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Physical and numerical modelling of a bedload deposition area for an Alpine torrent

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Abstract. Floods including intensive bedload transport represent a severe hazard to the often densely populated alluvial fans of small Alpine watersheds. In order to minimize the risk of future inundation, an existing bedload deposition area on the fan upstream of the village Vorderberg in southern Austria is planned for reconstruction. The suggested concept for protection measures includes dividing the area into three similar sections of reduced slope. The three sections are to be separated by a block ramp. To test this concept and to optimize the sedimentation process, an analysis was performed by using both a physical scale model (1:30) and a numerical simulation tool (SETRAC). Four configurations for the section-outlet were tested based on three flood scenarios. The results support the general protection concept and suggest a minimum construction configuration, including a woody debris filter. Employing a physical scale model for analysing small watershed processes is rarely found in literature. This contribution represents an applied study and provides quantitative information on bedload deposition and outflow from a deposition area. We test a novel simulation tool for bedload transport on the steep slopes against the measurements in the laboratory and show that the combination of physical and numerical modelling is a valuable tool to evaluate the efficiency of planned measures for torrent hazard mitigation.

1 Introduction

On 29 August 2003 a flood event hit the village of Vorderberg/St. Stefan, Austria, causing severe damage to several houses on the fan of the creek "Vorderbergerbach" (Fig. 1). A total of 285 mm rainfall has been estimated by the Hydrological Service of Austria. The back-calculated peak discharge of 120 $m^3 s^{-1}$ corresponds to a design peak discharge of an approximate 100-yr return period. The elevated water level in the channel resulted in significant bed erosion, bank erosion and in the undercutting of adjacent hill slopes in the upper parts, as well as in the middle part of the watershed. Sediment availability for torrential processes has additionally been fostered by small scale shallow landslides with slip surfaces on the interface between bedrock (limestone and schist) and the quaternary sediment in the upper reaches of the torrent. During the course of a detailed event documentation (Huebl et al., 2004), sediment budgeting resulted in a total volume of about 450 000 m^3 of eroded sediment in the channel and adjacent to the channel. Around 200 000 m^3 were deposited within the channel system and upstream of the check dams in the lower transit reach of the creek. 250 000 m^3 of sediment, including some 50 000 to 80 000 m^3 of bedload, were delivered to the fan. Unfortunately no quantitative assessment of woody debris recruitment and transport to the fan is available. However, due to limited channel capacity and woody debris blockages at bridges, the village Vorderberg was flooded; sediment was deposited outside of the channel and was only partially delivered to the receiving river Gail.

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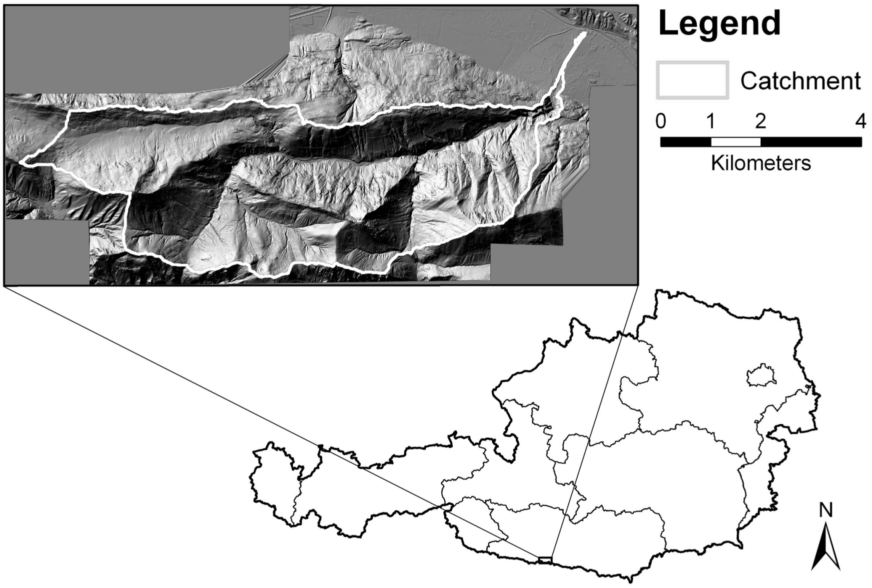


Fig. 1. Overview of the study catchment and its location in Austria.

