Debris-flow recognition using an extended version of the river basin simulation model

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ABSTRACT: The objective of debris-flow hazards mitigation is to develop a reliable simulation model for monitoring, recognition, and urgent warning of debris flows. Discussed herein is the 2D Debris-Flow Simulation Model (DFSM), which was developed from the original 2D River Basin Simulation Model (RBSM). The novelty of the DFSM lies in its ability for the local multiple-increase of the stream flow rate under several threshold conditions. The continued mapping of the debris-flow processes in a river basin using the DFSM is aimed to facilitate the recognition of debris flows. The DFSM was preliminarily calibrated and verified for one of the Caucasian basins in Russia. Features and conditions for implementing the DFSM in such a case study are discussed.

1 INTRODUCTION

An object of the study is an active river basin. External pressure and impacts by precipitation and air temperature, which are further combined with various geomorphologic conditions, determine water and sediment flows throughout a basin. Having such flows in a basin implies that a basin is a non-equilibrium natural system, which is subjected to the threshold of sediment movement. Continued estimation of water and sediment flows is the objective of the original 2D River Basin Simulation Model (RBSM) (Klenov 2000a). The RBSM was verified and applied to some basins with a spatial resolution from 10 m for a small tributary of the Moscow River to 1 km for the Moscow River upstream, and far up to 8 km for the Rhine Basin. The RBSM was also validated in the Moscow River Basin using the 20 years of daily records with satisfactory statistical criteria, and with small errors of flood discharge excess (no more than 20-40%). The RBSM was extended to a new model called the Debris-Flow Simulation Model (DFSM). The new feature of the DFSM is the local multiple-increase of the stream flow rate and the sharp rise of sediment transport capacity (Klenov 2000b, 2001). The DFSM was verified by comparing data on observed debris flows with computed results. After calibration, the DFSM has become a reliable computer tool for monitoring, recognition, and warning of debris flows.

Requirement for entering initial data in the DFSM is that the state of a basin under investigation must be represented inside the corresponding multi-layer 2D grid of square cells. The required data on meteorology and hydrology are their continued records for many years with a time step as small as desired. The grid-cell size and time step determines the resolution and sensitivity of the model. The major task for debris flow simulation is to generate a debris flow and then let it travel through a basin with combined geomorphologic and soil properties and under the excitation of heavy storms and/or rapid snowmelt. The computer mapping simultaneously animates the simulated debris flow, thereby making the debris-flow processes visible. The DFSM has been developed to the extent that the debris flow monitoring will be available in hazardous river basins. This paper is thus aimed to address issues on: (1) the notion that debris flow is one of the river-basin processes; (2) the calibration and verification of the DFSM for one of the Caucasian basins in Russia; and (3) the essential elements of the DFSM for application.

2 RIVER BASIN IN COMPUTER

To simulate any river basin in transit, a basin should be preliminarily written in the form of multi-layer grid. The grid of square cells includes input data on several coinciding layers, such as the basin elevation, spatial distribution of water depth, snow thickness, parameters of soil and rock, among others. The basin under investigation must be set inside a grid for the correct water and mass balance because a watershed prevents inflow from adjacent basins. Estimation for water and sediment flows through the basin is conducted in the following order: rainfalls and/or snow melt – overland flows on hill slopes – flows in streams and/or rivers. Water and sediment balance evaluation (Klenov 2000a, 2001) includes non-dimensional parameters for water exchange by precipitation, snowmelt, infiltration, evaporation, and air temperature, among others. A distributed delay of water flows is determined by a matrix (grid) of the retard coefficients varying between 0 and 1. The sources of debris material are the sites of low soil strength for moraine, slope depositions, and incoherent rock, and others. The parameter of the soil strength does not have an upper limit, but it is assigned a value between 0.1 for incoherent soil and 100 or more for monolith rocks.

A strictly restricted number of variables are the source of model uncertainties, but such restrictions are necessary because well-founded restrictions will make the model more operable. The initial values of the parameters are always assigned in case of insufficient data and demands for calibration. In practice, the values of the parameters are established empirically for the maps of data on vegetation, soil consistency, and geology, among other relevant information. The sediment transport capacity of water flows is an empirical function of slope inclination between source and neighboring target cells as well as that of surface water on both cells. The possible thickness of removed soil is limited by the initial thickness of shattered or incoherent soils and/or sediments. The current basin state is a sum of non-changeable grids of the parameters, and of changeable grids of the variables, such as water depth, snow thickness, soil erosion, and sedimentation. Most of the distributed parameters should be always made changeable.

