

Article

Rainfall-Triggered Landslides and Numerical Modeling of Subsequent Debris Flows at Kalli Village of Suntar Formation in the Lesser Himalayas in Nepal

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Abstract: Hazardous debris flows are common in the tectonically active young Himalayas. The present study is focused on the recurrent, almost seasonal, landslides and debris flows initiated from Kalli village in Achham District of Nepal, located in the Lesser Himalayas. Such geological hazards pose a significant threat to the neighboring communities. The field survey reveals vulnerable engineering geological conditions and adverse environmental factors in the study area. It is found that a typical complete debris transport process may consist of two stages depending on the rainfall intensity. In the first stage, debris flows mobilized from a landslide have low mobility and their runout distance is quite modest; in the second stage, with an increase in water content they are able to travel a longer distance. Numerical simulations based on a multi-phase flow model are conducted to analyze the characteristics of the debris flows in motion, including the debris deposition profiles and runout distances in both stages. Overall, the numerical results are reasonably consistent with relevant field observations. Future debris flows may likely occur again in this area due to the presence of large soil blocks separated by tension cracks, rampant in the field; numerical simulations predict that these potential debris flows may exhibit similar characteristics to past events.

Keywords: debris flow; internal angle of friction; basal friction; deposition pattern; runout distance; numerical modeling



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1. Introduction

The collision of the Eurasian plate and Indian plate beneath the Himalayas along the fault line and the continuous movement of the Indian plate at almost 17 mm/year [1] have rendered the youngest mountains of the Himalayas tectonically very active. Because of the rugged mountain topography, complex and fragile nature geological structure, soft soil cover, high-intensity rainfall in monsoon season, and frequent earthquakes, the countries along the Himalaya including Nepal, India, and Pakistan are especially vulnerable to landslides, debris flows, erosion, and other mass wasting phenomena [2]. Many destructive landslides and debris flows take place every year in Nepal [3–6]. Case studies of landslides or debris flows in different parts of Nepal have been reported in recent years [7–10] and there is a growing interest in better understanding the characteristics of landslides or debris flows in this region.

A large number of debris flows are commonly observed in the Suntar Formation of the Far-Western Development Region of Nepal. Kalli debris flows in Achham District are among the major recurring landslide-mobilized debris flows in this region. However,

these landslides and debris flows in the Suntar Formation have not yet been extensively investigated. Interestingly, similar trends of repetitive occurrences of landslides and debris flows have been reported in some case studies conducted in other parts of Nepal as well as neighboring countries, which possess similar lithofacies to the Suntar Formation; these reported debris events include several incidents at Siddhababa along the Siddhartha Highway and at Jugedi Khola along the Narayanghat Muglin Road, as well as some events in the Dagshai Formation and in the Murre Formation of India and Pakistan, respectively [11–16]. However, these studies are mainly focused on the field conditions, influencing factors and potential triggering agents; there has been very little attempt at quantitative analysis or numerical modeling of debris flows in the region. In the present study, we aim to explore both field surveys and numerical simulations to study a typical landslide-mobilized debris flow, which recurs frequently during the rainfall seasons near Kalli village in this region.

There has been a plethora of numerical models developed to examine the mechanisms of debris flows and quantify their physical processes. The main challenge in various model development lies in adopting proper rheology to represent the distinctive behavior of various mass flows. Most of the early models developed were single-phase models, which generally adopted Newtonian, Bingham, or dilatant fluid rheology for what is considered predominantly fluid flow behavior [17–19]. Granular frictional flow models were proposed for coarse-grained dry mass flows [20–23], and visco-plastic models for dense granular flows have also been developed [24]. A mixture approach has also become popular to describe the overall behavior of debris material as a whole, with various relevant models being developed [25–28]. Pudasaini [29] proposed a two-phase modeling framework to consider the solid phase and fluid phase simultaneously in the motion of the debris material and incorporate many essential physical aspects of mass flows; it was recently expanded into a multi-phase model with the introduction of an additional fine solid phase and this allows more complex material behavior to be considered in the modeling of the flow process. Since the debris flow mechanism is very intricate, determining the values of input parameters for such complex flows and phases is typically very challenging. There are very scarce resources devoted to the ranges of input parameters for such multi-phase models. The present study attempts to determine the input parameters through back analysis of past debris flow events.

The overall scope of the present study revolves around the recurring, almost seasonal, geological hazards that constantly plague the communities in this region; it is aimed to identify the key factors and explore quantitative numerical models to simulate the flow processes. A multi-phase mass flow model is employed for back analysis of past debris flows that occurred in the study area. Various flow characteristics including deposition pattern, runout distance, and impacted area are examined numerically. Numerical simulations based on the calibrated modeling parameters are also explored to assess their possible triggers and impact for potential future debris flows. These relevant parameters obtained from the back analysis of the present study can also serve as important references for further investigations as well as in the assessment of present events of debris flow hazards in this region.

2. Study Area

The study area is located in the middle mountains of the young Himalayas in the border area of the Surkhet and Achham districts of Nepal (Figure 1); it is in the proximity of the Karnali river. The coordinates of the initiation point of the major landslide that later mobilized the debris flows are 28.93° N, 81.34° E, in Kalli village of Achham District.

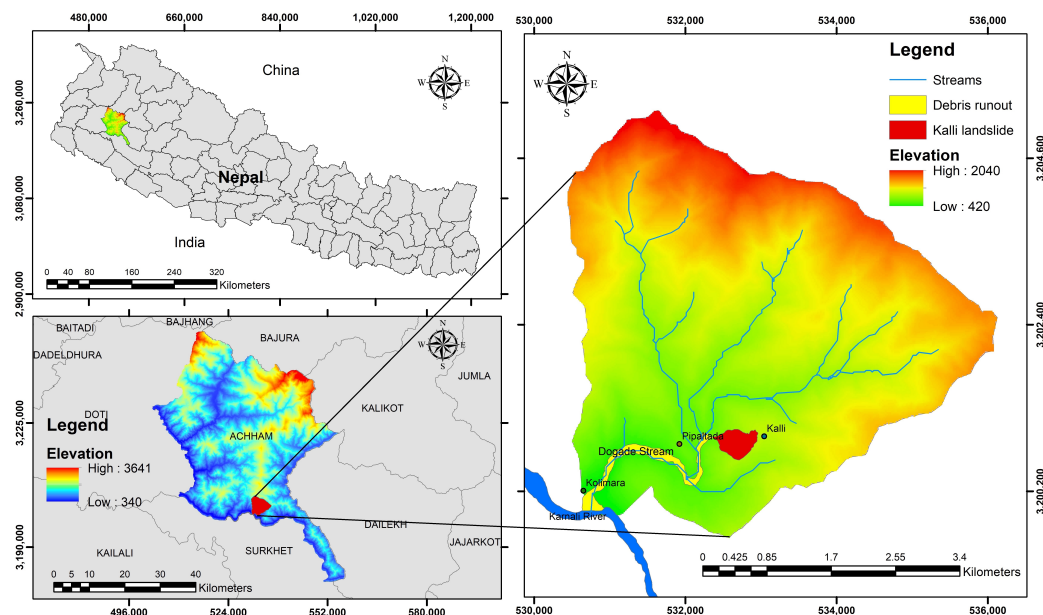


Figure 1. Study area around Kalli village of Achham District on the map of Nepal.

