Analysis of flood related processes at confluences of steep tributary channels and their receiving streams – 2d numerical modelling application

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ABSTRACT

The work presented within this paper deals with the crucial hydraulic and morphologic processes at confluences of steep torrent channels and receiving streams in case of exceptional extreme events. 2d numerical modelling is accomplished with the BASEMENT software for the confluence of Schnannerbach torrent channel and Rosanna River. There, the damage causing flood event from August 2005 is reconstructed. Processes of bedload deposition, flooding and overbank sedimentation, as they could be observed in August 2005 and analysed within a physical model at the University of Innsbruck, are simulated. The modelling results provide a valuable insight into the processes being crucial for the damages on the adjacent flood plain. Compared to the laboratory analysis, which delivers a very reliable and vivid process representation but is restricted to a rather small spatial extent, numerical modelling allows for an analysis of bedload transport and deposition further downstream in the Rosanna River and backwater effects upstream.

KEYWORDS

bedload transport, event reconstruction, confluence zone, 2D model

INTRODUCTION

Experiences from recent torrential hazard events in the Alps reveal that confluences of steep tributaries and their receiving waters are often critical spots concerning flood risk. Due to massive supply of sediments from the torrent catchments and insufficient transport capacities in the receiving streams, processes of regressive aggradation appear, possibly leading to overbank flooding and sedimentation on the alluvial fan. In this respect, physical scale modelling of bedload transport processes proved to be a suitable tool for optimizing mitigation measures at confluence zones (Gems et al. 2014).

However, to accurately reproduce natural conditions, the scale, and with it the similarity law, have to be defined carefully. In case of bedload pulses entering receiving waters, experimental modelling is typically restricted to the proximity of the confluence zone (Gems et al., 2014). In contrast, hydraulic and morphologic responses of the receiving streams extend far in upstream and downstream directions. The optimization of geometric patterns at the conflu-

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ence zone yields a significant onward movement of sediment (Gems et al., 2014), but critical spots, featuring aggradation and flooding, may appear further downstream in the receiving water. In this regard, the area of risk is rather spacious and its extent strongly depends on the bedload transport capacity of the whole system rather than at the confluence only. In order to assess their impact on flood safety and to determine areas of risk, the application of a numerical tool is suggested to be an adequate method, since it easily copes with the large areal extent of the area of interest.

METHODS

General Remarks

Numerical simulations of bedload transport in steep mountain streams are commonly accomplished by means of 1d hydrodynamic approaches. As long as water flow is laterally confined, these simplifications are of minor effects. In contrast, fluvial fans typically feature convex terrains with multiple flow paths in case of overbank flooding. Additionally, confluence zones exhibit complex flow patterns, since water enters from different directions.
In order to account for these conditions, at least a 2d hydrodynamic model needs to be applied for the simulation of hydraulic and involved bedload transport processes.
However, the set of equations in 2d hydrodynamic models is rather sophisticated (e.g. Vetsch et al., 2011) and its applicability to high gradient streams with huge sediment loads is hardly tested so far. To make a contribution to that, the simulation tool BASEMENT (© ETH Zurich) was applied to a case study in order to examine its performance.

Case Study Event

The case study comprises an extreme event in the Schnannerbach Torrent (Tyrol), which was intensively investigated and comprehensively documented concerning both, hydrologic (Chiari, 2008) and morphologic characteristics (Gems et al., 2014; Chiari, 2008; Hübl et al., 2006; Figure 1); in these literature references the reader also finds a detailed overview of catchments characteristics.

Summarizing, a heavy rain storm occurred in August 2005, which caused run-off generation and erosion along the steep scree slopes which are composed of lime stone rock and located in the upper catchment of the Schnannerbach Torrent. The total bedload that was transported to the fan apex was in the range of 36,000 m³ (Hübl et al., 2006) and 59,000 m³ (Gems et al., 2014). However, about 25,000 m³ of sediment (volume including pores) deposited on the alluvial fan (Hübl et al., 2006), which means that up to 34,000 m³ of bedload has entered the receiving Rosanna River.

