Adv. Geosci., 32, 23–30, 2012
www.adv-geosci.net/32/23/2012/
doi:10.5194/adgeo-32-23-2012

Advances in Geosciences

Bed-load transport modelling by coupling an empirical routing scheme and a hydrological-1-D-hydrodynamic model – case study application for a large alpine valley

B. Gems[1], S. Achleitner[1], M. Plörer[1], F. Schöberl[2], M. Huttenlau[3], and M. Aufleger[1]

[1]Unit of Hydraulic Engineering, University of Innsbruck, Innsbruck, Austria
[2]Institute of Geography, University of Innsbruck, Innsbruck, Austria
[3]alpS – Centre for Climate Change Adaptation Technologies, Innsbruck, Austria

Correspondence to: B. Gems (bernhard.gems@uibk.ac.at)

Received: 31 January 2012 – Revised: 23 July 2012 – Accepted: 4 November 2012 – Published: 11 December 2012

Abstract. Sediment transport in mountain rivers and torrents is a substantial process within the assessment of flood related hazard potential and vulnerability in alpine catchments. Focusing on fluvial transport processes, river bed erosion and deposition considerably affects the extent of inundation. The present work deals with scenario-specific bed-load transport modelling in a large alpine valley in the Austrian Alps. A routing scheme founding on empirical equations for the calculation of transport capacities, incipient motion conditions and drag forces is set up and applied to the case study area for two historic flood events. The required hydraulic data result from a distributed hydrological-1-D-hydraulic model. Hydraulics and bed-load transport are simulated sequentially providing a technically well-founded and feasible methodology for the estimation of bed-load transport rates during flood events.

1 Introduction

The transport of sediment and bed-load in particular is to some extend a stochastic process, which relies on sensitivities of hydraulic and topographic conditions and of the river bed structures. A strict functional relation of bed-load transport rates and hydraulic conditions usually does not exist, most notably at steep rivers. Two aspects mainly affect the characteristics of bed-load transport at steep slopes: drag forces caused by bed forms such as step-pool or riffle-pool sequences lead to a reduction of the dynamic forces acting on the grain. Secondly, the potentially available bed-load material is limited due to large blocks and boulders, which inhibit the local erosion of the river bed (e.g. Rickenmann et al., 2008; Chiari et al., 2009). However, some equations and approaches currently exist, which allow the assessment of theoretical bed-load transport rates at steep-slopes-characteristics. Well known and frequently used approaches are those from Rickenmann (2005) and Smart and Jäggi (1983). Drag forces are considered by reducing the channel gradient depending on the relation of the Manning-parameters representing the grain's roughness and the total roughness (Rickenmann, 2005; Rickenmann et al., 2006; Palt, 2001). Common approaches originate from Rickenmann (2005, 2007), Rickenmann et al. (2006), Palt (2001), Rice et al. (1998), Pagliaria and Chiavaccini (2006) or Canovaro and Solari (2007). The critical discharge, which defines the initiation of sediment movement, can be determined using equations of Bathurst (1985, 1987) and Rickenmann (1990) or Whittaker and Jäggi (1986). Recent research in the field of bed-load transport at steep slopes deals with the implementation of present empirical approaches into numerical models. Transport processes are thereby coupled to the hydraulics, where a dynamic interaction between hydraulics, bed-load transport and the river-bed level is optional. More advanced modelling approaches include even multi-grain multi-layer approaches allowing the consideration of armoring and sorting processes (e.g. software TOMSED, Friedl and Chiari, 2011; BASEMENT, Faeh et al., 2012).

Within the scope of this paper, approaches for bed-load transport calculation are applied in the context of an empirical routing scheme, which is coupled with a hydrological-1-D-hydraulic model. The presented work refers to a modelling concept dealing with the assessment of flood protection measures in a large alpine catchment (Gems, 2012; Gems et al., 2009; Achleitner et al., 2010). The concept is applied to the Ötz-valley, a main tributary catchment of the river Inn in the Tyrolean Alps. The results presented here focus on a hydrological sub-catchment, which is situated in the rear part of the Ötz-valley (Fig. 1).

2 Case study area

Figure 1, left, gives an overview on the location of the case study area. The spatial discretisation for hydrological and bed-load transport modelling is illustrated in Fig. 1, right. The catchment area amounts to 180 km^2. It comprises 28 sub-catchments, every one representing either a tributary to the receiving water course or a homogeneous river section of the receiving water concerning the channel slope and width. The catchment's altitude ranges between 1840 m a.s.l. and 3774 m a.s.l. According to Hafner and Fürst (2007) 37.3 % are permanently glaciated. Two discharge gauges are located close to the catchment's outlet (red dots in Fig. 1, right). They are used for calibrating the hydrological model component. The mean annual discharge (MAD) at gauge 1 (catchment area of 98 km^2) is 4.51 $m^3\,s^{-1}$ (46.0 $L\,s^{-1}\,km^{-2}$), the mean annual flood (MAF) amounts to 43.7 $m^3\,s^{-1}$ (Hydrographischer Dienst in Österreich, 2009). At the outlet of the case study area MAD = 8.30 $m^3\,s^{-1}$ (46.2 $L\,s^{-1}\,km^{-2}$) and MAF = 69.5 $m^3\,s^{-1}$. In recent history the Ötz-valley has been damaged by several disastrous flood events. Massive losses occurred due to the floods in June 1965 and August 1987 (Braun and Weber, 2002). More recent flood events (bearing less risk potential) occurred in September 1999, July 2001 and July 2010. Within all the mentioned flood events, sediment transport processes in terms of both fluvial transport and debris flow played a significant role.