3 TABLETOP COMPUTER MODEL IN ACTION

In each complete scanning of the grids, the water-mass exchange between all neighboring cells is calculated for a basin of any complexity. This calculation is aimed to provide the repeated simultaneous evaluation of water-mass flow balance between all bordering cells over the whole grids. Klenov (2000a, b) has developed an algorithm, referred to as the Evolution Matrixes Method (EMM), in which the calculation of flow is executed by a repeated scanning of the elevation matrix upon selection of the flow direction at each step of scanning. The EMM offers numerical operations for the whole grids using the desired accuracy within a time step. Spatial resolution is restricted by cell size.

Because of the necessity to understand the physical processes in debris flow, the visualization of the processes taking place in a basin was developed. The continued computer mapping of a basin maintains the continuous simulation of the processes for user's selected layer. All other layers are recalculated simultaneously in a grid/matrix form. A time step for mapping corresponds with that used in precipitation and air temperature records. The peculiarity of the mapping lies in the fact that the previous image is replaced cell-by-cell by the current image during the scanning, and resulted in a non-blinking animation. A visualized layer is transformed into contours by simplified fast raster vector reforming. The user defines contour steps. After any computing cycle, the model may be paused for any change in any cell at any layer. This makes the model convenient for calibration and flexible for making various scenarios. For example, local change(s) in the elevation simulate the dam (or channel) construction. The corresponding change in the local soil strength imitates the dam (or channel) strength.

The RBSM was validated for a flood simulation in the Moscow River upstream. Computed and observed daily discharges for the duration of 15 years were compared after having been calibrated on the other record for 5 years. Discussed below is the Debris-Flow Simulation Model (DFSM) extended from the RBSM (Klenov 2000b), in which the debris-flow processes are treated in addition to the existing processes. Both stream velocity and sediment transport capacity increases non-linearly under several conditions. Most debris flows are caused by a combination of the following attributes: steep slopes, focusing, and/or entrenching enlarged water streams (due to rainstorms and/or snowmelt), and the presence of incoherent sediments with low soil strength. Strong concentrated water inflows are mixed with debris/mud sediments to move most likely as a flow than as a solid body. The goal of the DFSM is to use it to identify debris-flow initiation and movement.

The following features and advantages of the DFSM over the RBSM motivated the modification of the RBSM:

First, the major restriction of the RBSM is a limit in the increase of the stream velocity. By contrast, the DFSM has the ability to increase the multiple local/linear flow rate of the water-sediment mixture.

Second, the corresponding layers for soil properties, such as water retardation, infiltration, and soil strength, in the DFSM are now arranged to depend on air temperature, snow-line dynamics, water content, and geomorphology conditions. For example, the distributed soil resistance parameter decreases nearby snow line when flows converge due to strong rainfalls and rapid snowmelt. The sites and lines of debris-flow initiation are recognized during the regular grid scanning. After having been initiated, a debris flow moves through a number of cells as far as the balanced conditions remain. In the surrounding basin, where the level of debris-flow threshold is not exceeded, the 'usual' RBSM algorithm calculates water/sediment flows.

Third, both 'lively' maps and generated graphs of the governing processes are combined to illustrate the spatial and temporal variation of the basin processes. Any map displayed usually consists of two or three layers in overlapping. The background is always the elevation contours. The other two layers are snow-cover thickness and water depth shown with contours in different colors. Elevation contours are seemingly stable with time because small changes at present are not visible, as shown in the separate summary (or current) layer of spatial erosion/sedimentation pattern. The generated graphs are placed on the right side of the computer image, where step-by-step data on the observed precipitation and observed air temperature are plotted. Plotted water discharge and sediment discharge are computed for an assigned site. The generated graphs are removed and the new ones refurnished each year. The duration of outside records must include one or more annual hydrology cycles because the state of a basin is determined by its history.

Fourth, based on the knowledge of geomorphology learned in several mountainous regions, debris flows are caused by the complex interaction of several processes. The major direct reason that debris flows are triggered is attributed to the confluence of strong flows from upstream and adjacent slopes. The other direct reasons are steep slopes with initially small or temporarily lower soil resistance, such as due to water penetration and 'greasing'. The indirect reason of debris-flow initiation is snow cover and snow line dynamics. Snow cover on the ground prevents winter debris flows because of reduction in the 'active' area. For example, a sharp rise in air temperature causes the rapid melting of snow cover, thus resulting in the so-called 'snow' debris flows. The DFSM also evaluates the process of snow displacement, which activates snow to move slowly down a slope due to slope steepness and snow cover thickness following the accumulation of snow in niches and canyon beds. The capability of modeling the avalanche processes has not yet been built in the

DFSM. The DFSM independently and continuously evaluates all processes in interaction with one another and using a high spatial resolution.

