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APPLICATION OF A TWO-DIMENSIONAL NUMERICAL MODEL IN RISK AND HAZARD ASSESSMENT IN SWITZERLAND

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ABSTRACT

In Switzerland a well-established method for debris flow hazard assessment is in use. However the method requires delineation of endangered areas by the expected intensity for a given return period. For this reason there is a strong need for process-based models to improve the quality of hazard mapping and for planning and evaluation of mitigation measures. In this paper, we present the application of a Swiss modeling system for rapid mass movements. The RAMMS debris flow model is a two-dimensional model for simulating the runout distance, velocity, flow depth and impact pressure of debris flows. It uses the single-phase Voellmy fluid friction relation which describes the debris flow resistance as a combination of a dry Coulomb-type friction and a viscous resistance which varies with the square of the flow velocity. The model solves the depth-averaged shallow water equations for granular flows in 2D using a finite volume scheme. We present two case studies in which RAMMS was used by practitioners as a support tool in hazard management and planning mitigation measures. The first site is located in Stechelberg in the western Swiss Alps and the second one in Walchensee, Bavaria (Germany). In both examples RAMMS was found to provide valuable support for practitioners.

Key words: *hazard mapping, hazard assessment, debris flow modelling*

INTRODUCTION

Debris flows are persistent natural hazard for people and infrastructure in mountainous regions (Rickenmann *et alii*, 1993; Zimmermann *et alii*, 1997). To improve hazard mapping as well as planning and evaluation of mitigation measures against debris flows, there is a strong need for process-based models. Hazard maps in Switzerland show expected intensities and return periods of dangerous processes for a certain area or location by a detailed outlining of areas where construction of buildings must be prohibited or where rules and recommendations should be established (Petrascheck & Kienholz, 2003).

In Switzerland debris flow hazard assessments in residential areas are carried out by a well-proven method (BWW *et alii*, 1997). Endangered areas are classified into one of five classes of equal degree of hazard which are assigned a color on the final map: high hazard (red), medium hazard (blue), low hazard (yellow), residual danger (yellow-white striped) and no or negligible danger according to current state of knowledge (white or uncolored). A high precision delineation of endangered areas is thought to be attainable and leads finally to a hazard map.

An allotment to a hazard zone is often associated with far reaching consequences for building owners. In areas with medium danger, local protection is required when planning construction projects, whereas in areas of high danger there is normally a prohibition on construction (Petrascheck & Kienholz, 2003;

BWW *et alii* 1997). This leads to a financial devaluation of land for construction or existent buildings and therefore significant financial losses for landowners and communities. Hence it is essential for practitioners to accurately establish in particular the boundaries of red and blue danger levels.

Different approaches exist to assess impact areas of potential debris flows. In addition to computer-aided methods (e.g. Huggel *et alii*, 2003; Gamma, 2000) practitioners in Switzerland often apply the "method of flow paths". In doing so, hazard areas are delineated directly in field based on flow paths delineated by topographic features. In the same work step intensities and debris accumulation are usually assessed, leading to the definition of an intensity scenario and the associated hazard level. An inspection of the catchment as well as a proper definition of breakout and sediment delivery scenarios are required.

Nevertheless practical experience shows that an exact determination of flow paths is a major challenge, mainly in the case of complex topography together with vegetation, the consideration of frictional parameters as well as the inclusion of mitigation measures such as sediment retention basin or deflection dams. In addition, calculations to determine process intensity such as flow velocity or flow heights have to be carried out, typically using empirical estimation formulas (e.g. Rickenmann, 1999).

Whereas different models for assessing mud flow inundation and rock fall activity are available (e.g. O'Brien *et alii*, 1993; Brunner, 2010; Tobler *et alii*, 2009), calibrated and well-established debris flow models are scarce. Existing models are only partially suited for detailed hazard assessment because they are based either on probabilistic or topographic approaches (e.g. Gamma, 2000; Huggel, 2003) and are applied mainly for small-scale hazard assessment in terms of hazard index maps.

Particularly in topographically complex situations, there is a strong need for models, which can not substitute for an expert's opinion, but which surely may provide considerable support.

First we describe the Swiss method of hazard assessment, followed by a description of the Swiss modeling system RAMMS which was designed partially with this goal in mind, and subsequently, we present two case studies in which RAMMS was used to support practitioners in debris flow hazard assessment.