The study area usually receives scanty rainfall during the winter. From November to April there is very little rainfall, and then, from the middle of April to the middle of October the area typically receives intense summer rainfall. The maximum rainfall generally occurs in July. The summer rainfall storms are very intense, often flooding the ephemeral channels. There is no rainfall gauge station in the study area, therefore the rainfall in the area was estimated from several nearby rainfall gauge stations (Asara Ghat, Bangga Camp, Mangalshen, and Pusma Camp) located within 25 km of the landslide area. Figure 2a shows the Thiessen polygon of this region around the four stations. The rainfall in the study area was then estimated based on its distance away from each station and the area of each polygon [30]. These rainfall data from the years 1982 to 2018 were obtained from the Nepal Department of Hydrology and Meteorology. The cumulative rainfall during a year is presented in Figure 2b. It is worth noting that to examine one of the largest debris flow events that occurred in Kalli village in 1983, the rainfall was also similarly estimated for the location of this village; evidently it was very high and could be the major triggering factor for the debris flows in that year.

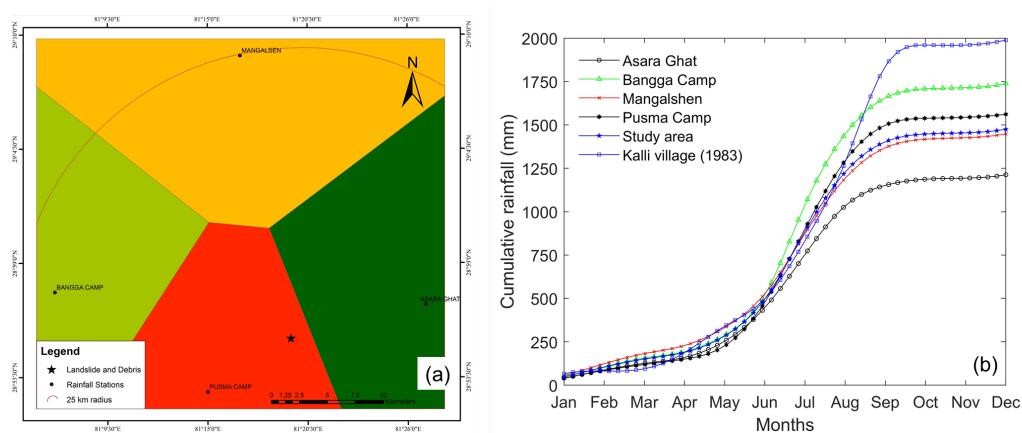


Figure 2. (a) Thiessen polygon for the rainfall analysis. The arc indicates the distance of 25 km away from the Kalli landslide area (marked with star) and shows that all the rainfall gauge stations are within this 25 km range. (b) Average cumulative rainfall recorded at nearby weather stations and estimated for the study area.

The Kalli landslide/debris flow watershed area exhibits several distinct geomorphic features. Among these, steep elevated mountains and deep river valleys with diverse landforms are particularly prominent. The highest elevation in the watershed is 2040 m and the lowest elevation, approximately 420 m is at the Karnali river. The perennial Karnali river together with its tributaries and adjoining ephemeral streams flow through the study area. Mass wasting events like landslides and debris flows are common in such topography.

Geologically, the study area is dominated by the Lesser Himalayan rocks in the Far-Western Development Region of Nepal [31]. The most prominent rock formations in the study area are the Suntar Formation and the Swat Formation [32], belonging to the Surkhet Group. The Swat Formation is mainly comprised of gray to dark gray, soft, carbonaceous shales with beds and lenses of fine-grained limestone, and the Suntar Formation consists of medium-grained, green-gray sandstones with purple shales [31,33]. The purple shale slope of the Suntar Formation is commonly exposed and visually evident in the study area (Figure 3).



Figure 3. The interbedded purple shale and gray sandstone slope common in the study area.

3. Mass Movements in the Area

3.1. Landslide and Debris Flows Events

Landslides and debris flows in the area are encountered almost every year during the heavy rainfall season. The landslides are predominantly made of solid material traveling at a moderately low velocity. A debris flow typically contains a significant fraction of water, whose presence facilitates the liquefaction of fine grains and renders the flow highly mobile [34,35]. The largest landslide and debris flows on record took place on the 12 September 1983. This event was so extreme that some of the debris material flowed over 3 km to reach Karnali river along the Dogade stream. It was initiated from fresh landslides, and then, grew significantly with the debris deposited nearby from earlier landslide events. The landslide and debris flow occurred during heavy rains. The rainfall recorded on that day at the Pusma Camp rainfall gauge station, located 9.67 km from the study area, was 230 mm; this strongly suggests that the landslide and debris flow were triggered by the heavy rainfall.

Recently, in July 2021 another landslide occurred at the same location. Figure 4 shows the mass depletion near the landslide crown area between 2020 and 2021. The crown area of the landslide has agricultural land with a thick soil deposit. The general characteristics and occurrence pattern of these recurring landslides and debris flows appeared very similar to the past events. Figure 5 shows the path of the Kalli landslide and debris runout along the

Dogade stream. It is possible to consider the primary process of debris flow development in two stages. In the first stage, the main debris flow generally initiates from a landslide whose crown is in Kalli village; subsequently the debris materials from the landslide travel further and are deposited in the Dogade stream. In smaller landslides, when there is not sufficient debris material or water to flow over a long distance, most of the debris is deposited in the Dogade stream, close to the landslide toe. Figure 6 shows the view at a distance of 600 m from the landslide crown; the trace of the Kalli landslide is evident and deposition marks of debris were left near the Dogade upstream.

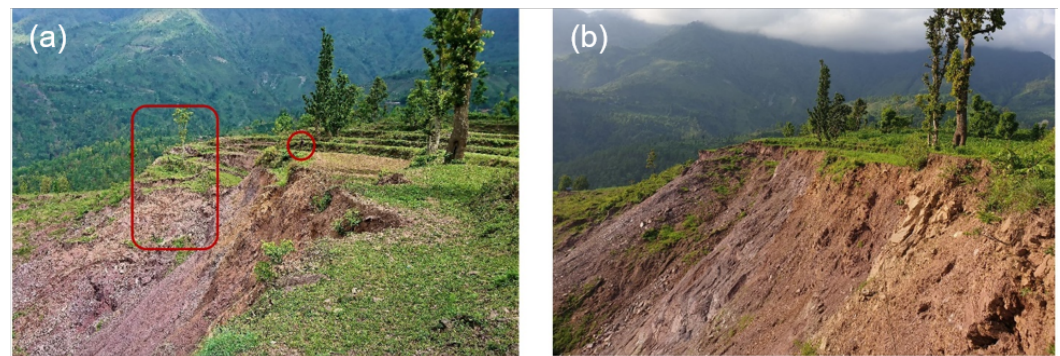


Figure 4. Photos of the landslide crown area taken (a) on 15 June 2020 and (b) on 22 June 2021. The area enclosed by the rectangle shows the displaced mass consumed by the landslide in 2021; the circle indicates a visitor (used as a scale).



