Bedload transport simulation with the model sedFlow: application to mountain rivers in Switzerland

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ABSTRACT

The sedFlow simulation model for one-dimensional calculations of discharge and bedload transport was applied to five Swiss mountain rivers. After calibration it was capable of reproducing the observed bedload transport behavior reasonably well in the study rivers. For most simulations, the variable power equation (VPE) was used together with a reduced energy slope for the bedload transport calculations. The simulations with the Rickenmann (2001) transport equation were found to be suitable for simulation periods including a major flood event. The Wilcock and Crowe (2003) equation, a reference shear stress based approach, resulted in better agreement with long-term observations of bedload transport with only moderate peak flows. Using scenario simulations for a flood event, the effect of important lateral sediment input from tributaries due to debris-flow activity was investigated, indicating that bedload transport along the main river is mainly altered near the tributary locations.

KEYWORDS

bedload transport; 1D model; mountain river; Switzerland

INTRODUCTION

In alpine environments, bedload transport processes are dynamic and complex compared to lowland streams. Although there is a strong need for modelling tools in scientific and engineering applications, bedload transport in mountain streams is still relatively poorly understood. Field observations indicate that river bed morphology and thus hydraulic processes become increasingly complex as channel gradients become steeper. The range of observed grain diameters becomes larger, which entails more complex grain–grain and grain–flow interactions as well. Examining a large dataset on flow velocity measurements in steep streams, Rickenmann and Recking (2011) concluded that a considerable part of the river's shear stress is consumed by turbulence due to complex bed morphology, summarized as macro-roughness. They proposed an procedure to quantify the impact of macro-roughness on bedload transport, which resulted in a better agreement between calculated and observed bedload transport in mountain streams and torrents (Nitsche et al., 2011).

The sedFlow model for the one-dimensional simulation of discharge and bedload in a rectangular channel was developed at the Swiss Federal Research Institute WSL to assess river

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bed morphodynamics and bedload transport on the catchment and reach scale in mountain rivers (Heimann et al. 2015a, 2015b; Heimann, 2014). The sedFlow model was applied in five Swiss mountain rivers, for which information on past bedload transport was available. The objective of this contribution is to present selected results and to discuss our experience with sedFlow.

MODEL CHARACTERISTICS AND INPUT REQUIREMENTS

The modelling tool includes the following main features: (1) consideration of state of the art approaches for the calculation of bedload transport in steep channels accounting for macro-roughness; (2) bedload transport calculation for several grain diameter fractions separately i.e. fractional transport; (3) fast calculations for modelling transport in complete catchments and for performing scenario studies with automated calculation of many variations.
A detailed description of the model structure and the numerical implementation is given by Heimann et al. (2015a). Using a simplified calculation procedure for the flow hydraulics, the sedFlow model can also simulate the effect of large sediment inputs by debris flows from tributaries.

The required input parameters are the longitudinal channel profile, channel widths along the study reach, grain size distributions of the bed surface and subsurface sediment, and stream discharge. Typically, a calibration is made by varying the channel parameters such as grain size distribution and possibly channel width, if the width of a river reach is not naturally incised or constrained by lateral levees. In addition, different modelling options have to be defined: selecting a flow resistance equation, a bedload transport formula, the threshold for initiation of transport and the thickness of the sediment exchange layer at the bed surface.

In sedFlow the stream channel is approximated by a rectangular profile; together with the Manning-Strickler equation, an analytical solution for the implicit flow routing using the kinematic wave approach is used, which results in fast calculation times. For steep streams with shallow flows it is recommended to use the variable power equation (VPE) of Ferguson (2007) (Rickenmann and Recking, 2011), and then the analytical solution for the implicit flow routing cannot be applied. Therefore, the VPE flow resistance calculation must be combined for example with explicit routing, but this requires relatively long computation times. An alternative option in sedFlow is to use of VPE together with a simplified hydraulic calculation, assuming constant flow per time step in channel reaches without lateral inflow. This model version results again in fast calculation times, and for (strong) lateral sediment inputs adverse channel slopes in the longitudinal profile are possible. For the application of sedFlow in the Brenno River it was found that a simplified backwater calculation produced similar bedload transport results as when using an implicit flow routing based on the kinematic wave approach. For the Kleine Emme, however this method of calculation resulted in substantially different, less plausible simulation results than the calculation with kinematic wave. The generally steeper channel reaches in the Brenno could be the reason that the simplified hydraulic calculation produced plausible results there. The model version combining the VPE with the simplified hydraulic calculation was used for all study rivers except for the Kleine Emmer River.