PROCEDURE

Generally a well-established method of hazard assessment in Switzerland (i.e. Petrascheck & Kienholz, 2003) was carried out for the case studies presented in the following. The method consists of the following steps:

1. Hazard identification and analysis (including analysis of previous events and assessment of spatial parameters such as flood discharge or potential volume of debris. The potential debris volume is based on geomorphic analysis methods which have been systematically developed for use in Switzerland. In this paper, the method proposed by Lehmann (1993) was used for the case study at Mattenbach and the method introduced by Gertsch (2009) was used for the case study at Walchensee (see chapter case studies).
2. Definition of event scenarios for a certain return period.
3. Hazard assessment derived from scenarios, and additionally the impact analysis.

This method, the sequences and the detailed description of the steps can be taken from BWW et al. (1997). The three common scenarios in Switzerland provided a basis for the Mattenbach (see chapter case studies), described in the following:

- 30 years scenario: return period of 30 years or less.
- 100 years scenario: return period of 30 to 100 years.
- 300 years scenario: return period of 100 to 300 years.

To describe the catchment area in the Walchensee case study the 300 years scenario was not considered. Depending on the case study, the following steps were added to the described procedure:

- assessment and definition of model parameters to carry out RAMMS.
- calculation using a 2D debris flow model (RAMMS).
- Considering planned measurements in hazard assessment.

For every single scenario an intensity map was generated. The intensity map shows the expected spatial intensity of debris flow hazard. Examples will be described later in this paper.

RAMMS RUNOUT MODEL

The RAMMS model was initially developed as a tool to assist practitioners for solving snow avalanche runout problems which could not be solved with existing 1D runout models. The Voellmy friction relation used to describe the motion of flowing snow has also been used to describe the motion of debris flows (e.g. Revellino *et alii*, 2004; Rickenmann *et alii*, 2006), the main difference being the density of the materials and the typical values of the friction coefficients. The initial application of RAMMS to debris flows was tested largely in the framework of research theses written by students (e.g. Scheuner, 2007).

Here, we briefly describe the governing equations which are solved in the RAMMS model. Additional details on the RAMMS model, including further remarks on the equations and their numerical solution are available in Christen *et alii* (2010) and Preuth *et alii* (2010). The model is based on a finite-volume solution to the depth-averaged equations of motion for granular flows:

$$\partial_t H + \partial_x (HU_x) + \partial_y (HU_y) = 0 \quad (1)$$

$$\partial_t (HU_y) + \partial_x (HU_x^2 + g_z \frac{H^2}{2}) + \partial_y (HU_x U_y) = S_{gx} - S_{fx} \quad (2)$$

$$\partial_t (HU_y) + \partial_x (HU_x U_y) + \partial_y (HU_y^2 + g_z \frac{H^2}{2}) = S_{gy} - S_{fy} \quad (3)$$

where H is the flow depth, U is the velocity, g is the gravitational acceleration; Sg is the driving gravitational; and S_f denotes the frictional resistance, with subscripts x and y indicating the quantities in the x and y directions. RAMMS uses the Voellmy friction approach, which splits the total friction into a velocity-independent dry Coulomb term which is proportional to the normal stress at the base of the flow (friction coefficient μ) and velocity-dependent so-called turbulent or viscous friction (coefficient ξ). The Voellmy relation can be written (analogously in both the x and y directions):

$$S_f = g_z H\mu + \frac{g_z U^2}{\xi} \quad (4)$$

In an optimal case, μ (–) and ξ (m s^{-2}) are selected to best match data from historical events. When data are not of sufficient quality to permit calibration, μ is typically initially selected to be the same as the local slope on the area where debris flows have stopped in the past, and then ξ is selected to provide plausible velocities which may be based on existing observations, back-calculated flow velocities estimated by geomorphic methods (such as super-elevation around channel bends).

CASE STUDY MATTENBACH

OBJECTIVE

The mountain torrent Mattenbach is situated in Stechelberg, a part of the political community of Lauterbrunnen in Switzerland (Fig. 1). In the upper part, the catchment mainly consists of limestones (lower cretaceous of the Doldenhorn nappe). The middle and the lower part consists of Malm limestones (Mesozoic autochthonous of the Aar massif). The lower most part (debris fan) consists of alluviums of the Mattenbach as well as the river Lütschine.