Fifth, the DFSM is elaborated in order to be sensitive to various kinds of debris flows upon combinations of several governing geomorphologic processes. The invaluable advantage of the DFSM lies in its ability to check continuously a basin for identifying sites where debris flows were initiated. The process of detecting, identifying, and tracking debris flows is made visible by marking the sites of debris-flow initiation. Such sites are marked in small squares, and colored in terms of flow activities. The DFSM simulates the fast movement of a debris flow(s) through a basin(s) on a background of the relatively slow water flows around debris-flow tracks.

4 CASE STUDY OF DEBRIS-FLOW SIMULATION

A case study was performed for debris-flow simulation in the Cubasanty basin (in Caucasus Mountains), a tributary of the river Baksan. The basin area is about 12 km^2. The elevation difference between the upstream top of the mountain and the river mouth is more than 2300 m. The total area of glaciers is 0.66 km^2. The spatial resolution for the 50 x 50 elevation grid is 100 m. The accessible data for the basin include dates on the former debris flows, incomplete daily records on air temperature and precipitation for 20 years at the nearest gauge station located outside the basin. Data on geomorphology includes the distribution of vegetation, moraines, soils, rocks, local sources of debris and mud, distances of travel, and approximate volumes of sediments (Seinova 1992, Seinova & Zolotarev 2001). Debris flows usually occur throughout the basin, and form the fan outside the basin. Regrettably, there is no existence of observed records on daily water and sediment discharges. The spatial correction for air temperature in terms of altitude is evaluated.

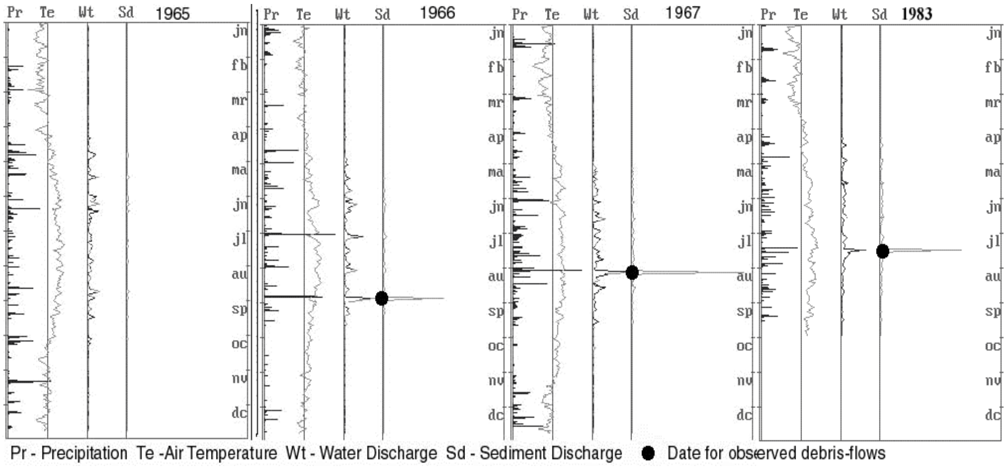

Figure 1. Verification of the DFSM by continuous daily simulation for subsequent several years.

The debris-flow simulation consists of two general steps. The first step is the calibration of the parameters using data for a period of two years (1965 – 1966). In 1965, debris flows did not occur. During 1966, one strong debris-flow event was observed. The task was to calibrate the parameters so that during 1965 the DFSM should not generate a false debris flow, yet during 1966 it should not miss the real one (Fig. 1). The second step is the verification of the DFSM by continuous daily simulation for the subsequent several years. As a result, the calibrated DFSM generated debris flows, which agree with the observed ones in terms of the time of occurrence (namely, the partial validation). For the subsequent 15 years, Seinova (1992) observed several debris-flow events, which coincide in time with simulated debris flows.