In order to protect the village from future inundation, the existing bedload deposition area upstream of the settlement is going to be modified by local authorities. The objective of this study is to elaborate a general concept for the restructuring of the retention area, to analyse the deposition process and to optimize the sedimentation capacity of the retention basin by means of a physical scale model (Huebl et al., 2007) and a numerical simulation tool. These types of applied studies for small watersheds are rare in engineering practice as well as in literature. We present continuous measurements of the deposition process for different hydrologic scenarios, three-dimensional deposition pattern resulting from three constructive measures to enhance the deposition process, as well as a comparison with a novel numerical simulation tool to model bedload transport and deposition in steep channels.

2 General concept of protection measures

The existing retention area has a length of around 530 m and a width varying between 40 and 80 m. The average slope is around 2 %. Based on suggestions of Zollinger (1983) for the design of retention basins, three approaches of restructuring measures are under consideration and were evaluated by this project:

- The deposition area is widened as far as property lines are not affected. This measure is expected to have two effects: first, the bedload discharge will be reduced since the transport capacity is also a function of channel width (Jaeggi, 1992). Secondly, the potential deposition volume is increased.
- The retention area is divided into three similar sections with a reduced slope of 1 % each. Block ramps are to be constructed between the three sections, as well as at the inlet to the basin (Fig. 2). This slope reduction will lead to a reduced transport capacity and an enhanced sediment deposition.
- Three types of structures are under consideration to be installed at the lower limit of these sections. By reducing the cross-section area, the water level upstream of the construction is increased and the flow velocity decreased. This enhances the deposition of sediments and woody debris.

3 Methods

To keep the scale of the miniaturized model as large as possible, it was decided to model bedload deposition only in the topmost basin in the laboratory, and to transfer the findings to the other two basins, which are geometrically very similar, using a numerical model. This approach seems feasible due to the same boundary conditions for each section (critical flow over the block ramps). Since we are modelling a deposition process, the physical scale model was realized with a non-erodible channel bed.

3.1 Physical model

The physical model was realized in a model scale of 1:30. A sketch can be seen in Fig. 3. The water is pumped from a reservoir with a volume of 36 m^3 over a Thomson weir,

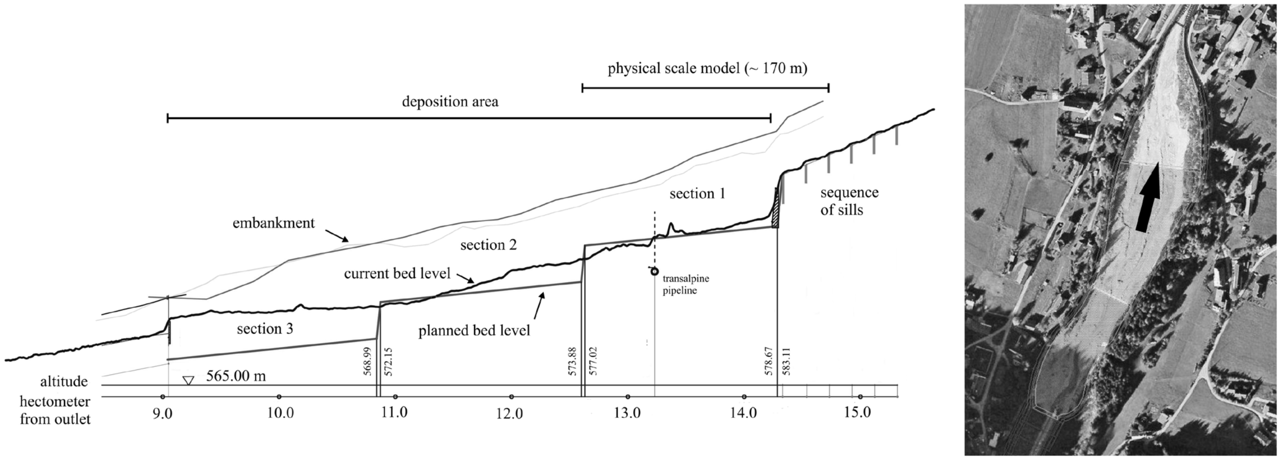


Fig. 2. General concept (left) and plan view of the bedload retention area (right; source: http://maps.google.de/).

which measures the discharge to the inlet of the model additionally to discharge measurement by the pump. The sediment is transferred into the system by a conveyor belt and regulated by altering the belt velocity. The system's sediment output from the model is measured continuously by the weighing of sedimentation basin.

During an experiment, the water level was recorded at four different locations using ultra-sonic sensors (Company Pepperl+Fuchs, Type UC500). Before and after each experiment, the topography was measured by a 2-D laser scanner (Company Sick, Model LMS 400). The laser was mounted on a programmable controlled guide rail, yielding a 3-D topographic model of the empty and filled deposition area.