However, in this study the event reconstruction of Gems et al. (2014) is used as boundary condition for the numerical investigations. In their study, the sediment flux that entered the lined trench at the fan was reconstructed by determining the system's capacity (critical load in the confluence zone and transport capacity of the Schnannerbach channel) by means of

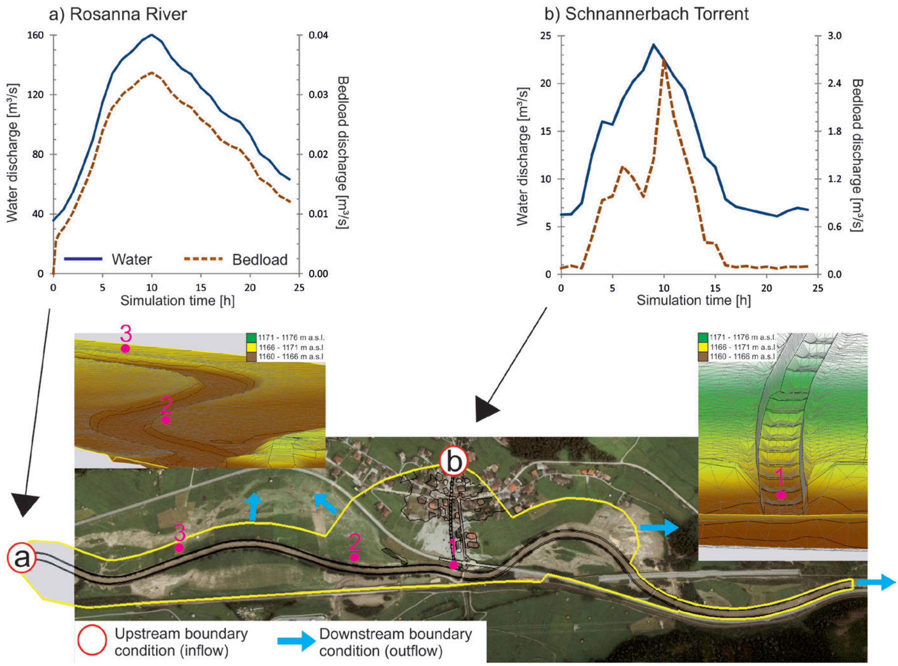

Figure 1: The extent of the 2d model used for the simulation including the hydro- and sedigraphs at the upstream boundaries and the location of downstream boundaries which are defined by constant friction slopes; the purple points are used as spatial reference only.

physical scale modelling. The boundary conditions as highlighted in Figure 1 sufficiently reproduced the spatial and temporal location of the system failures (overbank flooding) that were observed during the event in 2005.

Model Extent

The 2d numerical modelling tool BASEMENT (2006-2015) is used to simulate the hydraulics and the bedload transport of the considered flood event. Thereby, the numerical model covers the lower half of the alluvial fan of the Schnannerbach Torrent and extends over two kilometres of the receiving mountain stream (Rosanna River), with the confluence zone located in the middle (Figure 1). The computational grid of the modelling area (0.37 km²) is characterized by an unstructured mesh consisting of approx. 11,600 nodes which are either based on high resolution LiDAR data (floodplain) or bathymetric survey data (water courses). Summarizing, the alluvial fan features a mean gradient of 0.1 m/m and the channel is constructed as a lined trench with a sequence of small check dams (artificial steps) which prevents from channel bed erosion. The flow section of the artificial channel has a base and top width of approx. 5 m and 6 m and is on average 3 m deep. In contrast, the gradient of the receiving mountain stream is only 0.008 m/m and features a trapezoidal cross section with an average bed and top width of 16 m and 26 m, respectively. Although the geometrics of the

channels and the floodplain are of high resolution, local structures crossing the channels (bridges) could not be considered. Hence, the model does not enable to simulate clogging of bridge cross sections with sediment due to pressurized flow, which had been observed during the prototype event (Gems et al., 2014).
Except for the artificial steps and walls of the tributary channel, the water course of both, the Schnannerbach Torrent (tributary channel) and the Rosanna River (receiving mountain stream), was chosen to be mobile, allowing for river bed erosion. In addition, deposition and remobilization of bedload is considered within the entire computational domain.