The flow resistance calculations with the VPE used coefficients $a_1 = 6.5$ and $a_2 = 2.5$ as proposed both by Ferguson (2007) and Rickenmann and Recking (2011). A shear stress based bedload transport equation proposed by Rickenmann (2001) was used, modified for fractional transport calculations (Heimann et al. 2014a). To account for macro-roughness energy losses, a reduced energy slope was applied, based on an approach of Rickenmann and Recking (2011) and following a procedure described in Nitsche et al. (2011). Some calculations were also performed using the Wilcock and Crowe (2003) bedload transport equation, in combination with a reduced energy slope.

STUDY CATCHMENTS AND SELECTED RESULTS OF MODEL APPLICATIONS

The sedFlow model was applied to five Swiss mountain river catchments (Table 1). The best observations related to bedload transport were available for the Kleine Emme and the Brenno Rivers (Böckli et al., 2015c, 2015e). From consecutive surveys of river cross-sections, the net erosion and deposition along the longitudinal profile was derived, and additional information on gravel extraction and/or important sediment delivery from tributaries during the study period helped to constrain the total sediment budget (Rickenmann et al., 2014a; Heimann et al. 2015b). For the other three study catchments information of past bedload transport was less detailed (Böckli and Rickenmann, 2015; Böckli et al., 2015b, 2015d), for example with observed bedload volumes in a hydropower reservoir (Ferden at the Lonza River) or a sediment retention basin (Grosse Schliere). Below we summarize some results of our modelling experience.

Effect of changing input parameters and transport equations

The sedFlow model was first calibrated for the Kleine Emme and the Brenno mountain rivers over a study reach length of 20 km and 22 km, respectively. It produced a reasonable replication of the observed bedload transport for a five and ten year period, respectively (Rickenmann et al., 2014a; Heimann et al., 2015b). The Kleine Emme simulations included the extreme 2005 flood event (Rickenmann and Koschni, 2010) which resulted in substantial bedload transport due to important sediment input by bank erosion.

The simulations with sedFlow showed that, in addition to choosing a suitable bed load transport formula, the minimum value for the critical dimensionless shear stress (Shields number) for beginning of bedload transport is also important for calibration. The critical Shields number is used with the transport formula of Rickenmann (2001), whereas a suitable reference shear stress has to be selected with the transport formula of Wilcock and Crowe (2003). The reference shear stress, which is comparable to the critical Shields number, can be varied by choosing the sand fraction of the surface bed material. Overall, the choice of the

Table 1: Characteristics of the five study catchments.

	Kl. Emme	Brenno	Hasliaare	Lonza	Gr. Schliere
Catchment area (A) [km²]	478 (A)	397 (A)	554 (A) / 531 (B)	78 (A) / 131 (B)	27 (B)
Mean elevation [m a.s.l.]	1050	1820	2150	2630	–
Length simulation reach	19.4	21.8	17.2	9.5	11.6
Mean channel slope [%]	0.8	2.6	3.8	4.7	7.7
Sills or check dams	yes	no	no	no	yes
Channelized reaches	yes	no	few	no	few
Hydropower use	little	strong	strong	no	no
Tributaries with sed. input	no	yes	yes	yes	yes
Gauging stations	2	1	1	1	0 (C)

(A) area upstream of FOEN gauging station (Kleine Emme, Brenno, Hasliaare)
(B) area upstream of most distal point of simulation reach (Hasliaare, Lonza, Grosse Schliere)
(C) discharge data from the neighboring catchment Kleine Schliere was used and adapted

Shields number was important for the model calibration, particularly regarding the general level of bedload transport. The finally selected (optimized) Shields numbers were found to be in a plausible range, when compared with data from a recent field study on the beginning of bedload transport (Bunte et al. 2013). To best replicate the longitudinal pattern of net erosion and net deposition, only the grain size distribution along the river was optimized (in a plausible range) in the case of the Kleine Emmer River, and only the representative channel width was optimized (in a plausible range) for the depositional reaches in the Brenno River.

For the simulation of the flood event 2011 in the Lonza, the transport formula of Rickenmann (2001) resulted in plausible results, also when using different hiding functions (which govern the fractional transport behavior). Here is an exponent of 1.5 was used in the calculation of the reduced energy slope. For the Lonza long-term simulations were made for the period 1976 to 2013, for which the cumulative sediment transport into the Ferden reservoir is known for 19 separate survey periods. During this period only one major flood event occurred in 2011. For the sedFlow simulations using the formula of Rickenmann (2001), the bedload transport was clearly overestimated (by about a factor of 10), even when varying the critical Shields number and the energy-slope exponent (Fig. 1).