3 Model concept and application

3.1 Overview

The model concept is in general based on a hybrid, event-specific approach. It comprises a distributed hydrological model which is linked to a 1-D-hydrodynamic model and a bed-load transport routing scheme. Former is set up for all tributaries (torrents) within the catchment. The hydraulic model covers the river Ötztaler Ache as the main receiving water course. Both model components are run in a coupled mode, they provide discharge data as input for the bed-load transport computations. Where the hydraulic calculations are made for all tributary catchments, the bed-load transport scheme is only applied to the most relevant sub-catchments in terms of mobilized bed-load during flood events. For that, the classification of the torrents is based on a detailed field survey. In general, the routing scheme for the torrents and the main river follows the hydrological discretisation with using a classification of homogeneous sections. Still, some tributaries are modelled in the way that only the most downstream reach discharging to the mainstream is considered as "key section". This section represents the transport limiting conditions. The model concept eminently focuses on the characteristics of alpine catchments and steep slopes respectively. It has actually been developed for the application in large alpine valleys such as the Ötz-valley. The main features of the model components are briefly described below. A deeper inside is given in Gems (2012).

3.2 Hydrological and hydraulic model

The hydrological model is based on the SCS-CN procedure (US Department of Agriculture (USDA), 1985) and the lag-routing approach (software HEC-HMS, v.3.4). Snow and glacier melt processes are represented with the following simplified, non-physical method: Panchromatic Landsat 7 aerial images gathered at dates of the considered historic flood events are visually analysed in ARCGIS (v.9.4) in order to detect the extent of snow cover and glaciers within the case study area. Thus, every hydrological compartment is further subdivided into a snow- or glacier-covered area and a non-covered area. Both types of sub-catchments are run using individual parameter sets for curve cumbers, lag times and initial abstraction in order to mimic a delayed flow from snow areas. Additionally, a monthly constant base flow is applied to the snow- or glacier-covered sub-catchments. Hydrological model parameters are derived from a laser grid with a spatial resolution of 10 m and the mapping of land use, vegetation and soil type according to Hafner and Fürst (2007) and Peticzka and Kriz (2007).

The main river Ötztaler Ache from Zwieselstein down to the mouth entering the river Inn is modelled using the unsteady 1-D-hydrodynamic model HEC-RAS (v4.1.0). A terrestrial survey is accomplished in order to gain cross section data along the river Ötztaler Ache for the HEC-RAS-model. The models are driven by rainfall measured at 18 rain gauges within and close to the Ötz-valley. Regionalization is done using the quadratic inverse distance weighing. The results from the hydrological model represent the input for the hydrodynamic model.

Hydrological and hydraulic model calibration is done discretely for every considered flood event (event-specific) by using water levels and discharges at the gauges. The applied calibration procedure is a top down approach starting with the calibration of the topmost catchment and gauge. Subsequent calibrations of the further downstream gauges are done in the way that already calibrated upstream catchment parameters are considered as fixed. Since the procedure is accomplished event-specific, a model validation is not carried out.

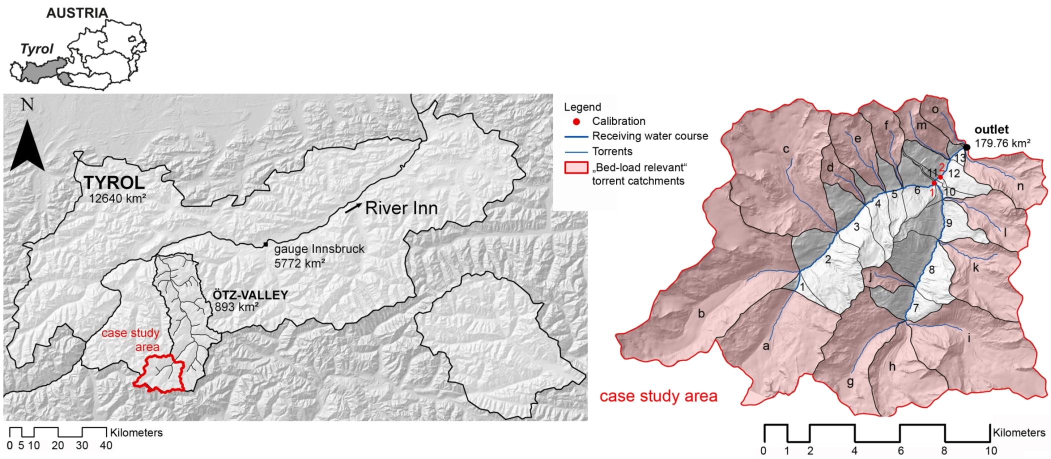

Fig. 1. Left: overview on the Ötz-valley in the Tyrolean Alps comprising the case study area in the rear part of the valley; right: spatial discretisation for hydrological and bed-load transport modelling – arrangement of the 28 sub-catchments.