Parameter Settings
The BASEMENT software simulates flow hydraulics by solving the shallow water equations that are commonly used to model a wide variety of physical phenomena (Vetsch et al., 2015). Next to the assumptions of a hydrostatic pressure distribution and steady-state resistance laws, this approach is only valid in case of small channel slopes ***(θ)***, with ***cos(θ)~1***. The alluvial fan features a mean slope of 0.1 m/m, but the error is assumed to insignificantly influence the outcomes of this study. However, hydraulics in the overall steep and artificially stepped Schnannerbach Torrent are highly non uniform, with a permanent transition of super- and subcritical flow. Hence, solving the governing shallow water equations numerically might generate instabilities due to problems in convergence. In order to minimize these error sources, emphasis was put on (i) the specifications of parameters at the hydraulic boundaries (e.g. friction slope, weighting type) which were defined carefully by trial and error and (ii) a regularly distributed computation mesh consisting of triangular elements on the channel bed. As recommended by Vetsch et al. (2015), the element size was small in regions of abrupt changes in flow conditions, while it was coarse on the alluvial fan and the floodplain. Sensitivity tests confirmed the importance of these issues.
A variety of flow resistance equations are available in BASEMENT. In this study, the approach of Manning-Strickler is used with spatially variable but temporally constant roughness scales (Strickler coefficients) of 23 $m^{0.33}s^{-1}$ for the channel bed of the Schnannerbach and 30 $m^{0.33}s^{-1}$ for the Rosanna River. Thus, the friction attributed to the river bed does not differ in case the formerly bed surface is covered by deposited bedload, but its impact on flow hydraulics is assessed by changes of geometric patterns (e.g. the burial of the artificial steps causes the longitudinal profile to smooth).
Bedload transport is calculated according the Meyer-Peter and Mueller (1949) equation which is extended to a fractionized approach in BASEMENT (Vetsch et al., 2015).
The mobility of single grain sizes is determined by the hiding function that assumes equal mobility of all fractions finer than the D40 (grain size for which 40 % are finer by weight) and size selective mobility for coarser ones. Therefore, the grain size distributions were determined separately regarding both, the source (bed sediment and bedload) and the stream (Schnannerbach torrent and Rosanna River).
In steep mountain streams, only a fraction of total shear stress is available for bedload transport. The form and spill drag around macro roughness elements, which are typically

present in steep streams, act as momentum sinks. However, there is no approach available in the simulation tool BASEMENT to account for momentum losses due to macro roughness elements. But the artificial steps of the tributary channel (Figure 1) have a similar effect on the shear stress. While the energy gradient (and hence the shear stress) is very large at a certain step, it is comparatively small along the mobile channel between two steps. Hence, form resistance is assumed to be adequately reproduced by the high resolution of the channel geometrics only, rather than by additional, empirical equations.
Next to the bedload transport that originates due to flow hydraulics, BASEMENT provides an option to account for gravitational transport, which is primarily attributed to river bank failures. However, gravitational induced relocations of sediment might also appear during the formation of large deposit cones due to slope failures or shallow landslides on the downwards facing slopes (Zollinger, 1983). In order to activate gravitational transport in BASEMENT, three critical failure angles must be defined beforehand. These distinguish for dry or wetted embankments or deposited sediment and are set to 35 °, 20° and 10°, respectively.

RESULTS

Basically, the results of numerical simulations reveal the capability of a 2d hydrodynamic modelling tool to accurately reproduce field and laboratory observations (Figure 2). However, there are still some areas where modelling results do not correspond to the aerial photograph. For instance the areal extent of overbank sedimentation on the alluvial fan is too small (Figure 2a), while deposit heights are generally too large when compared to the event reconstruction of Hübl et al. (2006). The cause of these differences is mainly attributed to local structures (e.g. walls, railings, etc.) that are insufficiently included in the model. In this respect, overbank flow might had been laterally confined by these structures and thus, the flow's competence to transport sediment was higher than calculated. Additionally, numerical simulations insufficiently reproduce the overbank sedimentation of the Rosanna River (Figure 2a), although all except of the most upstream part is flooded with water (Figure 2b). Probably, these sedimentations refer to suspended load which is not accounted for in the numerical simulations.
Despite these uncertainties, the failure mechanisms can be assessed in more detail and the results enable an event history analysis regarding the processes of bedload aggradation and their feedback on hydraulics and flood risk.
Within the first few hours of the event, artificial steps in the tributary channel were filled up and thus, the longitudinal profile was smoothed which minimizes form resistance and maximizes flow competence to transport bedload (Figure 3a and 3b). However, the bedload that passed the tributary channel initially accumulated in the confluence zone (Figures 3b and 3c). There, an abrupt change in bed gradient from 0.07 m/m at the lowermost reach on the alluvial fan to less than 0.01 m/m in the Rosanna River appears. Despite the fact, that water discharge in the receiving stream is almost 7 times larger, transport capacity is less than in the small Schnannerbach channel.