According to the Swiss permafrost map (Foen, 2005) the upper part of the catchment probably contains permafrost.

On a regular basis, the Mattenbach delivers damage-causing floods and debris accumulations within the Matta settlement of Stechelberg, most recently in 2004. The channel has to be maintained almost every year, resulting in costs of several thousand Swiss francs (oral communication by R. Janzi in 2009). Former events are known from 1929, 1987, 1997 and 2001 (Geotest AG *et alii* 2003).

The hazard map of the Mattenbach was initially generated in 2001 (Geotest AG *et alii*, 2003) then revised in 2009 (Geotest AG, 2009). Part of the settlement is categorized into the blue hazard zone; the areas close to the channel and a community road were assigned to the red hazard zone. Debris flows initiating in the upper catchment area are considered to be the most dangerous hazard. If debris flows reach the fan apex they may cause lateral overbank flow of water and sediment, carry driftwood and cause floods at both sides of the fan. Moreover sedimentation may jam the channel cross section and clog bridge cul-

Fig. 1 - Study area Mattenbach (red line), Stechelberg (community of Lauterbrunnen), Switzerland (Reproduced by permission of swisstopo BA100660)

Turbulent friction μ [-]	0.1
Dry friction coefficient ξ [m/s^2]	200
Density [kg/m^3]	1,900

Tab. 1 - Parameters for model calculations with RAMMS

verts alongside the channel. These processes may also cause overbank flooding and debris flow deposition (Geotest AG, 2009).

To assure protection of the Matta settlement, a debris retention construction was planned in 2009 with a retention capacity of 1,900 m^3. Cost-efficiency was an important constraint. Therefore the retention construction was optimized with regard to the retention volume. Compared to the maximum potential debris volume (Tab. 2) the construction is not capable to stop all of the total debris load. It is possible that, due to topography, part of the debris load may leave the channel above the retention construction (Geotest AG, 2009).

The construction of an additional protection or deflection dike respectively to prevent debris flow outbursts above the planned debris retention construction was considered. Due to expected costs, this measurement was not planned any further.

The only objective of this case study was to evaluate the impact of the described partial retention of debris on the hazard areas after completion of the debris retention construction. The aim was to analyze in which manner the missing protection dike influences the endangered area (e.g. changes in the hazard map). The hazard map shown in Figure 2 was already finished and published before modelling with RAMMS. The RAMMS model was solely used to support the expert's opinion with the objective to obtain repeatable model results and to confirm therewith the assumed hazard areas after the protection measures were completed. The evaluation was mandated by the local water authorities.

FIELD EVIDENCE AND PARAMETERS FOR RAMMS

The catchment of the Mattenbach with an area of 1.4 km^2 extends from the summit of the Schwarzmönch (2,648 m a.s.l.) to its outlet into the river Lütschine (900 m a.s.l.). It mainly consists of rock faces and debris slopes. Between the rock faces and the alluvial fan we find a section covered with grass and bush vegetation. Here part of the channel runs on loose material. On the fan apex, there is significant

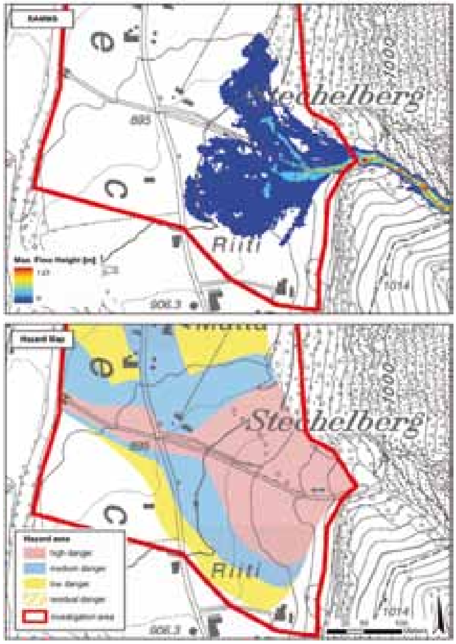

Fig. 2 - Debris flow modelling with RAMMS and hazard map , 300-years scenario (Map UP5© Office for Geographical Information Canton Bern)

evidence of former debris accumulation. The channel is steep, except of the section from the fan apex downwards. It is evident that the torrent is able to form debris flows (Geotest AG *et alii*, 2003).