However, the calibration parameter settings for every flood event are checked for plausibility and compared with each other respectively.

3.3 Bed-load transport

For the here considered case study area the bed-load Eqs. (1) and (2) are used:

$$\begin{aligned} \mathrm{TC} &= 1.5\cdot(Q-Q_c)\cdot I_{\mathrm{S,red}}^{1.5} \\ &= 1.5\cdot(Q-Q_c)\cdot I_{\mathrm{S}}\cdot\left(\frac{0.133\cdot Q^{0.19}}{g^{0.096}\cdot I_{\mathrm{S}}^{0.19}\cdot d_{90}^{0.47}}\right)^{\alpha} \quad 1\le\alpha\le 2 \end{aligned} \tag{1}$$

$$Q_c=\begin{cases} 0.484\cdot B\cdot g^{0.5}\cdot d_{50}^{1.5}\cdot I_{\mathrm{S}}^{-1.12} & \text{(2a)} \\ 1.065\cdot B\cdot g^{0.5}\cdot d_{65}^{1.5}\cdot I_{\mathrm{S}}^{-1.167} & \text{(2b)} \end{cases}$$

According to Rickenmann (2005) the (theoretical) bed-load transport capacity TC [$\mathrm{m^3\,s^{-1}}$] is computed as a function of the discharge Q [$\mathrm{m^3\,s^{-1}}$], the critical discharge Q_c [$\mathrm{m^3\,s^{-1}}$], which represents the initiation of sediment movement, and the reduced channel gradient $I_{\mathrm{S,red}}$ [–]. The latter is for the consideration of bed forms such as step-pool or riffle-pool sequences, which lead to additional drag forces and thus a certain decrease of the bed-load-transport-relevant shear stresses. Equation (1) contains a relation for $I_{\mathrm{S,red}}$, that depends on the discharge Q, the channel gradient I_{S} [–] and the grain parameter d_{90} [–]. α [–] represents a calibration parameter being set within the range $1\le\alpha\le 2$ (Rickenmann et al., 2006). Since there is no calibration data for bed-load transport available for the case study area, the global assumption of $\alpha = 1.5$ is firstly used for the computations. Equation (1) is applicable to conditions $I_S \geq 0.8\,\%$ (Rickenmann, 2005). Equation (2) comprises two approaches for the calculation of Q_c. Though, Eq. (2a) relies on the work of Bathurst (1987) adapted by Rickenmann (1990). It represents bed conditions without an armour layer. Equation (2b) is based on block ramp experiments by Whittaker and Jäggi (1986). The choice whether Eq. (2a) or Eq. (2b) is applied for the calculation of Q_c in every routing section depends on the channel characteristics and thus on the findings from the field survey (Table 1). Both approaches in Eq. (2) assume a value of 2.68 for the density-relation of grain and water. The parameter B [m] in Eq. (2) is the channel width, g [$\mathrm{m\,s^{-2}}$] is the gravity acceleration. The parameters d_{xx} [m] in Eqs. (1) and (2) describe the bed material particle size for which xx % of the material is finer.

According to Fig. 1, right, the case study area is spatially discretised into 28 sub-catchments. Every sub-catchment is represented by "key section" parameters (Table 1) marking the transport limiting section within the routing element.

Equation (3) schematically illustrates the routing procedure for one balancing section at time step i. TC_i [$\mathrm{m^3\,s^{-1}}$] is the transport capacity at time step i in the section, IN_i [$\mathrm{m^3\,s^{-1}}$] represents the incoming bed-load rate from the adjoining section(s) upstream, OUT_i [$\mathrm{m^3\,s^{-1}}$] is the bed-load rate at the section's outlet. VOL_i [$\mathrm{m^3}$] means the total amount of potentially available bed-load at time step i. According to Eq. (4), VOL_i depends on the initially available amount of bed-load POT [$\mathrm{m^3}$] in the channel and the mass balance of incoming and outgoing sediment. By using Eqs. (1) to (4) the presented routing scheme is based on a non-graded bed-load transport approach.

$$\begin{array}{lll} \xrightarrow{\text{yes}} & \mathrm{TC}_i = 0 & \rightarrow\ \mathrm{OUT}_i = 0 \\ \downarrow_{\text{no}} & \quad\downarrow & \\ & \mathrm{TC}_i \le \mathrm{IN}_i & \rightarrow\ \mathrm{OUT}_i = \mathrm{TC}_i \\ & \downarrow & \\ & \mathrm{TC}_i \le \left(\mathrm{VOL}_{i-1}/\Delta t + \mathrm{IN}_i\right) & \rightarrow\ \mathrm{OUT}_i = \mathrm{TC}_i \\ & \downarrow & \\ & \mathrm{OUT}_i = \mathrm{VOL}_{i-1}/\Delta t + \mathrm{IN}_i & \end{array} \tag{3}$$

$$\mathrm{VOL}_i = \mathrm{POT} + \Delta t\cdot\sum_{t=1}^{i}\left(\mathrm{IN}_t - \mathrm{OUT}_t\right),\quad \mathrm{VOL}_0 = \mathrm{POT} \tag{4}$$