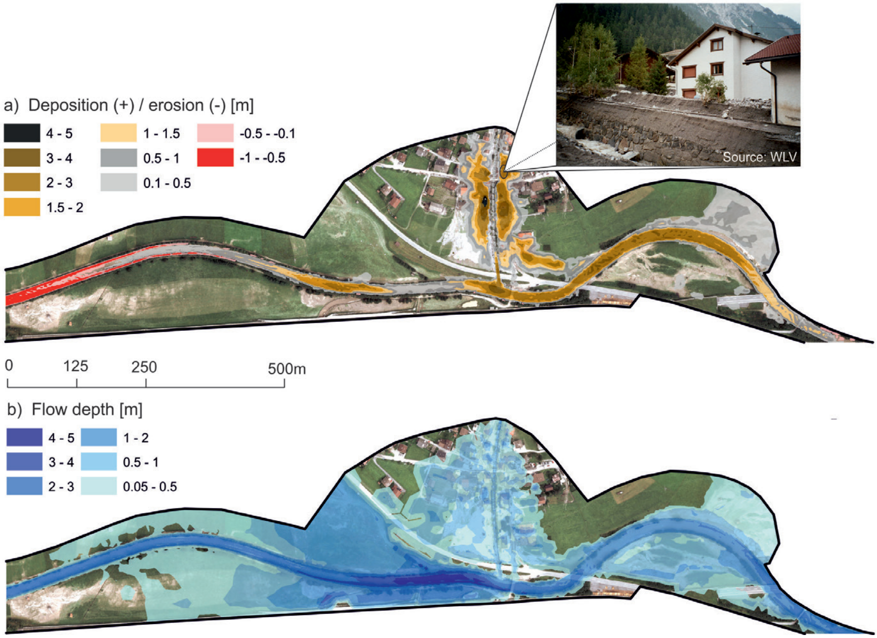

Figure 2: a) Magnitudes of deposition and erosion after the torrential hazard event (at the end of the simulation) and b) maximum flow depth of each node. The aerial photo (© Bundesamt für Eich- und Vermessungswesen) in the background of the figures shows the study area a few days after the extreme event (see also Figure 1 and Hübl et al., 2006).

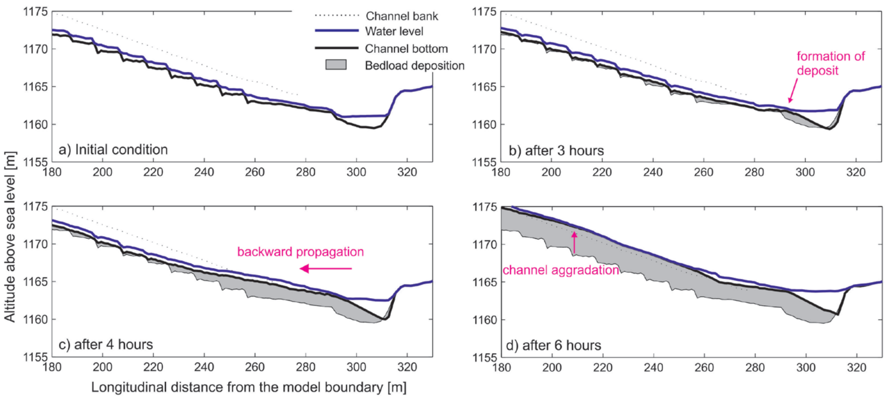

Figure 3: Evolution of the bed level in the lowermost reach of the tributary channel at certain times (a-d) during the case study event

Consequently, the entering bedload forms a deposit cone. Thereby, the level of the cone's crest defines the downstream base level of the tributary channel which contributes to a decrease of slope with growing bedload accumulation in the confluence zone (Figure 3c).

By that, the transport capacity decreases as well, resulting in severe channel bed aggradation (Figure 3d). Hence, bedload accumulation successively propagates against the flow direction of the tributary channel and the channel's flow capacity decreases until it is insufficient to cope with the discharge from the tributary catchment. Due to overbank flooding on the alluvial fan, the channel's transport capacity rapidly decreases once more with most of the entering sediment depositing on the alluvial fan. In addition, modelling results further highlight the impact on flow hydraulics in the upstream reach of the receiving stream. Backwater effects caused a dramatic increase of the water level which was accompanied with the flooding of agricultural areas nearby the receiving stream (Figure 2b).
According to the boundary condition in the Schnannerbach Torrent (Figure 1), the sediment load diminished after about 14 hours (Figure 1). As a consequence, the water cuts into the sediment filled channel by remobilizing the accumulated bedload. Corresponding to eye witness observations of the event in August 2005, the lined trench of the tributary channel is almost free from sediment at the end of the simulation. It is worth to note that channel incision propagates forward, starting at the upstream end and thus, differs from aggradation. However, there remain large sediment accumulations on the alluvial fan and in the confluence zone (Figure 2).
Although the transport capacity of the receiving stream is far less than the sediment input from the tributary catchment, a significant amount of bedload is transported further downstream during the event. According to the numerical simulations, this is accompanied