Using the transport formula of Wilcock and Crowe (2003) with an energy-slope exponent of 1.5, resulted in similarly plausible results for the 2011 event as the formula of Rickenmann (2001). For the long-term simulations of Lonza, the transport formula of Wilcock and Crowe (2003) also yielded plausible results when either the sand fraction was set to 0.05 (high reference shear stress), or when a sand content of 0.20 (low reference shear stress) was used with an energy-slope exponent of 2 (Fig. 1). This result is not so surprising in the sense that a reference-based bedload transport equation can be expected to be better suited for weak to moderate bedload transport conditions. In fact, the bedload transport formula of Wilcock and Crowe (2003) in combination with a reduced energy slope and an exponent of 1.5 was found to provide reasonable agreement with field measurements of weak to moderate bedload transport over a wide range of channel conditions (Schneider et al., 2015).

<u>Effect of lateral sediment input</u>

The sedFlow model was applied to a 17 km long study reach of the Hasliaare River. There, several important debris-flow events occurred in tributaries during the last decade. In August 2005 a large debris-flow event occurred in the Rotlauibach, a torrent catchment upstream of the village of Guttannen, and deposited a total volume of 500,000 m³ on the fan and in the main valley (Böckli et al., 2015d). After the 2005 event, sediment deposits with a thickness of about 1 m and a volume of about 15,000 m³ were observed in the Hasliaare channel at Innertkirchen, which is situated some 8 km downstream of the Rotlauibach. After calibration, the sedFlow model was able to replicate the observed deposition at Innertkirchen.

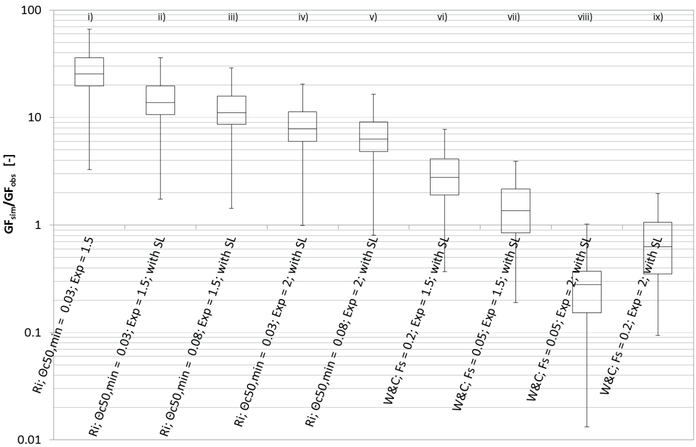

Figure 1: Long-term simulations for the period 1976-2013 in the Lonza River without any major flood event. (GFsim/GFobs) is the ratio of simulated to observed bedload volume in the reservoir Ferden. Shown are results for different combinations of transport formulas (Ri: Rickenmann, 2001; W&C: Wilcock and Crowe, 2003), different Shields numbers (***θc50***), different sand fractions (Fs) and different energy-slope exponents (Exp). Simulations labelled "SL" were performed with a coarser layer of surface material. The box plots represent the variation over the 19 survey periods. The boxes include the median value and are limited by the upper and lower quartile. The whiskers indicate the maximum and minimum value.

Extremely high debris-flow activity was observed in the Spreitgraben tributary in the period 2009 to 2011, delivering a total of about 590’000 m³ into the Hasliaare River. Surprisingly only a very small part of this sediment was transported further downstream. Over six kilometers downstream of the Spreitgraben tributary, the sedFlow model predicted a strong decrease in bedload transport capacity, in qualitative agreement with the observations (Rickenmann et al., 2014b).

The delta of the Hasliaare was surveyed repeatedly from 1905 to 1938 (Böckli et al., 2015d). From these data and accounting for fine material, we estimate the bedload supply to the Lake of Brienz to be about 40,000 to 70,000 m^3/a. This amount is supported by geochronologic dating of the sediments in the alluvial plain between Meiringen and Lake of Brienz for the past 500 years (Carvalho and Schulte, 2013). Simulation results of bedload transport in the Hasliaare for entire years predicted an annual sediment delivery to the lake of Brienz which is in agreement with these observations (Rickenmann et al., 2014b).

Scenarios of increased sediment input due to future debris flows from five tributaries were defined for further simulations. The basis was a flood hydrograph as in August 2005 with a peak flow of about 350 m^3/s at the downstream end of the simulation reach, and a channel width of the order of 10 to 20 m. The simulation results show that both continuous (Fig. 2) and instantaneous (Fig. 3) lateral sediment input changes the bedload transport in the Hasliaare over a length of about 1 to 2 km both upstream and downstream of the active tributary. It can be observed that both the magnitude and the timing of the debris-flow inputs with regard to the duration of the flood event in the Hasliaare River have an important effect on the local bedload transport along the main river. An early input results in a larger decrease upstream and a larger increase downstream of the active tributary; more time is available for a reduction or increase of the bedload transport. The effect on the debris-flow deposit in the immediate confluence area tends to be greater, the later the sediment input occurs during the floods, while some distance further upstream an early entry may lead to more deposition.