Figure 5. Kalli landslide, occurring at Kalli village, and the debris runout along the Dogade stream to the Karnali river. The blue arrow indicates the landslide mobilized from the crown area at Kalli village. The red line indicates potential debris flow path along the Dogade stream. The upstream portion of the Dogade stream from the Kalli landslide area cannot be noticed clearly as the channel is constricted; but the portion between the Kalli landslide and the Karnali river is evident due to the widened channel resulting from the debris flow. A very wide debris fan along with the Karnali river constriction at the confluence point of the Dogade stream and the Karnali river due to debris deposit can be clearly observed.



Figure 6. The deposition marks remained at the sides after the debris from the first stage. The location is 600 m from the landslide crown.

Of more concern is the case of very heavy rainfall when there are large landslides along with sufficient water in the Dogade stream, the fresh debris from the landslides together with the debris deposited in the Dogade stream from earlier landslides can continue to flow to the Karnali river, which is almost 3 km away from the landslide toe (Figure 5). This stage of long runout distance along the Dogade stream is regarded as the second stage of the debris flow evolution. Figure 7 shows typical deposition patterns at the two locations, one closer to the landslide toe (Figure 7a) and the other far away and almost near the end of the Dogade stream (Figure 7b). The debris deposition pattern shows that finer particles are deposited very close to the landslide toe and the coarser particles are deposited far away from the landslide area. It is common that large boulders are found to deposit at the bank of the Karnali river, which is around 3 km from the landslide crown area [36].

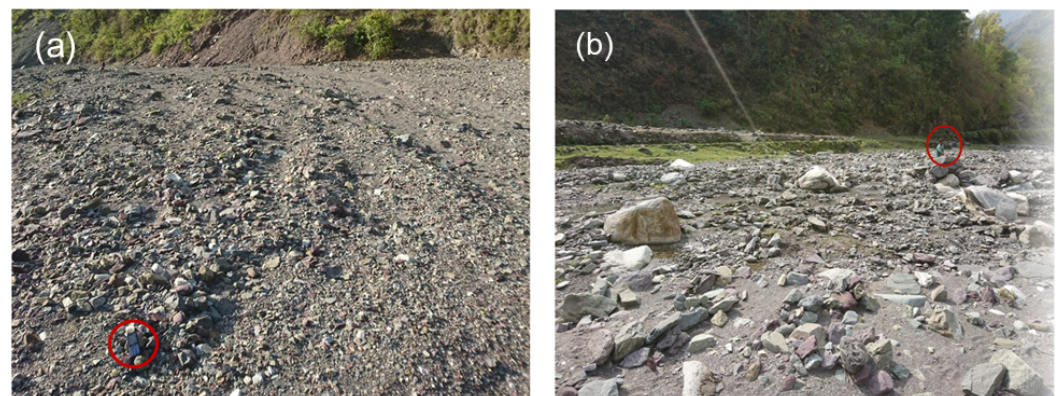


Figure 7. (a) Deposition of finer particles at 500 m from the landslide toe; the red circle on the left encloses a cell phone. (b) Deposition of coarser particles at 2500 m from the landslide toe; the circle on the right shows a visitor.

The total volume of the main debris flow that has already traveled to the Karnali river is more than hundreds of thousands of cubic meters. A few households have been displaced in Kalli village along with the loss of some agricultural land due to landslides; a large piece of agricultural land about 32,000 m² has been converted into a debris fan in Kolimara village. It is possible that future losses may occur as a result of such recurring flow events, hence the study of landslide/debris flow in this area is crucial from a future development perspective. There have been widely reported cases where landslides and debris flows have damaged infrastructure around the rivers in Nepal [37].

3.2. Rock and Soil Properties

To investigate the properties of the underlying rock in the landslide area, the freshly exposed part of the sandstone was drilled for sample collection. The deeper shale samples could not be retrieved for strength test. Uniaxial compressive strength testing was carried out on three samples of sandstone according to the Bureau of Indian Standards [38]. The average compressive strength was 52.1 MPa, the modulus of elasticity 38.5 GPa, the modulus of rigidity 16.2 GPa and Poisson's ratio 0.19. These results indicate that the sandstone in the Kalli landslide is fairly strong.

Petrographic analysis was carried out on the collected sandstone samples to determine the mineralogical and chemical composition. The results suggest that the sandstone can be characterized as subarkose, as the fractions of quartz, feldspar, and matrix are 60%, 15%, and 5%, respectively. The remaining fraction is occupied by various cementing materials that can be qualified as calcareous, argillaceous, and ferruginous, which were found to be around 15%, 3%, and 2%, respectively.

Sieve analysis and consistency tests were carried out on the soil samples collected at the landslide crown area. Based on the results of the sieve analysis [39], the coefficient of uniformity C_u was determined to be 28.57, while the coefficient of curvature C_c was found to be 0.45. In the consistency tests [40], the liquid limit (LL) was obtained as 32% and plastic limit (PL) 26%. The soil is a poorly graded sand with silt and gravel (SP-SM) according to the Unified Soil Classification System. Based on the empirical relationship proposed by Alyamani and Sen [41], the hydraulic conductivity of the soil can be estimated as approximately 6.0×10^{-6} m/s. Table 1 summarizes the key material properties measured during the laboratory testing.

Table 1. Rock and soil properties measured in the laboratory testing.

Property	Value
Rock	
Uniaxial compressive strength	52.1 MPa
Modulus of elasticity	38.5 GPa
Modulus of rigidity	16.2 GPa
Poisson's ratio	0.19
Soil	
Coefficient of uniformity	28.57
Coefficient of curvature	0.45
Liquid limit	32
Plastic limit	26
Plasticity index	6
Hydraulic conductivity	6.0×10^{-6} m/s

The estimated hydraulic conductivity of the soil is significantly higher than generally observed hydraulic conductivities of sandstone and shale. Therefore, enough water may infiltrate from the crown area of the landslide to the underlying sandstone and shale, and thus, saturate the slope. It is worth noting that the presence of surface cracks will also facilitate the infiltration of water into the soil, aggravating the water saturation in the ground. The hydraulic conductivity of shale is in general significantly lower than sandstone. The difference in relevant physical and mechanical properties of sandstone and shale such as strength and weather resistance is very high. Hence, one major cause for repetitive landslide occurrence in Kalli village may be attributed to the interbedding of shale and sandstone, as these two rocks have likely undergone different weathering due to the difference in their physical and mechanical properties and the interbedding of these two has considerably weakened the overall in situ strength.