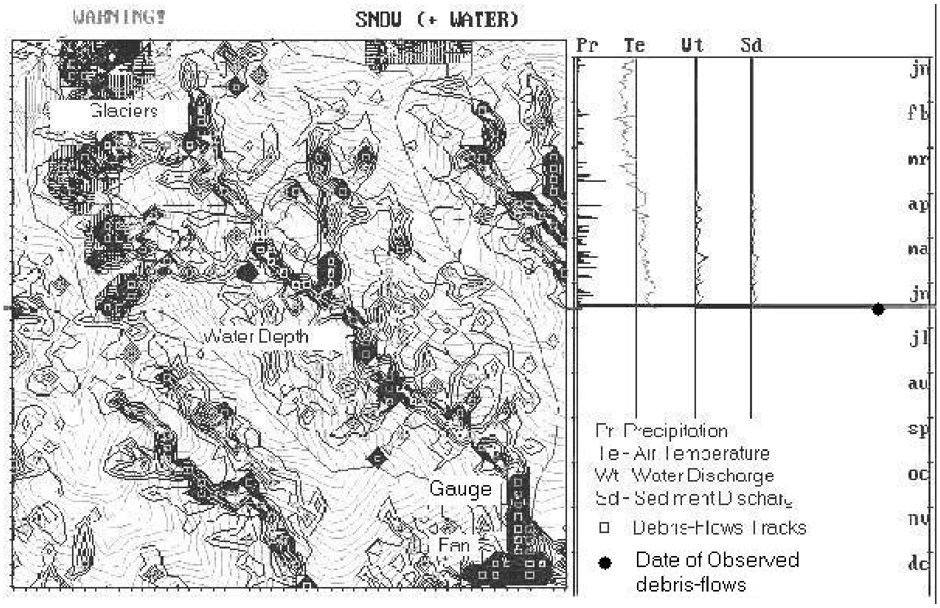

Figure 2. The simulated multi-source disastrous debris flows in the Cubasanty basin in June 2002.

The heavy 3-day rainstorms in the Baksan area in June 2002 resulted in many disastrous debris flows in the region. After having the tabletop DFSM calibrated for the case of the Cubasanty basin, the recent disastrous case in the Cubasanty basin was computed a posteriori. The initiation, sites, and tracks of debris flows were recognized and their processes were shown as a movie on the computer map (Fig. 2). The DFSM checked for all initiations of debris flows in the basin and tracked it. It is remarkable to see the whole basin 'on the move', which is often impossible to be realized in realty. The key feature of the DFSM is the multiple dissection of a time step during the threshold in the geomorphologic processes, which permits us to observe readily the dynamics of the debris-flow processes in detail.

It can be seen from Figure 2 that debris flows were initiated in all adjacent basins inside the study area. The activity of the debris-flow processes is shown by small squares in variable colors depending on the velocity. The continued mapping of the debris-flow processes also shows the process of a fan growth. The most debris material was removed from outside the basin. Actually, the debris-flow processes were seen in detail spatially and temporally. The observed (in the model) processes complicate the debris-flow movement due to the pulsation of the flow, locally strong sedimentation/erosion, and irregular building and cutting of temporary sediment jams. In fact, the task for reliable recognition 'in nature' for sites of possible sediment jams is difficult, and it needs more observed geomorphologic data. The pulsation of the debris flow was described in the literature (Seinova & Zolotarev 2001). A viable DFSM feature lies in its ability to recognize the sources of the debris-flow initiation and intensification. The instabilities and thresholds are the properties of the Opened Non-Equilibrium System (to which a basin belongs), which becomes enlarged with the escalation of the flow energy. When the DFSM identifies a site of the debris-flow initiation and if the stream velocity exceeds the threshold level anywhere in the basin, then the 'warning' signal appears.

A separate task is the simulation of scenarios to build checking dams for debris-flow hazards mitigation. A comparison of different scenarios to build dams was conducted. All tentative scenarios adopted in build checking dams for debris-flow mitigation resulted in the quick overflow of reservoirs by water and sediments, causing dams to break, which subsequently resulted in catastrophic floods. A similar disaster was observed in the Issyk Reservoir in the Northern Than-Chan in 1968.