Table 1. "Key section" parameters of the torrent catchments (a) to (o) and the river sections 1 to 13 of the receiving water course.

torrent catchments					receiving water course				
No.	catchment area [km^2]	"channel key section" gradient I_S [%]	width B [m]	bed-load potential POT [m^3]	No.	river section length [km]	"key section" gradient I_S [%]	width B [m]	bed-load potential POT [m^3]
a	16.62	6.0	8.0		1	0.95	20.0	5.0	zero
b	26.70	4.0	7.0	infinite	2	2.64	6.1	8.0	10 700
c	22.66	6.0	5.0		3	1.81	3.8	7.5	zero
d	2.11	28.0	2.5	4000	4	1.20	4.0	8.0	4000
e	4.89	6.0	2.5		5	0.81	3.6	8.0	
f	3.40	9.0	2.5		6	1.64	3.7	8.0	
g	10.92	5.5	5.0		7	1.63	4.3	8.0	
h	8.19	13.0	5.0		8	2.54	5.8	8.0	
i	17.29	8.0	6.0	infinite	9	2.06	5.8	7.0	zero
j	1.67	19.0	1.0		10	0.98	5.0	9.0	
k	8.78	20.0	5.0		11	1.23	2.3	10.0	
l	5.43	20.0	4.0		12	0.82	2.3	12.0	
m	2.92	14.0	3.5		13	0.14	2.0	14.0	
n	5.80	12.0	4.0						
o	1.98	30.0	1.5	2400					

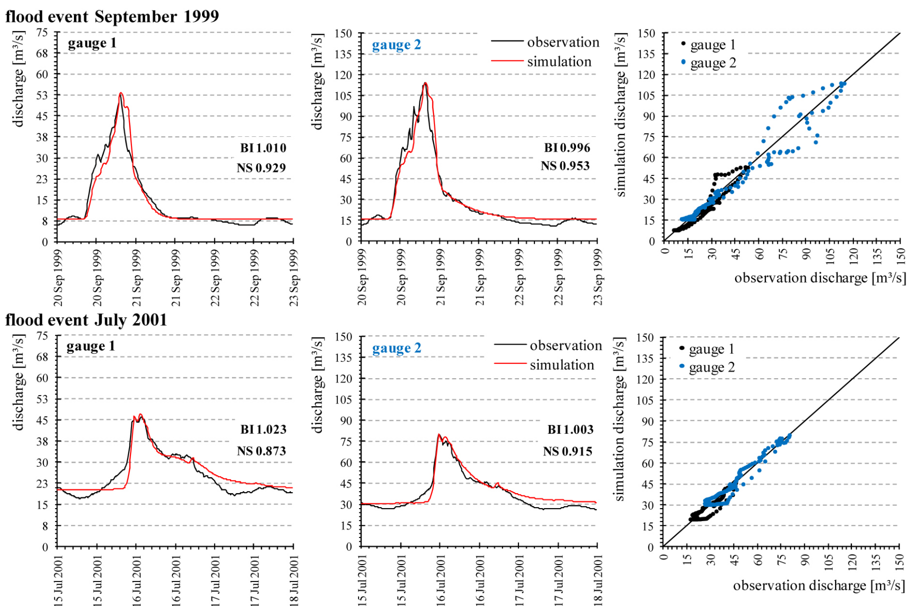

Fig. 2. Hydrological model calibration – comparison of observed (black) and simulated (red) discharge hydrographs at the gauges 1 (black) and 2 (blue) for the flood events in September 1999 and July 2001; BI [–] (e.g. Achleitner, 2008) represents the Bias of the flood peaks, NS [–] is the Nash-Sutcliffe-coefficient (Nash and Sutcliffe, 1970) of the discharge hydrographs.

Discharge and bed-load data of both the hydrological-1-D-hydrodynamic model and the bed-load transport routing scheme are temporally discretised with a constant time step $\Delta t = 15$ min. The definition of the "key sections" and the corresponding grain parameters d_{50}, d_{65} and d_{90} result from a field survey and grain samples respectively. For the parameters POT the general assumptions of an infinitely high amount of sediment in the torrent catchments and zero values for the receiving water sections underlie the computations (Table 1). Though, the torrents (d) and (o) are limited to a certain bed-load potential and the river sections (2) and (4) feature an erosion layer on the river bed (Table 1).

