schwemmholzpotenzials in Wildbächen; Internationales Symposium „Wasser- und Flussbau im Alpenraum“, 25.-27.06.2014 in Zürich; Tagungspublikation S. 443 ff; Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der Eidgenössischen Technischen Hochschule Zürich Nr. 228; Zürich; Eigenverlag DOI: 10.13140/2.1.1460.5768. Richards, L.A. (1931): Capillary conduction of liquids through porous mediums, Physics, Vol. 1, pp. 318-333.
Reger, B. and Ewald, J. (2011): Waldtypenkarte Bayerische Alpen. In AFZ – Der Wald (2011), 24, 14-26.
Rimböck, A (2001): Luftbildbasierte Abschätzung des Schwemmholzpotentials (LASP) in Wildbächen. In: Festschrift 75 Jahre Oskar von Miller-Institut, 1926-2001: Berichte des Lehrstuhls und der Versuchsanstalt für Wasserbau und Wasserwirtschaft der technischen Universität München (2001), 91. 202-221.
Stetter, F. (2014): Verkleinerungsprozesse von Schwemmholz in Gebirgsflüssen und Wildbächen. Projektarbeit. WSL, Versuchsanstalt für Wasserwirtschaft (VAW)