3.3. Present and Potential Future Landslides and Debris Flows

Recurring, almost seasonal, landslides and debris flows occur frequently in this area. Most of the landslides were detected in the northern part of the Karnali river, i.e., on the right side of the river where the slopes are comprised of sandstone and shale, or interbedding of sandstone and shale. On the southern side of the river there are steep dolomite slopes, but landslides are not common in these slopes.

The present field study strongly suggests that this site is potentially very vulnerable to future landslides or debris flows. The entire region is characterized by steep slopes, on top of which often lie paddy cultivated fields. These fields accumulate significant amounts of water, leading to saturation of the slopes. Other causes such as intense rainfall in the rainy season and heavily weathered shale are still persistent. It is worth noting that there are rampant tension cracks on the landslide crown area; many separated blocks are formed which may soon slide down initiating a landslide and debris flow. Figure 8 shows the purple shale slope and the tension cracks at the landslide crown area. The combined length of the cracks is approximately 300 m. If all these separated blocks fail, it is estimated that approximately 200,000 m³ of debris material could be generated. This potentially poses a considerable threat to the residents and agricultural land in this area.

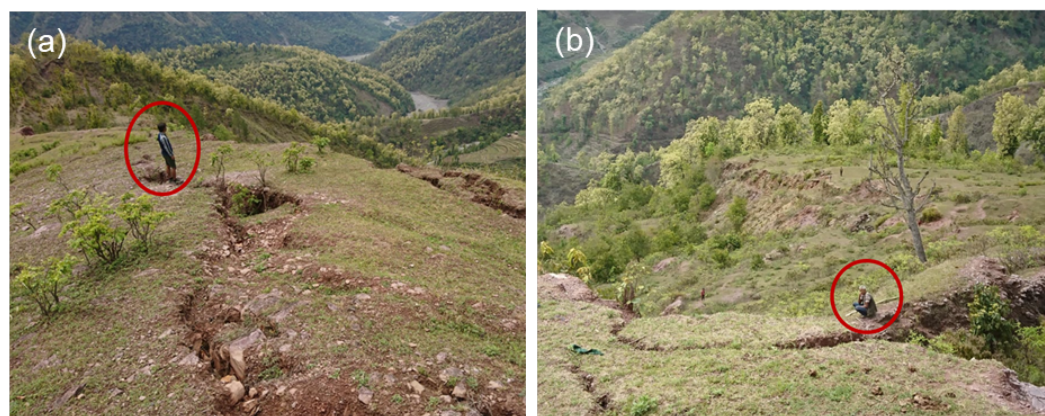


Figure 8. (a) The rampant tension cracks at the landslide. (b) Another view of the tension cracks that form separate mass blocks. The red circle in both images indicates the size of a visitor.

4. Numerical Simulations

4.1. Modeling Background Parameters of the Two-Stage Debris Flow Development

It is of great interest to assess the processes of landslide and debris flow development in a quantitative manner via theoretical or numerical simulations based on the evidence or data collected from the field survey examined so far. In particular, the debris deposition pattern as well as the debris volume have great implications in the impact on the surrounding environment or society, and consequently are the primary focus of numerical simulations in the present study. Numerical simulations are conducted with an open-source computational package, r.avaflow 2.1 [42]. It is supported by GIS software for simulations of complex multi-phase mass flows over any arbitrary topographies. It is freely available as a raster module of the GRASS GIS 8.3 software, employing the programming languages Python and C along with the statistical software R.

The computational framework is based on the multi-phase mass flow model proposed by Pudasaini and Mergili [43], which considers multiple phases in motion and incorporates many essential physical aspects of mass flows. It expands the theoretical formulations of a two-phase model [29] with the introduction of an additional phase of fine solid. This model considers the moving mass flow as composed of three phases, i.e., solid, fine solid, and fluid. The first phase, the fluid phase represents a mixture of water and very fine particles such as silt, clay, and even colloids. It is modeled with shear-rate-dependent Herschel–Bulkley rheology. The second phase, termed as fine solid, contains fine gravel and sand. The rheology of this mixture is characterized by the rate-dependent visco-plastic

behavior, as Jop et al. [24] show that dense granular flows share similarities with classical visco-plastic fluids. For this phase, shear and pressure-dependent Coulomb visco-plasticity is adopted, where both viscous stress and yield stress play a significant role. The third phase, the solid phase, is composed of coarser particles such as boulders, cobbles, and gravels. These coarse particles are considered as frictional materials with no viscous contribution. Hence, Mohr–Coulomb plasticity is used to model the constitutive behavior of this phase. It is noted that this three-phase model has been shown to be capable of unifying several widely used models [20,26,29,44] by setting specific phase fractions. Further details of the theoretical formulations can be found in Pudasaini [29] and Pudasaini and Mergili [43]. The relevant Digital Elevation Model (DEM) data are necessary for simulating a flow event on real topography. The DEM data of the study area are available online from the Alaska Satellite Facility [45]. They have a 12.5 m resolution based on the original data detected by the ALOS PALSAR satellite. The background images are obtained from Google Maps and Google Earth and subsequently geo-referenced with GIS before they are ready for the simulations.

It is necessary to calibrate the input parameters for the numerical simulations based on the collected field evidence and relevant ranges of typical material properties. They can be further modified through back analysis to match the observed trends in the debris flows reported so far; subsequently, they can be used for prediction of future debris flows. It is of particular interest to focus on the main process of sediment transport in the form of landslides or debris flows before the debris eventually reaches the stream, and the stream water flow carries the material to travel further.

Table 2 summarizes the fractions of each phase in each stage and relevant parameters for each phase. It is worth noting that the complex interactions among these phases are considered through generalized interfacial forces, including the drag forces on the particulate phases and the virtual mass force due to the relative acceleration between different phases. The internal friction angle represents the internal frictional resistance, while the basal friction angle characterizes the frictional resistance of the bed material on which the mass flow moves.

Table 2. Key parameters used in the numerical modeling.

Parameter	Value
Solid	
Density	2650 kg/m ³
Internal friction angle	30°
Basal friction angle	25° (stage 1) 6° (stage 2)
Drag coefficient	0.02
Fine solid	
Density	2000 kg/m ³
Internal friction angle	15° (stage 1)
Basal friction angle	5° (stage 1) 3° (stage 2)
Kinematic viscosity	100 m ² /s
Fluid	
Density	1000 kg/m ³
Kinematic viscosity	0.001 m ² /s
Fluid friction coefficient	0.01

As discussed in the preceding section, in the first stage of the landslide/debris flow development around Kalli village, a landslide typically occurs. The debris mass in this stage can only flow on very steep slopes and its runout distance is short. There is relatively a very low water content in the debris mass, the solid particles behave like purely frictional

solids. Hence, the motion of the debris in this stage is modeled by adopting a very low water content for the debris material, which travels over a short distance; the fraction of the fluid phase is set to be 15%. This is hereafter referred to as the stage 1 simulation in the present study.