To reproduce bank roughness and roughness of the block ramp, gravel of 6–12 mm in diameter (180–360 mm in nature) was glued to the respective sections of the model. Channel bed roughness corresponded to the mean grain diameter of the model bedload, which was 0.8–1.2 mm (24 mm–36 mm in nature). The development of a scour-hole downstream of the ramp will be prevented in the prototype situation by using large boulders as bed material in this area. Therefore, a scour-hole is not shaped in the model.

3.2 Scenarios and test cases

The experiments were based on the runoff – hydrograph of a rainstorm event with a 150-yr return period (Scenario 1), a rainstorm event with a 150-yr return period hitting a pre-filled deposition area (Scenario 2) and the reconstructed flood wave of August 2003 (Scenario 3). The design hydrograph was generated by the simulation tool "ZEMOKOST" (Kohl and Stepanek, 2005), a hydrological model which is based on the "time of concentration" model suggested by Zeller (1974). The input parameters were derived from field investigations and analysis of aerial pictures (Totschnig, 2007). The discharge of Scenario 1 (Q_{150}), therefore, represents the typical engineering design event. The reconstructed flood wave of the August 2003 event (Scenario 3) was modelled by the software HEC-HMS (Scharffenberger and Flemming, 2005) and calibrated using peak discharge estimates in the field and information on event duration from the flow gauges in the receiving Gail river downstream of the confluence. The flood wave of the design event has a higher peak flow ($150\,\mathrm{m}^3\,\mathrm{s}^{-1}$) than the reconstructed peak flow of the event in 2003 ($120\,\mathrm{m}^3\,\mathrm{s}^{-1}$), however, the reconstructed hydrograph yields a higher total water and sediment volume because of its long duration and was, therefore, considered to be also relevant for physical modelling. Both hydrographs are shown in Fig. 4.

The bedload transport into the modelled basin section (via the channel section above the deposition area) was calculated using sediment transport equations as suggested by Meyer-Peter and Mueller (1948), Smart and Jaeggi (1983) and Rickenmann (1990), assuming the unlimited sediment availability in the upper reach. Due to the overall steepness of the torrent, the equation after Rickenmann (1990) was finally chosen.

Three different constructive measures, located at the lower limit of the modelled section of the retention area, were tested (see Fig. 5):

- two overlapping groynes ("groyne" configuration);
- woody debris filter ("filter" configuration);
- check dam – sectional barrier ("check dam" configuration).

Since no legal standards exist, the geometry of the constructions is based on experience from current practice. To account also for the effect of woody debris, the openings were kept larger than ten times the d_{90} the bed material in this reach (70 mm). Geometry and position were not varied in this study. For comparison purposes, the model was also run without any constructive measure ("no structure").

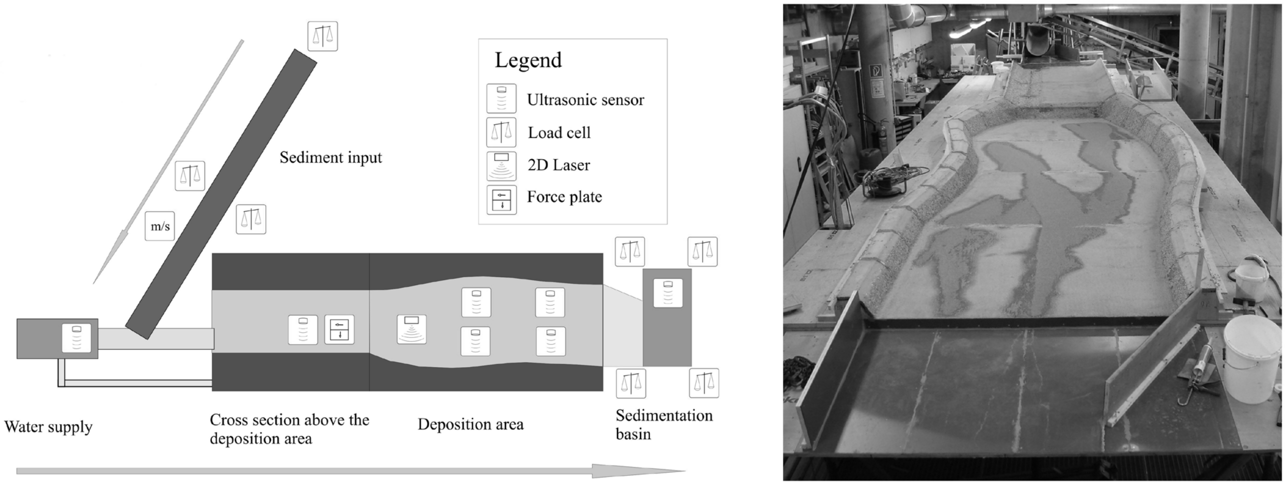


Fig. 3. Sketch (left) and picture (right) of the physical model.