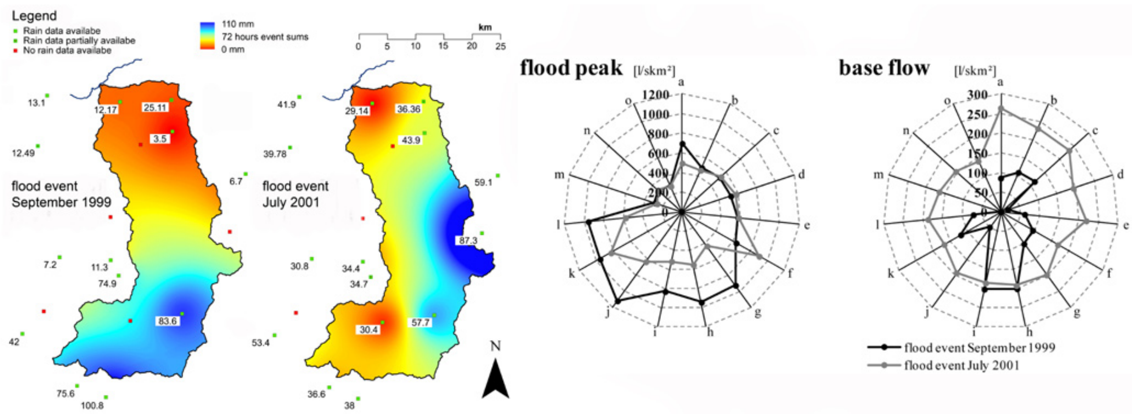

Fig. 3. Left: rainfall distribution in the Ötz-valley – regionalization for the flood events in September 1999 and July 2001 (squared inverse distance weighting, 72-h event sums) with measurement data of 18 rain gauges; right: flood peaks and base flows at the outlet of the torrents (a) to (o) resulting from the hydrological model.

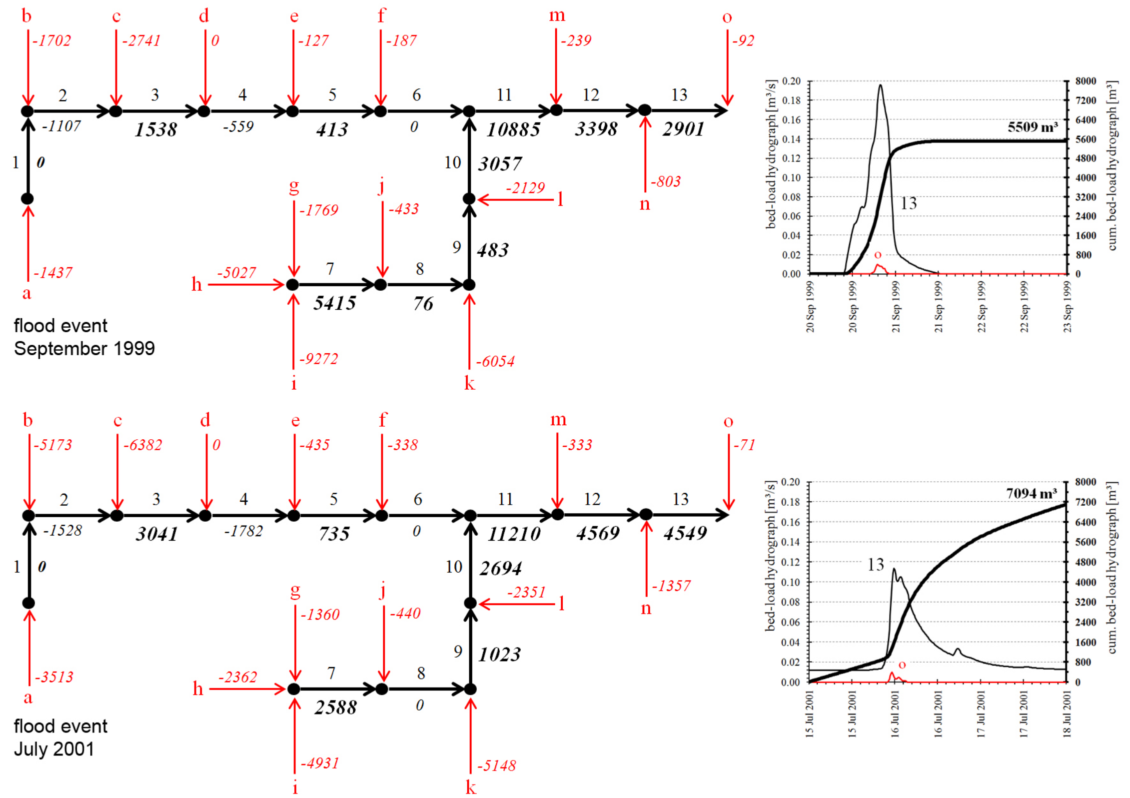

Fig. 4. Left: bed-load routing scheme applied to the case study area – final states of erosion and deposition (VOL_{end} – POT [m^3]) within the routing sections (red... torrent catchments; black... receiving water course) for the flood events in September 1999 and July 2001; right: bed-load hydrographs (OUT_i [$m^3\,s^{-1}$]) and cumulative hydrographs ($\Sigma_i OUT_i$ [m^3]) at the outlet.