In the second stage, the debris mass deposited from the first stage is mixed with more water (around 50%) in the rainy season and more fresh landslides may occur under heavy rainfall. In this stage, water mixed with fine solids (clay, silt, and fine sand) produces a high-density viscous intermediate fluid that surrounds and lubricates the other coarse materials such as coarse sand, gravels, cobbles, and boulders. The viscous intermediate fluid has the capacity to hold the large particles of coarse sand, and those large particles in turn support cobbles and boulders [46], such that the entire blended mixture flows even on relatively flat slopes. In such conditions, the resistance to the flowing mass from the surroundings is very low, i.e., the basal friction can decrease drastically due to the presence of the lubricating fluid made of water, clay, silt, and fine sand [43]. The development in this stage is modeled by employing a moderate water content, which renders a partially viscous type debris flow whose runout distance is long. It is hereafter referred to as the stage 2 simulation.

4.2. Stage 1 Numerical Simulations

4.2.1. Modeling Debris Flow Development during the First Stage

Recurring landslides and debris flows take place almost every year in the study area, as discussed in the preceding section. In the present study, we are especially interested in one of the major landslide/debris flows recorded in this area, i.e., the event that occurred in September 1983; we intend to calibrate the involved parameters to match the estimated debris volume. In this stage, the debris flow was directly initiated from slope failure, such as toppling or landslide. Hence, the debris mass did not have a high water content in this stage. The debris materials were released from the upper scarp of the landslide and later deposited along a distance of 600 m at the end of the stage. Figure 9 shows approximately the deposition area where the debris material settled, as estimated based on the debris deposition marks or traces observed in the field, as well as the information provided by the local residents.



Figure 9. Deposition area (marked in red) of debris material near Pipaltada village (Figure 5), accumulated during the first stage, as observed in the field. Deposition along the longitudinal direction, AB, and the transversal direction, CD, is examined in the subsequent simulation.

The information collected from the field is also used to estimate the volume of debris material considered in the numerical simulations. In this model, the volume of solids is

considered to be $48,600 \text{ m}^3$, the volume of fine solids $20,250 \text{ m}^3$, and the volume of water $12,150 \text{ m}^3$. The internal angle of friction and basal friction for the solid phase are assumed to be 30° and 25° , respectively; for the fine solid phase they are assumed to be 15° and 5° , respectively, and for the fluid, both parameters are assigned 0. The kinematic viscosity of the fine solids and fluids are considered to be $10^{-2} \text{ m}^2/\text{s}$ and $10^{-3} \text{ m}^2/\text{s}$, respectively.

4.2.2. Simulation Results

Figure 10 shows the detailed deposition results generated by the numerical simulation; they match very well with the field observation of the area of the deposited mass (Figure 9). The symbols P1, P2, and P3 in Figure 10 represent the solid, fine solid, and fluid phase, respectively; H and Q represent the flow height (depth) and the discharge, respectively. The area enclosed by the red dotted line is the release area (Figure 10). The deposition height is demonstrated by contours. The outermost contour represents the lowest deposition height and the innermost contour represents the highest deposition height. Each phase is represented by a different color, as indicated in Figure 10.

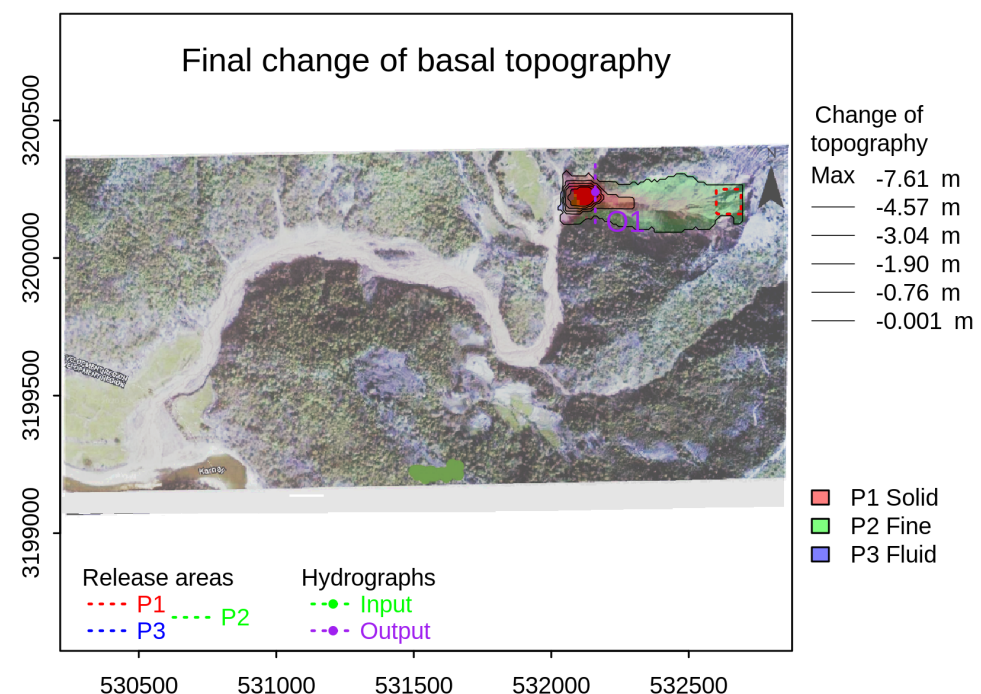


Figure 10. Deposition profile obtained from numerical simulation.

As shown in Figure 10, the fine solids mixed with water are deposited at the front, the solids at the middle, and a much lower amount of fine solids at the tail of the travel path. To analyze the deposition profile obtained from the numerical simulation in detail, two deposition profiles are selected along the longitudinal direction, AB, and the transversal direction, CD, of the deposition area, as shown in Figure 9; AB is located at the middle of the flow in the debris flow direction and CD at 50 m away from the left-most point, i.e., point A. The deposition depth (thickness) along these two distances is plotted in Figure 11. Evidently, the massive soil debris material deposits near the toe, i.e., point A of the steep slope AB. The maximum depth of deposition is about 7.6 m, roughly the half way towards CD. The depositional depth gradually declines further away from the center of CD. This depositional depth after the landslide can be observed by the depositional marks in the field.