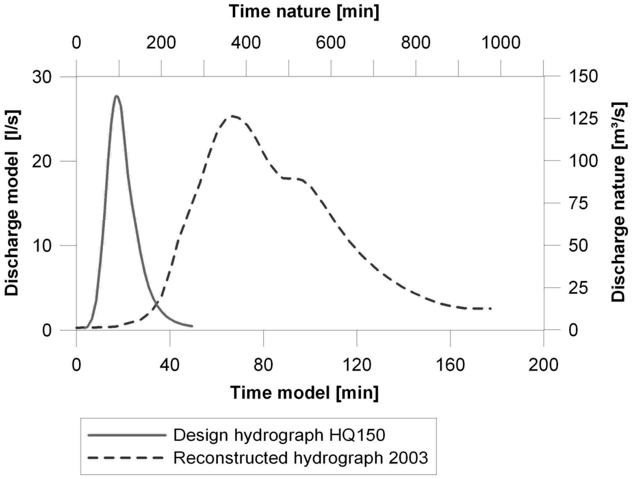


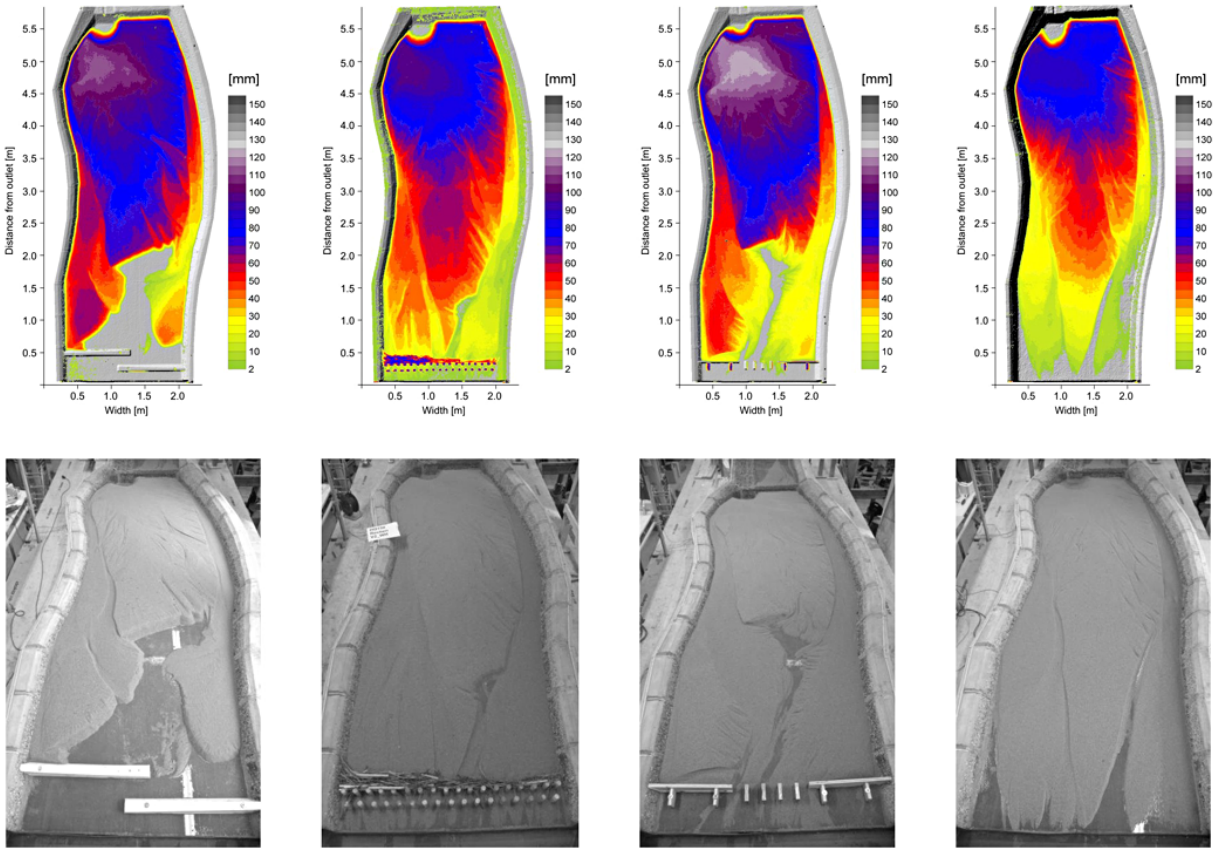
Fig. 4. Model hydrographs (solid line: Scenario 1 and 2, dashed line: Scenario 3).