4 Results and discussion

Figure 2 contains the results from hydrological model calibration using the measurement data at the gauges 1 and 2. The flood events from September 1999 and July 2001 are considered, each with a simulation period of 72 h. According to the bias BI [–] (e.g. Achleitner, 2008) of the flood peaks and the Nash-Sutcliffe-coefficients NS [–] (Nash and Sutcliffe, 1970) of the hydrographs the model fits the reference data very well. The BI-values range within 0.996 and 1.023, whereas NS amounts to values between 0.873 and

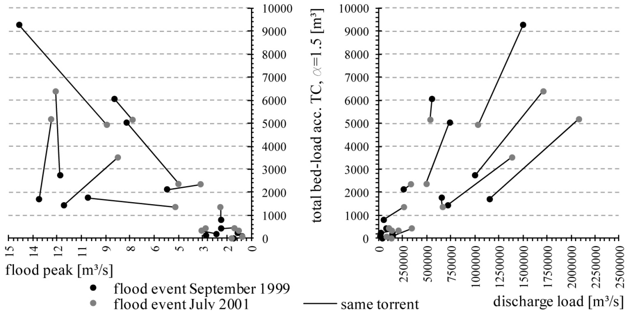

Fig. 5. Model results for the torrents (a) to (o) and the flood events from September 1999 and July 2001 – left: flood peaks vs. total bed-loads according TC [$m^3\,s^{-1}$] with $\alpha = 1.5$; right: discharge loads vs. total bed-loads according TC with $\alpha = 1.5$.

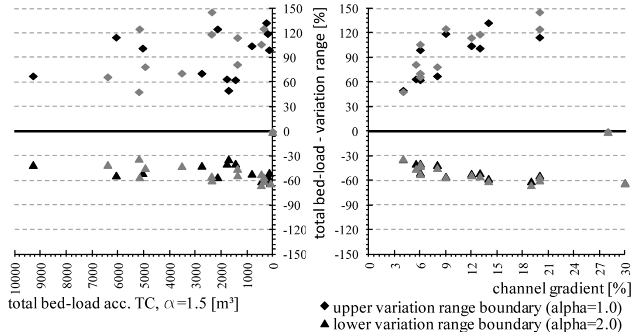

Fig. 6. Model results for the torrents (a) to (o) and the flood events from September 1999 and July 2001 – left: percentage-wise variation of the expectable total bed-loads according TC [$m^3\,s^{-1}$] ($\alpha = 1$ and $\alpha = 2$), depending on the total bed-loads according TC with $\alpha = 1.5$ (Eq. 5); right: percentage-wise variation of the expectable total bed-loads according TC ($\alpha = 1$ and $\alpha = 2$), depending on the channel gradients I_S (Eq. 5).

0.953. Both flood events were predominantly induced by rainfall. Therefore, the application of the SCS-CN-procedure combined with the non-physical approach for the consideration of snow melt processes lead to good results. The 2001-hydrographs illustrate that the latter causes a certain attenuation of the hydrograph's falling limb. Snow- and glacier-covered catchment areas serve as detention storage. It's curve numbers are considerably lower than those of the snow-free catchments, whereas the lag times are at least an order of magnitude higher. Figure 3 shows the rainfall-distributions in the entire Ötz-valley for the two considered flood events (left) and the flood peaks and base flow conditions of the torrent catchments (a) to (o) (right). The geostatistic analysis displays the 72-h rainfall sums. Based on a significant difference in the spatial characteristics in general, the amount of rainfall within the case study area in the rear part of the Ötz-valley is considerably higher for the flood event in September 1999. Likewise, the flood peaks in the torrent catchments are higher in September 1999 – they range between 288 $L\,s^{-1}\,km^{-2}$ and 1120 $L\,s^{-1}\,km^{-2}$. The peaks in July 2001 are in the range between 267 $L\,s^{-1}\,km^{-2}$ and 906 $L\,s^{-1}\,km^{-2}$. However, due to the larger extent of snow-covered area and thus the higher mean daily water flow in July 2001, a higher base flow occurred at that time (Fig. 3, right).

Some basic results of the bed-load transport routing scheme are illustrated in the Figs. 4, 5 and 6. Figure 4 gives an overview on the routing procedure and contains the final states of eroded and deposited bed-load within the routing elements. Further, the bed-load hydrographs leaving section (13) and torrent catchment (o) – the sum of both hydrographs is equivalent to the hydrograph at the outlet – and the cumulative bed-load curves at the outlet are displayed. A total amount of 5500 m^3 leaves the case study area during the 1999-flood, whereas in July 2001 the total load is 7100 m^3. Due to the higher base flow conditions in July 2001, the total bed-loads are higher, even though the observed flood peaks are about 29 % smaller than the peak discharges in September 1999 (Fig. 2). As a consequence of the small transport capacities TC in the river sections (3), (7), (10), (12) and (11) in particular, significant amounts of bed-load are deposited there in both events. The total amounts of mobilized bed-load within the case study area are 33 800 m^3 (September 1999) and 37 500 m^3 (July 2001). The specific transported bed-loads account for 188 $m^3\,km^{-2}$ and 209 $m^3\,km^{-2}$.