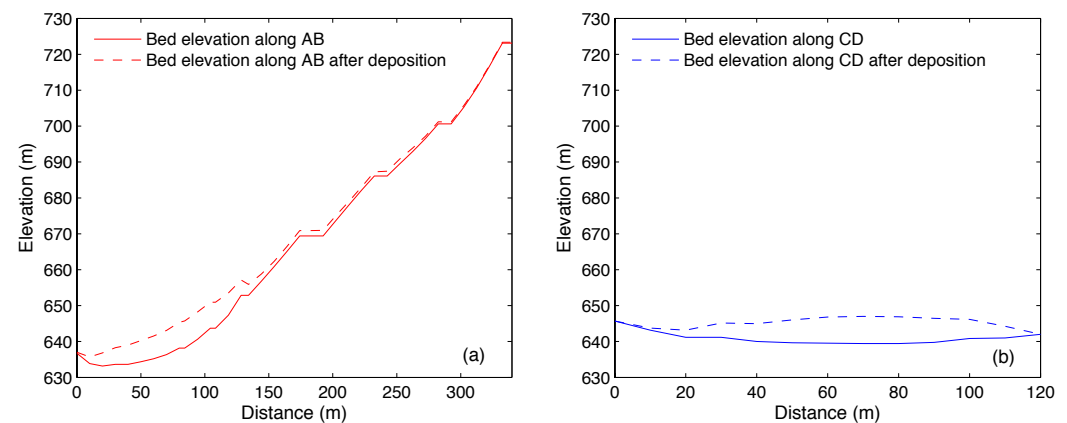


Figure 11. Deposition profile obtained from numerical simulation (a) along AB (the origin is established at point A); and (b) along CD (the origin is established at point C).

It is also of interest to examine the details of the debris flow around the area and at specific locations along its path. Figure 12 shows the overall the maximum flow height around the area. The debris is highly concentrated at the center and dominated by the solids fraction at the initiation. A point is selected and marked as O1 near the end of the deposition in Figure 12; it is located at the section 450 m from the landslide crown. Figure 13 shows the flow height of each phase and the discharge rate at this section. The debris material reaches this section at 26 s from the initial release time, and then, the maximum flow height and discharge occurs at 31 s. During this 5 s interval, the discharge rate has increased sharply, and then, decreased gradually after the peak discharge. The time from zero discharge to peak discharge is almost one-fifth of the time between peak discharge and zero again when the flow passes this section entirely. This shows that during debris flows most of the flowing mass is at the front.

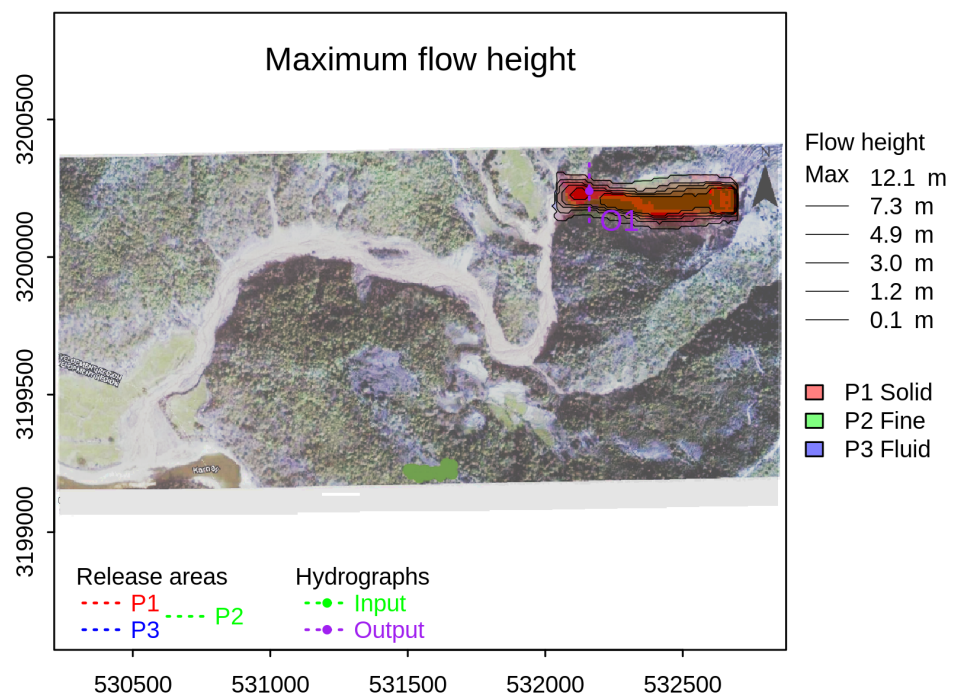


Figure 12. Distribution of maximum flow height during the first stage.

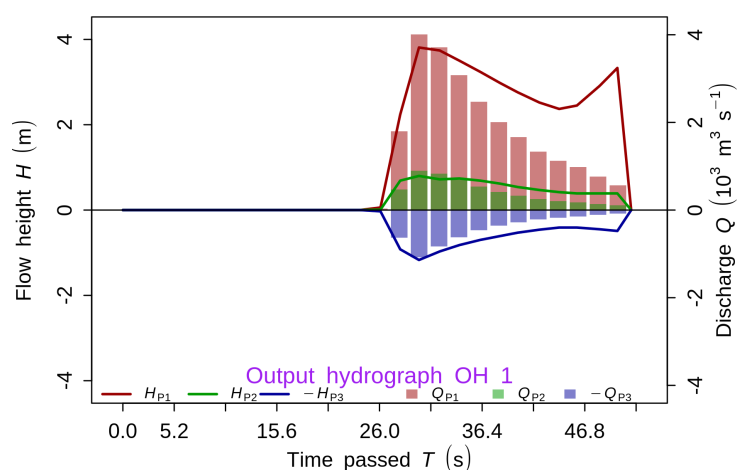


Figure 13. Debris flow height and discharge passing the specific location (O1) during the first stage.

4.3. Stage 2 Numerical Simulations

4.3.1. Modeling Debris Flow Development during the Second Stage

The initiation of the second-stage debris flow is caused by the combination of fresh landslides and the debris deposited from the first-stage debris flows, as addressed in the preceding section. With the surge in water volume in the debris mass during the intense rainfall, the motion of the debris mass typically exhibits the well-known fire-hose effect [47,48], along with the fresh debris mobilized from the fresh landslide. In September 1983, a large amount of material was transported to the Karnali river as part of a debris flow; however, it was not the only event in that year and many debris flows followed. Debris flows are generally initiated during intense rainfall. A large amount of fine soil from agricultural land was depleted by the landslides. The presence of fine solids with water made the flowing mass more viscous. The viscous mass produced by mixing fine solids and fluid lubricates the base and significantly reduces the basal friction. The internal angle of friction also decreases with the increase in water and clay content [49]. Hence, in the second-stage simulation, the relevant material constants are adjusted to incorporate the effect of water and fine solids and address the potentially different phase behavior. As summarized in Table 1, the basal angles for solids and fine solids are taken to be 6° and 3° , respectively. The internal angles of friction for solids and fine solids are taken to be 25° and 13° , respectively.

Although the precise volume of debris in the field is impossible to determine accurately since much of it flows along the Karnali river, based on the field analysis and information provided by the local residents, the total volume of debris is estimated to be roughly around $300,000 \text{ m}^3$. In the numerical simulations, the volumes of solid, fine solid, and fluid considered are $107,651 \text{ m}^3$, $46,126 \text{ m}^3$, and $153,765 \text{ m}^3$, respectively. Considering the fact that some portion of debris was freshly produced from the landslide and the rest was the deposited debris from the first stage, in the simulations the initial debris mass is set up to be released from the scarp of the landslide to the deposition area of the first stage.