3.3 Scaling considerations and calibration

In order to transfer all processes and observations from model to prototype (nature), geometric, kinematic and dynamic similarity has to be fulfilled (Preissler et al., 1989). However, the condition of full dynamic similarity (i.e., dimensionless numbers like Froude number and Reynolds number in the model have to equal the numbers that hold for nature), cannot be fulfilled when ‘natural water’ is used in the model. In open channel flow, the flowing medium is water, which has a very low Newtonian viscosity. Hence, for turbulent flow regime (found in most open channel flows) fulfilling Froude similarity (accounting for inertial and gravity forces and neglecting viscous forces) yields satisfying results. In order to keep unavoidable errors small (especially in sediment transport), the geometrical scaling factor was kept as small as possible (i.e., the physical model was performed as large as possible). The geometric scale for the model “Vorderbergerbach” was chosen to equal 1:30.

The physical modelling of sediment transport is problematic when the cohesive forces between scaled particles become relevant. For these cases, alternative material of larger grain size and smaller density is preferred. The grain size analysis (surface sampling after Fehr, 1987) of the bedload material from the Vorderbergerbach Creek revealed a relatively narrow grain size distribution, with a d_{50} of 23 mm and a d_{90} of 70 mm. The corresponding model values are 0.8 mm and 2.3 mm, respectively. For these grain sizes, no cohesive force effects were expected. For practical reasons, we had to restrict our model sediment to a less wide grain size distribution with a d_{50} of 1.3 mm and a d_{90} of 1.9 mm. This seems justified because we aim to compare different scenarios and have no detailed information on grain sizes during the flood event.

Because of the lack of in situ water level and flow velocity measurements (which are generally rare in torrents), model roughness was calibrated by numerical simulation of steady flow at several clear water discharges. Using the 1-D hydrodynamic model HEC-RAS (Brunner, 2010), we modelled water surface profiles in sub-critical, supercritical and mixed flow regime. Manning coefficients of $0.038\,\mathrm{m}^{-0.33}\,\mathrm{s}$ and $0.05\,\mathrm{m}^{-0.33}\,\mathrm{s}$ were used for the channel and for the banks, respectively, which is realistic for a creek. The comparison of flow depth measured with ultra-sonic sensors and mean velocity measured with a hydrometric vane revealed a maximum difference between the physical and numerical model of around 10 %. Table 1 exemplarily gives an overview of values calculated and measured at a section half-way between the inlet and the outlet of the physical model. Since we are mainly interested in the relative difference of the given scenarios, this correspondence was accepted as reasonable.



‘groyne’

‘filter’ + woody debris

‘check dam’

‘no structure’

Fig. 5. Examples of the deposition pattern due to different constructive configurations for Scenario 1 (Q_{150}).

Table 1. Comparison of calculated (subscript c) and measured (subscript m) flow velocity and flow depth in the physical scale model for different clear water discharges Q half-way between inlet and outlet of the modelled section.

Q ($\mathrm{l\,s^{-1}}$)	Vc ($\mathrm{m\,s^{-1}}$)	Vm ($\mathrm{m\,s^{-1}}$)	Hc (mm)	Hm (mm)
27.6	1.2	1.29	58	60 ± 1
24.3	1.16	1.19	55	49 ± 1
15.6	1.04	1.07	48	46 ± 1
3.4	0.66	0.7	28	27 ± 1

3.4 Overview of the experiments

Experiments were conducted with all four configurations on the basis of the 150-yr design hydrograph (Scenario 1) and with selected configurations on the basis of the reconstructed event in 2003 (Scenario 3). For the “check dam” and “woody debris filter” cases, the effects of woody debris were tested in three experimental runs. For the “no structure” and “groynes” configurations, the effect of woody debris was expected to be negligible. Finally, three experiments were carried out based on the scenario that the deposition area had not been cleared and another 150-yr event hit the sediment retention area (Scenario 2).