Figure 5 illustrates the model results for the torrents (a) to (o). In the left diagram the flood peaks of the different torrents are plotted against the total bed-loads according TC with $\alpha = 1.5$, whereas in the right diagram the relation of discharge loads and total bed-loads according TC with $\alpha = 1.5$ is shown. The diagrams show that an increase in bed-load is not exclusively dependent to any of the flood-wave-characteristic parameters. The spatial variability of the 72-h rainfall event sum, the fractions of snow- and glacier-covered areas and as well the "key section" parameters I_S, B, d_{50}, d_{65} and d_{90} lead to a statistical spread. For this reason and due to the fact that there is no measurement data available for calibrating the bed-load transport model the expectable bandwidths of the total bed-loads are determined by varying the calibration parameter a within the reasonable range $1.0 \leq \alpha \leq 2.0$. Figure 6 shows the variation when applying $\alpha_i = 1.0$ and $\alpha_i = 2.0$ in Eq. (5).

$$\text{variation range boundary}[\%] = \frac{100 \cdot \left(\mathrm{TC}_{\alpha_i} - \mathrm{TC}_{\alpha=1.5}\right)}{\mathrm{TC}_{\alpha=1.5}}$$
$$\begin{cases} \text{upper range} \;\rightarrow\; \alpha_i = 1.0 \\ \text{lower range} \;\rightarrow\; \alpha_i = 2.0 \end{cases} \tag{5}$$

In the left diagram the expectable variation range is set in relation to the total amounts of bed-load according $\mathrm{TC}_{\alpha=1.5}$, whereas in the right diagram the variation range bears on the channel gradient I_S. Based on the results with $\alpha = 1.5$, deviations between −70 % and +150 % have to be expected. A relation of the variation range with the amounts of bed-load according $\mathrm{TC}_{\alpha=1.5}$ is actually not evident. However, the variation range tends to increase with increasing channel gradient I_S.

5 Conclusions

Flood causing storm events in alpine regions are characterized by a distinct spatial variability of precipitation such as shown in Fig. 3, left. The application of a distributed hydrological model, which is further linked with a hydrodynamic model, on the case study area proved to be a well adapted approach when considering mainly rainfall-induced flood events. The non-physical consideration of snow and glacier melt processes on the basis of satellite data is a pragmatic methodology for event-specific models, when initial parameters for snow or glacier melt models are not available. Nevertheless, it has to be noted that melting processes are merely considered in a qualitative manner therewith. A lifelike representation of the physical processes needs indeed more complex approaches.

The presented modelling concept for hydrology, hydraulics and flood-related bed-load transport is developed for the application to large alpine valleys. The implemented equations for the calculation of bed-load transport rates, critical discharges, and reduced channel gradients account for the hydraulic characteristics of steep slopes. The consideration of drag forces is of high relevance. It leads to a significant difference between I_{S} and $I_{\mathrm{S,red}}$ and thus to smaller transport rates. The spatial characteristic of the transport processes is reproduced well with the routing scheme. It allows both the assessment of the transport rates leaving the case study area and the determination of sections tending towards erosion or deposition.

As a basic result of the model application to the case study area ($180\,\mathrm{km}^2$) in the Ötz-valley, flood-specific amounts of bed-load passing the catchment's outlet were determined with $5509\,\mathrm{m}^3$ and $7094\,\mathrm{m}^3$. A total of $188\,\mathrm{m}^3\,\mathrm{km}^{-2}$ and $209\,\mathrm{m}^3\,\mathrm{km}^{-2}$ were mobilized within the catchment thereby. These results for bed-load transport could not be calibrated indeed. Though, they were checked for plausibility on the basis of a detailed field survey and measurement data from neighbouring or similar catchments in the Austrian Alps (Klenkhart & Partner Consulting ZT GmbH, unpublished data).

The spatial discretisation by representing sub-catchments with "key sections", the determination of the topographic parameters I_{S} and B, the grain parameters d_{xx} and as well the choice of equations for the transport calculations strongly affect the obtained results. Besides the given parameter uncertainties the bed-load transport computations often suffer from missing calibration data. Thus, being aware of the sensitivity of the obtained model results is highly recommended. Parameter variations and further equations should be tested within this context in order to gain realistic bandwidths for the expectable amounts of bed-load.

Acknowledgements. The presented work originates from a research project funded by alpS – Centre for Climate Change Adaptation Technologies and the Austrian Research Promotion Agency (FFG). ILF – Consulting Engineers and the TIWAG – Tiroler Wasserkraft AG were acting as firm partners thereby. Support was further achieved by Klenkhart & Partner Consulting ZT GmbH. The authors are grateful for the chance to work on this topic.

Edited by: K. Schneider and S. Achleitner
Reviewed by: two anonymous referees

References

Achleitner, S.: Modular Conceptual Modelling in Urban Drainage – Development and Application of City Drain, Forum Umwelttechnik und Wasserbau, Band 3, ISBN: 978-3-902571-64-9, Doctoral Thesis, University of Innsbruck, 2008.

Achleitner, S., Huttenlau, M., Gems, B., Stötter, J., and Aufleger, M.: Sensing the uncertainty of cumulative flood damages due to varying flood peak distribution functions in a monte-carlo based damage modelling framework, Proceedings of the first European IAHR Congress, Edinburgh, 2010.