4.3.2. Simulation Results

Figure 14 presents the final deposition of the debris material; the debris runout distance is considerably longer than in the first stage. Some portion of debris is deposited along the bank of the Karnali river, while a major portion flows into the Karnali river. The deposition pattern shows that some fine solids are deposited at the back and coarser solids are deposited at the front. The deposition height along the Karnali riverbank is around 4 m. It can be seen that the fine solids are deposited closer to the debris initiation area and the coarser solids are deposited far away from the debris flow initiation area. Such a distribution trend was observed in the field, as shown in Figure 7.

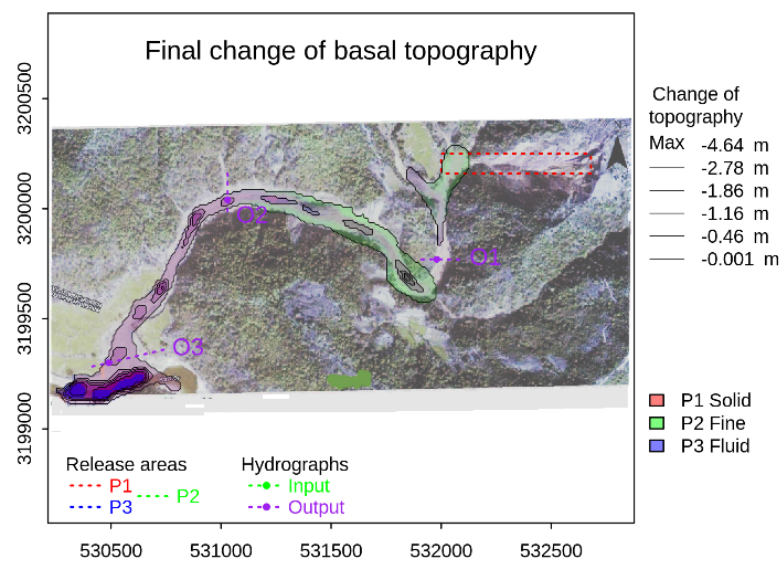


Figure 14. Final deposition of debris material at the end of the second stage.

It is worth exploring in detail the evolution of the debris flow along its path; three locations, O1 which is close to the starting point, O2 at the intermediate distance, and O3 that is close to the final deposition fan, are selected in Figure 14. They are located at 1100 m, 2200 m, and 3300 m, respectively, from the crown of the landslides. The hydrograph that shows the flow height and the discharge rate at each location is presented in Figure 15. Figure 15a shows a significant amount of solids and fine solids passing through location O1; however, at O2 (Figure 15b) and O3 (Figure 15c) there is no significant amount of fine solid. A high volume of solids passes through O3, which eventually either flows into the Karnali river or deposits along the Karnali riverbank. Combined with the results of the base change, shown in Figure 14, it can be concluded that water travels to the deepest part, i.e., the middle of the river; however, a large amount of solids (coarse debris) settle down before they reach the middle of the Karnali river. This can be clearly confirmed in the field that the continuous deposition on the right bank has shifted the river towards the left, constricting the flow path of the Karnali river.

The deposition profile along the debris flow in the Dogade stream and along the Karnali riverbank is presented in Figure 16. In this stage, with a sufficient amount of water that mixes with fine particles such as clay, silt and fine sand, the debris behaves like a moderately high density solid–fluid mixture which can hold together large particles such as boulders and cobbles during the flow. It also lubricates the coarser particles and decreases the basal friction; therefore, the whole debris mass can flow relatively easily at a high velocity and travel over a long runout distance of over 3000 m, as shown in Figure 14. In such a case, the runout distance of solids (coarser particles) is longer than fine solid. Indeed, the deposition along the Dogade stream is not very significant as the debris tends to flow along the stream. As shown in Figure 16a, the elevation change in the Dogade stream is hardly appreciable when plotted, with the elevation height ranging from 400~900 m; hence, the deposition depth, i.e., the change between the elevations, is also plotted separately on the axis on the right side in Figure 16a. It shows that the deposition is less than 2 m along the Dogade stream, except at the end of the stream where the deposition depth grows considerably to about 4 m at the fan near Kolimara village; the results are supported by the field observation of the accumulation of a large amount of debris material in this area. The simulation also shows large deposition along the Karnali riverbank (Figure 16b) after a considerable amount of debris material continues its runout and reaches the Karnali river. This is also consistent with the field observation.

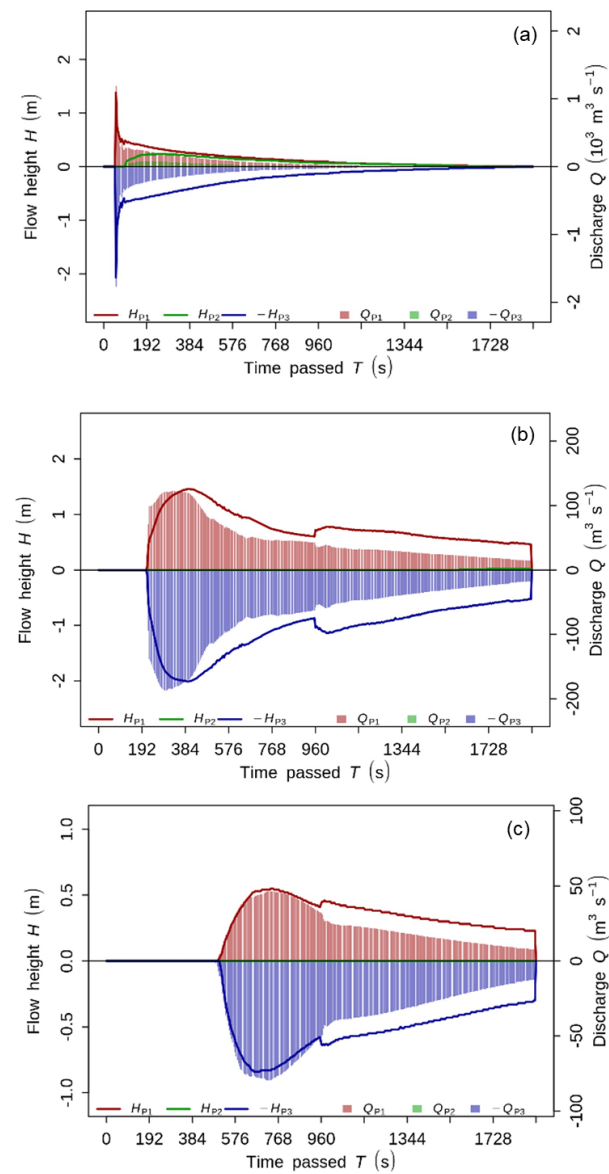


Figure 15. Hydrographs at (a) O1, (b) O2, and (c) O3 along the flow path.