The models decisive parameters were derived from the expert's opinion according to his experience from other debris flow events at similar catchment areas. In this manner the slope's friction parameter and the density of potential debris flows have been roughly assessed (Tab. 1). After completion of the first debris flow modeling, the estimated parameters were refined by on site mapping of debris accumulations at the slope.

SCENARIOS

Based on the on site inspections by Lehmann (2005) and Geotest AG *et alii* (2003) as well as the estimations by Geotest AG (2009) the expected debris load was determined for every return period (Tab. 2).

Based on Table 2, the scenarios for the Mattenbach hazard assessment were defined as follows:

- 30-years scenario: It is expected that the total amount of debris will be retained by the sediment retention basin (Tab. 2). Neither hydraulic nor

Information on debris	30-years events	100-years events	300-years events
Potential debris (Lehmann 2005, GEOTEST AG 2009)	900	2,200	2,500 – 3,000
Accumulation from fan apex to planned debris retention construction (estimations according to Lehmann, 2005)	400	400	400
Decisive debris load in to debris retention construction (difference) (Lehmann, 2005)	500	1,800	2,100 – 2,600
Planned volume of retention construction (Bettschen & Blumer AG, 2009)	1,900	1,900	1,900
Difference, debris not held by the retention construction	0	0	200 – 700
Debris flow outbursts above the planned retention construction at orographic right side of the cone*	Not probable	probable	probable
Failure points below the planned debris retention construction.	none	none	Entire channel incl. channel bed and bridge at the main road.

Tab. 2 - Amount of debris of the Mattenbach (all data in m³)

technical problems with debris are to be expected near the channel and the bridge at the altitude of 895 m a.s.l. This scenario was not calculated with RAMMS.

- 100-years scenario: During a 100-year event debris flow outbursts above the planned sediment retention basin construction at the orographic right side of the cone are possible. It is expected that most of the debris load can be held back by the sediment retention basin (Tab. 2). There are no failure points located below the sediment retention basin. To calculate the model with RAMMS we took a single debris flow surge of a size of 300 m^3.
- 300-years scenario: The sediment retention basin essentially stops the debris and reduces the peak discharge. It is able to hold a maximum load of 1,900 m^3 debris. Sediments from 200 to a maximum of 700 m^3 can flow out of the sediment retention basin and end up in the channel. Debris flow outbursts above the planned sediment retention basin at the orographic right side of the cone are expected to deposit their debris load on parts of the farmland. Debris flows do not affect residential buildings (Figure 2). To calculate the model with RAMMS we took a single debris flow surge of a size of 700 m^3. Most of the debris is expected to be transported as far as the bridge at 895 m a.s.l. or is deposited at the left side of the cone. Sedimentation of approx. 270 m^3 in the channel is expected up to the culvert at the altitude of 895 m a.s.l.. Due to the higher bank at the right waterside debris and water can not leave the channel to the orographic right side and do not affect the Matta settlement. Debris flows can leave the channel at the left side of the cone. It is very probable that debris and flood material will block the bridge. Large amounts of debris and water discharge near the bridge at the altitude of 895 m a.s.l. are expected.

HAZARD ASSESSMENT

The hazard assessment was carried out by the method described in chapter "Procedure". As described above, RAMMS was used to support the assessment of possible outbursts at the fan apex. As a basis, a high precision digital terrain model with a 2x2 m grid was used. The altitude-accuracy is 0.5 m (swisstopo, 2005).

The modelling results with RAMMS (Fig. 2) show that outbursts to the right side of the fan apex are still possible, even when the protection measures are built. Additionally, the modelling shows that outbursts to the orographic left side of the fan apex are possible as well. The hazard map shown in Figure 2, published before the RAMMS modelling was carried out, shows a correct, but more spacious classification of the red and partially of the blue hazard zone. Most part of the blue and yellow hazard zones are not shown in the results of RAMMS modelling due to a process change from debris flow to overbank sedimentation and inundation. This process change had to be delineated in the field by the expert's opinion and cannot be modelled within the RAMMS model.