Bathurst, J. C.: Flow resistance estimation in mountain rivers, J. Hydraul. Eng.-ASCE, 111, 625–643, 1985.

Bathurst, J. C.: Measuring and modelling bedload transport in channels with coarse bed materials, in: River Channels – Environment and Process, edited by: Richards, K., Blackwell, Oxford, 272–294, 1987.

Braun, L. and Weber, M.: Droht im nächsten Sommer Hochwasser vom Gletscher? Rundgespräche der Kommission für Ökologie der Bayrischen Akademie der Wissenschaften (BAdW), 2002.

Canovaro, F. and Solari, L.: Dissipative analogies between a schematic macro-roughness arrangement and step-pool morphology, Earth Surf. Proc. Land, 32, 1628–1640, 2007.

Chiari, M., Friedl, K., and Rickenmann, D.: A one-dimensional bedload transport model for steep slopes, J. Hydraul. Res., 48, 152–160, 2009.

Faeh, R., Müller, R., Rousselot, P., Vetsch, D., Volz, C., Vonwiller, L., Veprek, R., and Farshi, D.: System Manuals of BASEMENT, Version 2.1. Laboratory of Hydraulics, Glaciology and Hydrology (VAW), ETH Zürich, available at: http://www.basement.ethz.ch, last access: May 2012.

Friedl, K. and Chiari, M.: TOMSED – A one-dimensional bedload transport model for steep slopes, Manual TOMSED v0.0, 2011.

Gems, B.: Entwicklung eines integrativen Konzeptes zur Modellierung hochwasserrelevanter Prozesse und Bewertung der Wirkung von Hochwasserschutzmaßnahmen in alpinen Talschaften – Modellanwendung auf Basis einer regionalen Betrachtungsebene am Beispiel des Ötztales in den Tiroler Alpen, Forum Umwelttechnik und Wasserbau, Band 13, ISBN: 978-3-902811-53-0, Doctoral Thesis, University of Innsbruck, 2012.

Gems, B., Achleitner, S., Huttenlau, M., Thieken, A., and Aufleger, M.: Flood Control Management for an Alpine Valley in Tyrol – an Integrated Hydrological-Hydraulic Approach, 33rd IAHR congress, Vancouver, ISBN: 978-90-78046-08-0, 1779–1786, 2009.

Hafner, N. and Fürst, J.: Hydrologischer Atlas Österreichs – Bodenbedeckung, 2007.

Hydrographischer Dienst in Österreich: Hydrographisches Jahrbuch von Österreich 2007, 2009.

Klenkhart & Partner Consulting ZT GmbH: Ausbau Kraftwerk Kaunertal – FB Feststoffe, Teil 1 – Geschiebefrachten an den beiden Wasserfassungen Vent und Obergurgl, report on behalf of the TIWAG – Tiroler Wasserkraft AG, unpublished.

Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I – A discussion of principles, J. Hydrol., 10, 282–290, 1970.

Pagliara, S. and Chiavaccini, P.: Flow resistance of rock chutes with protruding boulders, J. Hydraul. Eng.-ASCE, 132, 545–552, 2006.

Palt, S. M.: Sedimenttransportprozesse im Himalaya-Karakorum und ihre Bedeutung für Wasserkraftanlagen, Doctoral Thesis, University of Karlsruhe, 2001.

Peticzka, R. and Kriz, K.: Hydrologischer Atlas Österreichs – Bodenübersichtskarte, 2007.

Rice, C. E., Kadavy, K. C., and Robinson, K. M.: Roughness of Loose Rock Riprap on Steep Slopes, J. Hydraul. Eng.-ASCE, 124, 179–185, 1998.

Rickenmann, D.: Bedload transport capacity of slurry flows at steep slopes, VAW-Proceedings 103, 1990.

Rickenmann, D.: Geschiebetransport in steilen Gefällen, VAW-Proceedings 174, 2005.

Rickenmann, D.: Modellierung von Murgängen und Sedimenttransport in Wildbächen, Tagungspublikation zum 1. Departmentkongress Bautechnik und Naturgefahren, University of Natural Resources and Life Sciences Vienna, Ernst & Sohn, 29–35, 2007.

Rickenmann, D., Chiari, M., and Friedl, K.: SETRAC – A sediment routing model for steep torrent channels, River Flow 2006 – Proceedings of the International Conference on Fluvial Hydraulics, Lisbon, 843–852, 2006.

Rickenmann, D., Hunzinger, L., and Koschni, A.: Flood Events and Sediment Transport during the Rain-Storm of August 2005 in Switzerland, Interpraevent 2008, 465–476, 2008.

Smart, G. M. and Jäggi, M. N. R.: Sediment Transport on Steep Slopes, VAW-Proceedings 64, 1983.

US Department of Agriculture (USDA): National engineering handbook, Section 4 – Hydrology, Washington DC, 1985.

Whittaker, J. and Jäggi, M.: Blockschwellen, VAW-Proceedings 91, 1986.