4 Results

4.1 Physical model

All values of net sediment input, deposition and output from the modelled topmost section of the deposition area are listed in Table 2. As expected, the “check dam” and “‘groyne”’ configurations are the most effective measures in terms of sediment deposition. There is no significant measurable output for the design event (Scenario 1). In both cases, a distinct deposition front with a steep margin evolves and moves slowly downstream towards the respective construction. As

Table 2. Overview of results from all experiments (WD = woody debris; Vol = estimated deposited volume in nature, “full” refers to the volume of complete filled Section 1).

Scenario	Test case	Input (kg)	Output (kg)	Output (% of input)	Deposition (kg)	Vol (m^3)	% of full
1	no structure	910	248 ± 36	27	662 ± 34	11 180	37
	filter	900	182 ± 4	20	718 ± 3	11 610	39
	filter + WD1	906	137	15	769	12 450	41
	filter + WD2	894	81	9	813	13 820	46
	groynes	908	4 ± 4	0	904 ± 17	15 650	52
	check dam	908	8 ± 3	1	900 ± 16	15 650	52
	check dam + WD1	890	2	0	888	15 280	51
2	no structure	1813	678	37	1135	16 520	55
	groynes	1842	214	12	1628	29 480	98
	check dam	1842	251	14	1591	27 920	93
3	no structure	3709	2249	61	1460	24 300	81
	filter	3701	2184	59	1517	24 870	83
	groynes	4058	2054	51	2004	33 720	112

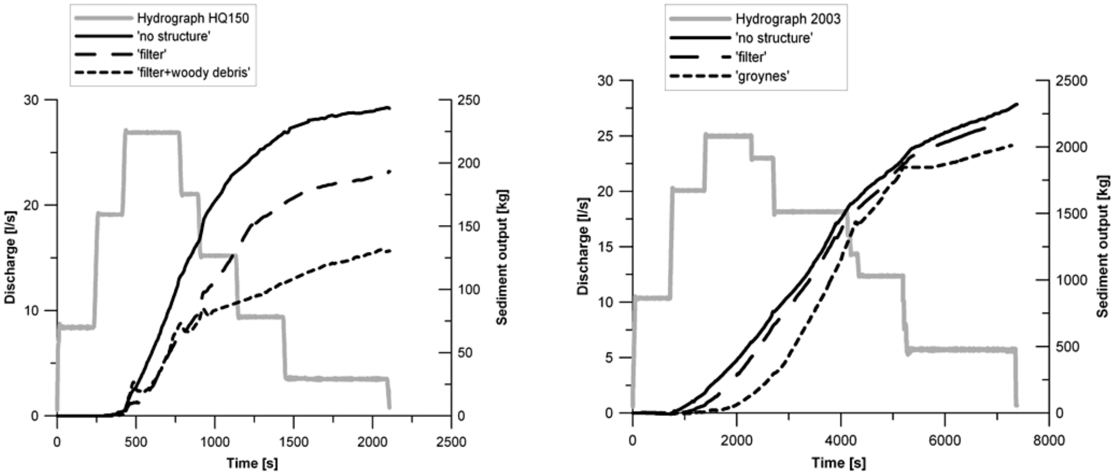


Fig. 6. Continuous cumulative output rate of bedload from the topmost section of the planned deposition area: test cases “no structure”, “filter”, and “filter + woody debris” for Scenario 1 (left), and test case “filter”, “groynes” and “no structure” for Scenario 3 (right).

can be seen in Fig. 5, the deposition fronts do not reach the end of the basin. Transferred to nature, almost all of the bedload delivered onto the fan will be deposited in the first section of the deposition area.

For the Scenario 2 (design event impinging the deposition area already prefilled by a previous Scenario 1 flood) the amount of total sediment input to the model doubled and a significant output from the first section is recorded in all test cases. However, only the first and second section of the deposition area is expected to be affected by bedload deposition. Unsurprisingly, the “no structure” configuration had the highest sediment output with 27 % and 37 % relative to the input for Scenario 1 and 2, respectively. Scenario 3, representing the sediment yield of the flood event 2003, shows output rates around 60 %. At first glance, the “check dam” or “groyne” configurations seem preferable, as they retain the largest amount of bedload. However, the experiments based on Scenario 3 reveal the possibility of backward deposition of sediment within the channel upstream of the deposition area, which may lead to overtopping in this reach. For this reason, configurations “check dam” and “groyne” are not favourable for installing in the topmost basin.