CONCLUSION

In this case study it is evident that calculations with the RAMMS model led to a comprehensible and transparent decision making. The modelling results with RAMMS show that an outburst is likely for both sides of the fan apex. Hence, the modelling results support the experts opinion derived from the "method of flow paths" and the conclusion of the hazard map shown in Figure 2. The model served as a support tool for the

Fig. 3 - *Study area Reissenwand, Walchensee (Bavaria, Germany)*

expert in evaluating the necessity of a deflection dam near the fan apex. The model indicates that the flows are expected to stop above the settlements and that substantial quantities of the debris load will not reach the residential area. Therefore, the previously described additional reflection dam was deemed unnecessary and planning was stopped. This led to lower costs for the construction of countermeasures and therefore to financial savings for the community.

CASE STUDY WALCHENSEE

INTRODUCTION

The high traffic road between Walchensee and Urfeld (Bavaria, Germany) is endangered by debris flows from the so-called Reissenwand (Fig. 3). On behalf of the local authorities a detailed hazard assessment was carried out followed by the design of protective countermeasures. Model calculations were made using RAMMS as a support tool.

FIELD EVIDENCE AND PARAMETERS FOR RAMMS

The catchment area of the assessed channel reaches from the forest covered Rauchkopf crest at the altitude of 1,380 m a.s.l. down to the Walchsee at the altitude of 800 m a.s.l. Below the steep scarp at the Reissenwand the channel runs on bare rock, then the channel runs through massive slope debris accumulations resulting from intensive rock fall out of the Reissenwand. The sediment accumulations constitute a large debris reservoir

Upon the well-defined debris cone the channel is deeply cut into the slope (up to 3 m deep). Beyond the channel the debris cone is covered with vegetation. With a short distance above the road there are large, small-grained debris flow heads. They are evidence that the channel is active in terms of debris flow processes.

Turbulent friction μ [-]	0.15
Dry friction coefficient ξ [m/s^2]	125
Density [kg/m^3]	1,900

Tab. 3 - *Parameters for model calculations with RAMMS*

30 years	100 years
2,200 – 2,500 m^3	6,800 – 7,100 m^3

Tab. 4 - *Estimated potential debris for 30-years and 100-years scenario*

On one hand the decisive model parameter were deduced from grain analysis and on the other hand based on experienced data from other debris flow events (Scheuner, 2007). By this means the friction parameters and the density of potential debris flows were estimated (Table 3). We subsequently refined the estimated parameters based on information on mapped traces from debris flow deposits at the slope

SCENARIOS

The amount of potential debris was estimated according to the method of Gertsch (2009), which is based on observed patterns and tendencies and was calibrated with the experienced and limiting values of 58 debris flow events. This method is an empirical, system based and strongly process oriented estimation procedure. The debris load calculation is made for single homogenous channel sections where slope and channel processes are distinguished.

Table 4 shows the estimated debris load for the corresponding return period.

There are two critical points along the investigated channel. After a steep section of the channel (> 60%) running on bare rock, there is a distinct shift in direction of the channel axis at the fan ape, where bank erosion and the potential for overbank flow endanger the orographic right side of the cone. Similarly, shortly before the forest, the channel may change its position (channel slope < 20%), leading to a new flow path towards the road. Such channel avulsions and consequent directional changes are expected especially when the channels slope is low and sediment is deposited (e.g. Zimmermann *et alii*, 1997).

HAZARD ASSESSMENT

30-years scenario

In this case, no debris flows endanger the road directly (Figure 4). The decisive sediment deposition occurs below the flat section (channel slope < 20%) where the flows run out at the altitude of 860 m a.s.l. Only small amounts of debris are expected to reach the forest. Small grain diameter sediment loads and water may reach the road and by flowing through the forest mobilize leaves and branches as well, which may cause jams at the culvert and therefore initiate flooding of the road (depth of inundation < 0.5 m).

100-years scenario

Debris flow discharge affects large sections of the road (Figure 4). The debris accumulation may be up to 1m high. It is expected, that large areas above the road will be covered by debris, because the flow velocity is strongly reduced by the presence of forest and long flat reaches, and a forest road. Moreover it is possible that debris flow leave the channel and fan out above the forest. Trace of previous events on the slope support this scenario.