CONCLUSIONS

After calibration, the sedFlow simulation model was capable of reproducing the observed bedload transport behavior reasonably well in five Swiss mountain rivers. For most simulations, the variable power equation (VPE) was used together with a reduced energy slope for the bedload transport calculations. The simulations with the Rickenmann (2001) transport equation were found to be suitable for simulation periods including a major flood event. The Wilcock and Crowe (2003) equation, a reference shear stress based approach, resulted in reasonable agreement with long-term observations of bedload transport for a 37 year period in the Lonza River with only moderate peak flows. Using scenario simulations for a flood event, the effect of important lateral sediment input from tributaries due to debris-flow activity was investigated. These simulations indicated that bedload transport along the main river is mainly altered near the tributary locations, suggesting that the transport further downstream may require multiple floods or longer flow durations.

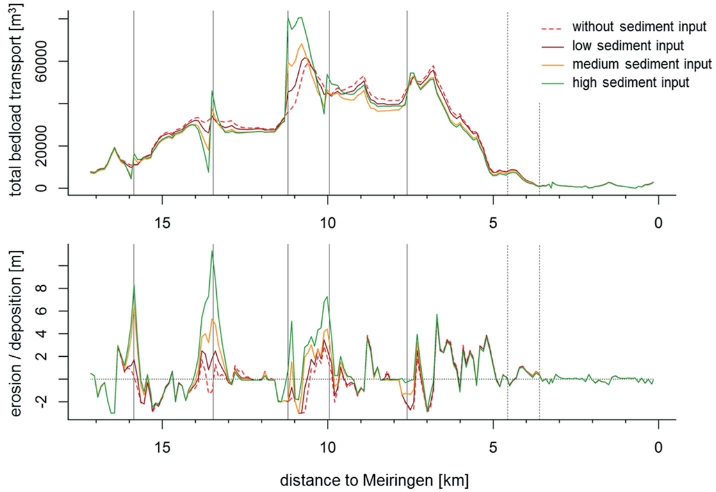

Figure 2: Simulated bedload transport in the Hasliaare River for the case of continuous sediment input from five tributaries. The simulation reach extends from Handegg (km 17) to Meiringen (km 0). A flood event as in August 2005 was simulated, and a total sediment input of 31000 m³ (low), 90000 m³ (avg.), 165000 m³ (high) due to debris flows from five tributaries (indicated by vertical solid lines in the graph) was assumed. Results are shown for different magnitudes of the debris-flow inputs during the flood event in the Hasliaare River. The vertical dotted lines indicate the location of the village Innertkirchen.

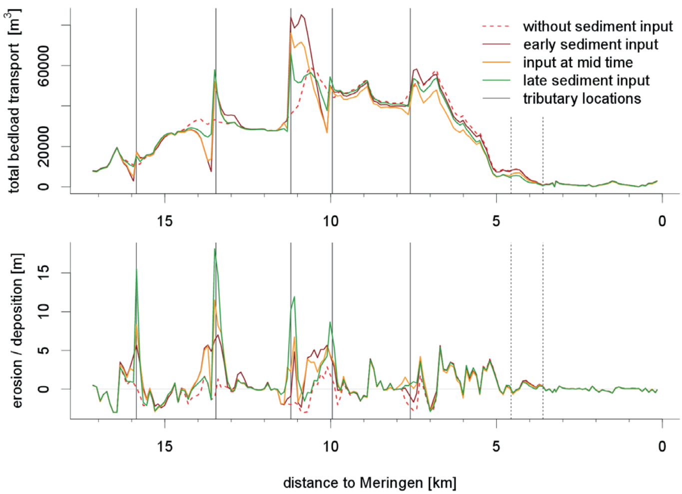

Figure 3: Simulated bedload transport in the Hasliaare River for the case of instantaneous sediment input from five tributaries. The simulation reach extends from Handegg (km 17) to Meiringen (km 0). A flood event as in August 2005 was simulated, and a total sediment input of 165,000 m³ due to debris flows from five tributaries (indicated by vertical solid lines in the graph) was assumed. Results are shown for different timings of the debris-flow inputs during the flood event in the Hasliaare River. The vertical dotted lines indicate the location of the village Innertkirchen.

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