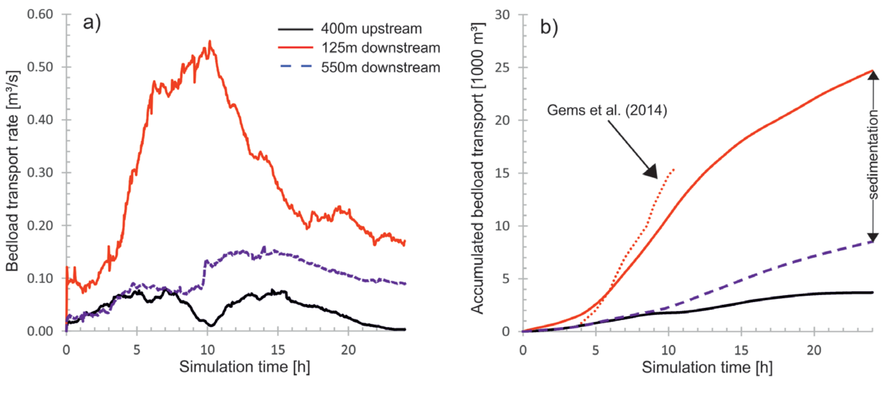

Figure 4: Time series of a) bedload transport rate and b) accumulated bedload transport (volumes refer to solid volumes) at certain locations in the receiving Rosanna River

with an obvious river bed aggradation downstream of the confluence zone leading to a reduction of flow capacity, followed by overbank flooding and sedimentation. According to Gems et al. (2014) about 15,400 m³ of bedload passed the downstream end of their physical scale model (120 m downstream of the confluence zone) within the first 10.5 hours of the event that properly matches with the simulation results (11,700 m³; Figure 4). In total, a considerable fraction (approx. 25,000 m³) of the entire sediment pulse that originated from the tributary channel (59,000 m³ according to Gems et al., 2014) is remobilized at the confluence zone during the event. But the propagation distance is limited to a few hundred meters (Figure 4) with severe river bed aggradation and overbank flooding in this region (Figure 2).

CONCLUSION

The application of a 2d hydrodynamic simulation tool is suitable to reproduce the complex interactions of bed morphology (aggradation / incision) and flow hydraulics present at a river confluence zone during an exceptional event in the tributary catchment. It is worth to note that simulation results properly matched with observations although most parameters referred to their default values.

Results reveal that the magnitude of bedload accumulation in the confluence zone majorly controls channel bed aggradation and overbank flooding in both, the tributary and the receiving stream; at least in this case study event. In terms of modelling, the growing rate of the deposit cone strongly depends on the angle of response of the deposited bedload, which was defined by 10°. However, there is a lack of knowledge regarding this parameter and thus, more emphasis is needed to evaluate the performance of 2d hydrodynamic modelling under different geometric configurations.

LITERATUR

- BASEMENT – Basic Simulation Environment for Computations of Environmental Flow and Natural Hazard Simulation. Version 2.5. ©ETH Zurich, VAW, Vetsch, D., Siviglia A., Ehrbar D., Facchini M., Gerber M., Kammerer S., Peter S., Vonwiller L., Volz C., Farshi D., Mueller, R. Rousselot P., Veprek R., Faeh R., 2006-2015.
- Chiari M. 2008. Numerical modelling of bedload transport in torrents and mountain streams. PhD Thesis at the University of Natural Resources and Applied Life Sciences (BOKU), Vienna.
Gems B., Sturm M., Vogl A., Weber C., Aufleger M. 2014. Analysis of damage causing hazard processes on a torrent fan – scale model tests of the Schnannerbach Torrent channel and its entry to the receiving water. Digital Proceedings of the Interpraevent 2014 in the Pacific Rim, Nara.
- Hübl, J., Ganahl, E., Bacher, M., Chiari, M., Holub, M., Kaitna, R., Prokop, A., Dunwoody, G., Forster, A., Schneidenbauer, S., 2006. Dokumentation der Wildbachereignisse vom 22./23. August 2005 in Tirol, Band 2: Detaillierte Aufnahme (5W+ Standard); IAN Report 109 Band 2, Institute of Natural Hazards, University of Resources and Life Sciences Wien.
- Vetsch D., Siviglia A., Ehrbar D., Facchini M., Gerber M., Kammerer S., Peter S., Vonwiller L., Volz C., Farshi D., Mueller, R. Rousselot P., Veprek R., Faeh R. 2015. System Manuals of BASEMENT, Version 2.5. Laboratory of Hydraulics, Glaciology and Hydrology (VAW), ETH Zurich.
- Zollinger, F. 1983. Die Vorgänge in einem Geschiebeablagerungsplatz: ihre Morphologie und die Möglichkeiten einer Steuerung, PhD Thesis, ETH Zurich, No. 7419, 265 p (in German).