Due to the results from the modelling with RAMMS as well as from the empirical verification with estimation formulas in common use, higher flow velocities have to be expected at the altitude of 950 m a.s.l. The reasons why we expect this phenomenon are the decisive declination of the channel (> 60%) as well as the long channel section running on bare rock. We expect flow velocity of up to 8 m/s. These circumstances facilitate bank erosion. Together with morphological and topographical characteristics of the debris fan as well as blockages caused by bank failures, an outburst at the fan apex and a debris flow further south of the main direction is possible. Changes in topography during a debris flow (bank failures, erosion processes) are not yet incorporated in RAMMS. Therefore, notwithstanding the modelling results (Fig. 4) the southern part of the fan is potentially endangered, as is the northern part. Such a debris flow on the southern part of the fan apex may follow the still visible former debris channel down to the road

PROTECTION MEASUREMENTS

Here, only one possible protection measurement for events with a return period of 100 years will be described. Events with a return period of 30 years do not endanger the road and therefore only protection measures preventing road flooding have to be taken into account (especially maintenance of the culvert).

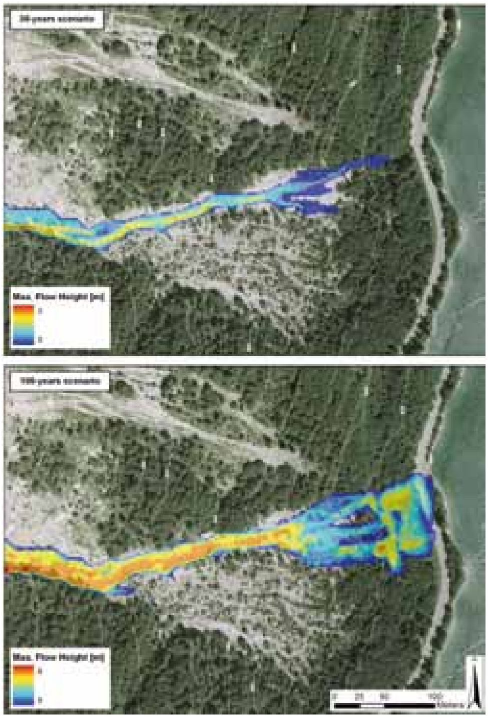

Fig. 4 - Debris flow modelling with RAMMS for 30- and 100-years scenario

The road is endangered by debris flow events with a probability of occurrence of 100 years. A wedge shaped retention dam may be capable of holding back debris above the road. Water will be drained off controlled by a culvert (concrete pipe). To prevent jams during frequent events an appropriate debris screen has to be installed above the culvert. In this case plain water can be drained of over the peak of the dam in a controlled manner.

Flow velocity was calculated by RAMMS and is low (< 3 m/s) , mainly due to a low slope (< 20%). Therefore the dynamic impact is expected to be small, however debris accumulation will certainly elevate the static stress. Due to back-filled material behind the retention dam debris deposits are expected to accumulate up to 2 m thickness. Besides flow velocity and height of deposition, the weight of the back-filled material and the energy-impact of a debris flow impacting on the dam have to be taken into consideration.

At the upper part of the cone, a smooth stone embankment may protect the orographic right side of the bank from erosion. By this means the probability of channel outbursts can be minimized.

CONCLUDING REMARKS

The two case studies, Mattenbach and Walchensee have illustrated that RAMMS is a useful support tool for experts evaluating natural hazards. The model results provide estimates of flow paths, maximum flow depths and velocities. Using these results, it is possible to estimate the dynamic forces for use in evaluating the dimensions of protection measures.

Additionally, the model is useful for providing additional support on the application of simple empirical formulas often used in hazard assessment and may lead to an additional degree of certainty in the results, especially in cases where model verification with good-quality field data is possible.

However no model is a replacement for field work or for the estimation of parameters necessary for hazard analyses, and in any case field inspections are necessary to establish the plausibility of model results. In the discussed case studies we found that a process change from debris flow to inundation can hardly be represented by the modelling system. The flood-prone areas had to be delineated in the field by an expert's assessment. Furthermore channel-bed or bank erosion is not yet incorporated. Due to this constraint it is not possible to assess break-out points solely by the modelling system.

The RAMMS model is under further development for the eventual general release to practitioners in the field. Additional developments, currently in the testing phase, include the possibility to use an input hydrograph instead of a block release, and to include the influence of channel-bed erosion on the flow properties.

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