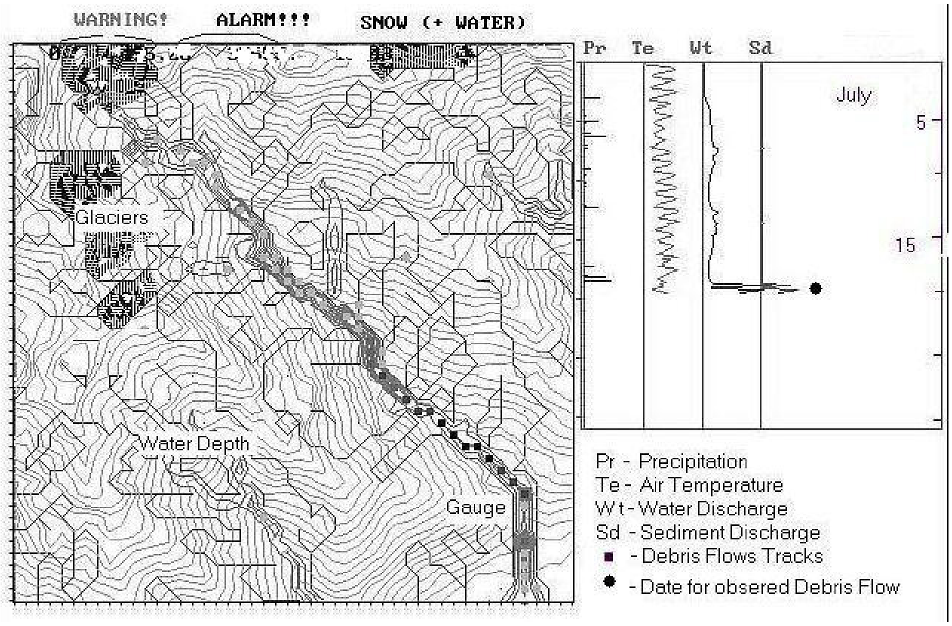

Figure 3. The simulated debris flow in July 1983 reached the Gauge with the ‘alarm!' signal.

Another attempt for simulating the Cubasanty basin processes has been made using the record of 3 hours resolution (Fig. 3) for the July 1983 debris flow. In this case, the corresponding graphs were refurnished for each of the subsequent months. Resulted in comparison was coincidence in date between the computed debris flow and the observed one. Also, the graph of the 3-hour step simulation coincided generally with that of the daily step computation for the same year (Fig. 1). The signal 'warning' appeared as soon as the hazardous process was detected far upstream of the basin. The signal 'alarm!' appeared when a high-speed debris flow reached the previously established vital site far downstream of the basin. The computed time between the 'alarm!' and 'warning' signals depended on whether the external impact on the basin was local or general and where the debris flow happened. In this case, it was less than one hour. This information was potentially vital, enabling habitants downstream to escape before the debris flow arrived.

5 CONCLUSIONS

The Debris Flow Simulation Model (DFSM) is capable for simulating high velocity water/sediment flows inside a basin, the latter being referred to as debris flows. The simulation of the Cubasanty basin by DFSM has resulted in satisfactory coincidence in the time (date) of occurrence between the computed debris flow and the observed debris-flow event without generating false debris flows or missing true ones. The DFSM possesses unique features in comparison with the River Basin Simulation Model (RBSM), which simulates relatively slow processes. By contrast, the DFSM has the potential of recognizing hazardous debris-flow events under no observed records of water and sediment discharges and even under only a daily step of meteorology records. Moreover, the DFSM can perceive and track debris flows in any part of a river basin in a cell-size resolution. Besides, the DFSM offers a study of a basin response to natural and human activities using provisional scenarios. Finally, the efficient separation of flows in several adjacent basins inside the common grid and the simultaneous evaluation of the processes in basins belong to DFSM properties. The complete validation of the DFSM must be provided by data on distributed meteorology, observed water and sediment discharges, high-resolution elevation grids, and numerical grids of the relevant parameters. In case of a single record of precipitation, the DFSM distributes it equally over the grids. In case of a single record of air temperature, the DFSM continuously corrects it for all cells, depending on the cell altitude.

The clear-cut advantages of the DFSM are as follows: (1) Installing the DFSM for any basin is equivalent to letting it act as a role of a portrait of the basin; (2) the DFSM can simulate scenarios which facilitate calibration; and (3) a skill for overlapping the mapping makes the DFSM flexible as a tabletop computer copy of a basin. The limitation of the DFSM is the ignorance of the distinction among transported materials, such as debris, metal, and mud, in the debris-flow processes. In one word, the DFSM as a whole is a simplified model of a complex system. It is thus suitable for preliminary use in monitoring and managing a basin with option to calibrate parameters in the simulation process.

Computer monitoring, recognition, and forecasting are expensive in view of the necessity for the continued input of a vast amount of the required temporal/spatial data on meteorology, water and sediment discharges, etc. However, their costs are small in comparison with those incurred by heavy economical losses and human casualties due to debris-flow hazards. Furthermore, it has been shown that the DFSM enables the computer modeling not only of the debris-flow processes in mountains, but also of the countermeasures against catastrophic floods caused by dam-break, etc.

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