The configuration “filter” shows similar results like the “no structure” case for Scenario 3, but reduced sediment output for Scenario 1 (see Table 2). Adding woody debris to the “filter” configuration (case “filter + WD1”) resulted in a subtle decrease in sediment output (15 %). This is because the miniaturized stems block a considerable fraction of the cross-section resulting in further increases of the flow depth upstream of the filter. Increasing the mass of woody debris (case "filter + WD2") yields a further decrease of relative sediment output (9 %). A comparison of the continuous output is shown in Fig. 6 (right).

4.2 Numerical model

A novel 1-D sediment routing model for steep torrent channel networks, called SETRAC (Chiari et al., 2010; Chiari and Rickenmann, 2011) has been tested to simulate physical model results on the first section of the deposition area and to predict bedload deposition in subsequent sections. SETRAC is the acronym for **Se**diment **Tr**ansport Model in **A**lpine **C**atchments. Different sediment transport formulas and flow resistance approaches can be selected for special application in steep channels. To take form roughness losses into account, several approaches are available to modify the calculated transport capacity to better match observations on bedload transport. Armouring effects can also be considered. Additionally, it is possible to calculate fractional bedload transport and to consider grain sorting effects in combination with mobile bed conditions. In SETRAC the channel network is represented by nodes, cross-sections and sections. Sediment is transferred through the channel network considering a pre-defined sediment budget in the sections. Initial erosion depth can be assigned for each channel reach and morphologic changes due to erosion and deposition are calculated. A graphical user interface with visualizations of the longitudinal sections, as well as the cross-sections, has been developed. For the calculation, each cross-section is divided into strips to get a representative discretization of the profile. The number of strips depends on the number of points that are used to specify a cross-section, implying that the number of strips increases with the complexity of the cross-section. Flow hydrographs are routed as kinematic waves through the channel system. Sediment input as sedi-graphs is also possible. The successor of the SETRAC model (Tom$^{\mathrm{Sed}}$) as well as a user manual and tutorials are available as a free download at www.bedload.at.

The physical scale model covers only the upper third of the investigation area. Therefore, the numerical model has been applied for the scenarios without structures to expand the information on bedload deposition in the downstream sections. For calibration the deposition in the first section has been taken as reference. To get a better representation of the 2-D deposition pattern, the average lateral deposition heights were determined at cross-sections with a distance of 25 cm in a longitudinal direction. The deposition heights, resulting from the simulation by SETRAC, were compared to the average deposition of the physical model.

The spatial discretization for the SETRAC simulation was 0.1 m. In SETRAC the flow velocity was calculated based on the formula suggested by Smart and Jaeggi (1983) and the bedload transport using Rickenmann's (1990) formula, where the incipient motion condition θ_{cr} served as a calibration parameter ($\theta_{\mathrm{cr}} = 0.046$). Figure 7 shows a comparison of the measured mean cross-sectional deposition height in the physical model and the SETRAC simulation for Scenario 1 (no structure). In the physical model, only the first section of the whole deposition area was modelled. The calibrated simulation of Scenario 1 without structures allows the predicting of the depositional behaviour in the other sections. The deposition behaviour, as well as the slope of the deposited material, could be modelled accurately with the exception of the scour close to the inlet of the basin, which could not be reproduced by the simplified hydraulics of the SETRAC model (Fig. 7).

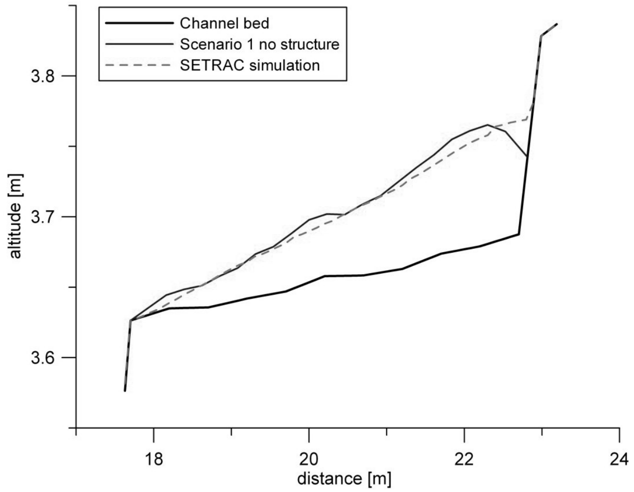


Fig. 7. Comparison of modelled (SETRAC) and measured deposition heights for Scenario 1 and the no structure configuration.

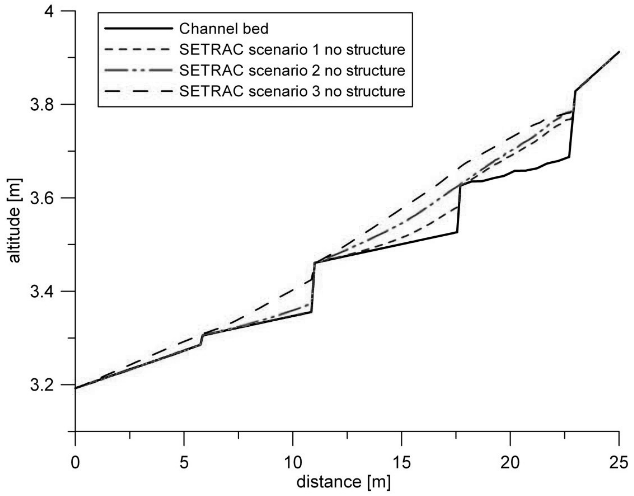


Fig. 8. SETRAC model simulation results for the whole deposition area (distance 6 m–23 m) for Scenario 1, 2, and 3 – without structures.

With SETRAC all three depositional sections, as well as the planned channel downstream of the depositional area, have been simulated for Scenarios 1, 2 and 3 without structures (Fig. 8). For Scenario 1 without structures all the sediment that is not deposited in section 1 (physical model reach) will be deposited in the downstream section 2. In Scenario 2 (= two times Scenario 1) some sediment is deposited in the third section additionally, but no sediment reaches the downstream channel. Scenario 3 has the highest sediment input. Therefore, massive deposition can be expected in all three reaches. A direct comparison with the physical model is not possible, because the first and the second section of the basin cannot be regarded independently due to the change of boundary conditions: the massive sediment deposition in the first and second section becomes connected and a homogeneous slope of the deposited material develops. Some sediment is transported and deposited in the downstream channel.

5 Conclusions

Physical scale models represent a useful tool to evaluate the efficiency of flood protection measures. In contrast to river engineering practice, physical scale models have not often been used in the context of small Alpine watersheds. One example is the optimization of two subsequent sediment retention basins at the Baltschiederbach Creek in Switzerland (Jordan et al., 2003, 2004). Similar to our study, the functionality of different configurations were tested based on several hydrologic scenarios. The focus of the study was the optimization of the outlet area of the first retention structure. Other work on mitigation measures for torrent catchments concentrates on design criteria for the geometry of open silt-check dams (Armanini and Larcher, 2001), morphologic changes due to construction of check dams (Busnelli et al., 2001; Conesa-García et al., 2007) and impact on vegetation due to check dam construction (Bombino et al., 2009). Our study investigated the spatial deposition of bedload on a wider area without significant change of the inflow hydrograph. The developed general concept of protection measures which modifies and divides the widened reach into three sections of reduced bed slope is supported by the experiments performed on a physical model of the topmost section. In all tested configurations of this section, a large fraction of the bedload was retained. Based on our results, it is to be expected that most of the passing bedload will be deposited in the second and the third section. For the scenarios without structures, this has been proven by additional numerical simulations. For the other scenarios, more sophisticated models including flow routing and dimension (2-D or 3-D) should be applied. It was shown that a massive barrier structure, like a check dam or groynes, exceeds the capacity of the area and may cause backward deposition in the approaching channel and, thus, overtopping of the banks. It is noted that we replaced the wide, natural grain size distribution with near uniform sand with a d_{50} of 0.8–1.2 mm, since we had to deal with several m^3 of sediment during the experiments. Considering that we mainly focused our investigations on the relative effect of different configurations, this seems to be justified.

The inclination of the deposits is similar for all scenarios and ranges between 1.7° and 2.1°. The values closely match the results from empirical equations suggested by Hampel (1974) and Smart and Jaeggi (1983) with 1.8° and 2.5°, respectively, and support the applicability of these formulas for engineering purposes.

In small Alpine watersheds, the presence of woody debris is of high relevance for planning protection measures. Studies like Mazzorana et al. (2009), emphasize the importance of a qualitative and quantitative assessment of woody debris recruitment and transport during flood events. However, for this study no data on woody debris yield to the fan is available, so test cases including woody debris are based on rough estimates. The construction of a filter structure is favourable in preventing the damming of narrow channel sections downstream. The experiments showed that strong backwater effects can be avoided by keeping the spacing between the filter elements large. A second row of filter elements has not been effective in our experiments.

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