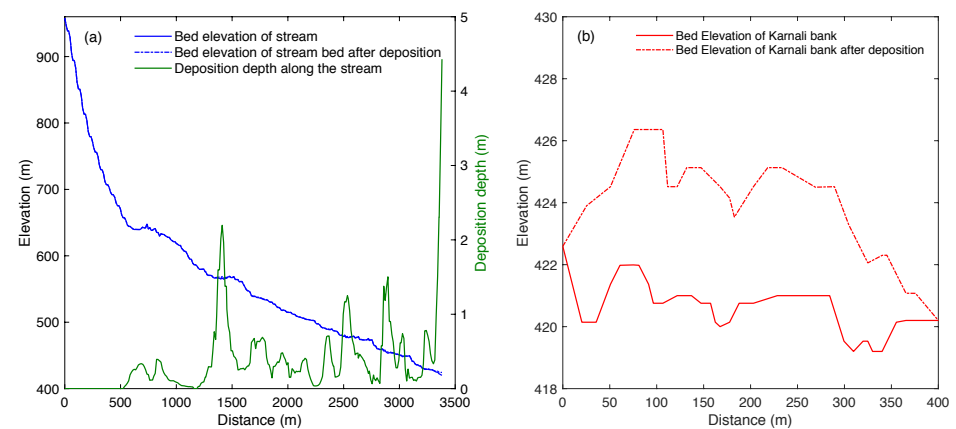


Figure 16. Deposition profile (a) in the Dogade stream, and (b) along the Karnali riverbank obtained from numerical simulation.

5. Discussion

The Himalayas in Nepal are extremely vulnerable to gravity-driven mass movement due to the presence of weak rocks in the high slopes that often receive intense summer rain. Mass wasting events such as landslides and debris flows are very common in these mountains. There are some other locations in Nepal similar to Kalli village, examined in the present study, where recurring landslides and debris flows are experienced almost every year. Rainfall is often a main triggering factor for these events; the poor underlying geology, which consists of interbedded shale and sandstone, could be the major cause of landslides. It is worth noting that extremely hazardous repetitive landslides also occur frequently in other parts of the region, including Nepal and neighboring countries. For example, at Siddhababa along the Siddhartha Highway and at Jugedi Khola along the Narayanghat Mugling Road, the geological formations have similar interbedded litho-units of sandstone and shale as those found in the Suntar Formation around Kalli village in the present study [13–15]. The Dagshai Formation and Murre Formation of India and Pakistan feature similar litho-units as the Suntar Formation and also experience extensive recurrent landslides [11,12,16]. However, effective mitigation of such geological hazards would demand more than mere identification of causes and triggers; theoretical and numerical investigations [50] may considerably benefit the understanding of the physical and mechanical processes involved in the landslides and debris flows in the studied mountainous range. In the present study, a less mobile debris flow is considered in the first stage with a greater internal angle of friction and basal friction used in the numerical simulations. The numerical results are found to match reasonably well with the actual field observation of the deposition. With the increase in water content, the internal angle of friction is assumed to decrease slightly and basal friction decreases significantly, this assumption yields results that are consistent with the observation of a long runout distance in the field.

It is of great interest to use the numerical approach examined in the present study to explore the possibilities of future debris hazards. As discussed in Section 3, at present the study area is highly susceptible to future debris flows; many large blocks are formed by the tension cracks on the crown of past landslides (Figure 8) and it is highly likely these massive blocks will slide down to form debris flows sooner or later. Additional numerical simulations are carried out by considering the estimated 200,000 m³ of solid debris material ready to move downward to initiate the debris flow; since it is impossible to predict whether all this mass would fail at once or progressively, this choice represents a worst-case scenario, and thus, is assessed in the present study to predict the potential deposition area and runout distance.

Two stages of debris development are considered in the prediction. The first considers low-water-content debris that initiates at the current crown area (Figure 8); the volumes of solid, fine solid, and fluid are considered to be 146,023 m³, 60,984 m³, and 36,492 m³, respectively. Figure 17 shows the deposition profile at the end of the debris flow. The area of deposition is mainly confined to a rather limited area, indicating little or modest threat to the nearby residents, as the debris is deposited in the stream without entering the farmland and village. However, still reasonable care should be taken around the landslide-prone areas in Kalli village and it is suggested that those areas should be avoided for animal grazing in the rainy season, as catastrophic landslides can occur at any time in the rainy season.

The second simulation examines a high-water-content debris flow that initiates in a wide area close to the Dogade upstream; the volumes of solid, fine solid, and fluid are considered to be 143,514 m³, 61,506 m³, and 205,020 m³, respectively. Figure 18 shows the final deposition of the debris. A small portion of the debris can travel over almost the entire Dogade stream and reach the fields of Kolimara village. Much of the debris can also flow to the Karnali river, with considerable deposition along the banks of Karnali river. Overall, the results show the tremendous destructive potential of current geological hazards in this area. Of course, in reality, it can be debated whether all the blocks separated by tension cracks may fail at the same time in a worst-case scenario; it is more likely to flow progressively

part by part each year. The influence or destruction of future events may be not as drastic as the scenario examined in the present study.

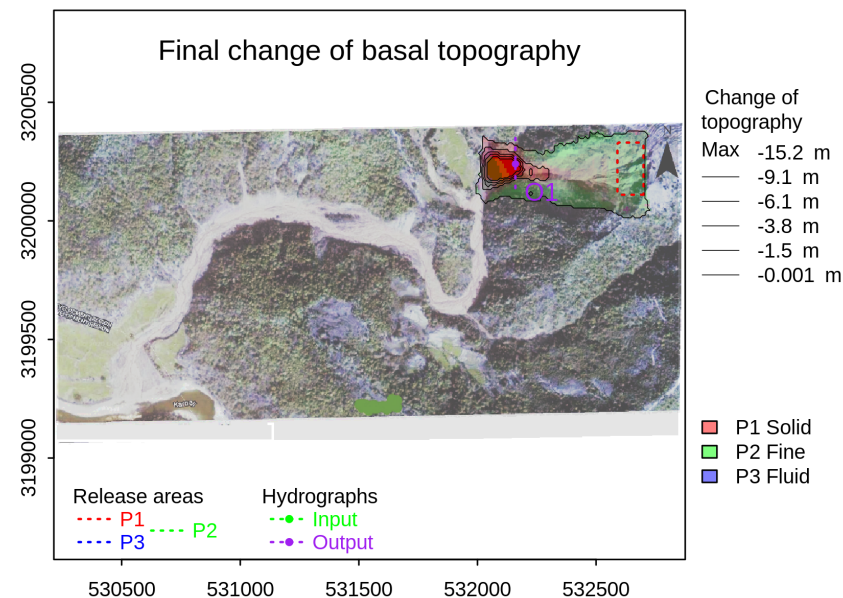


Figure 17. The deposition based on the simulation of a low-water-content debris flow.

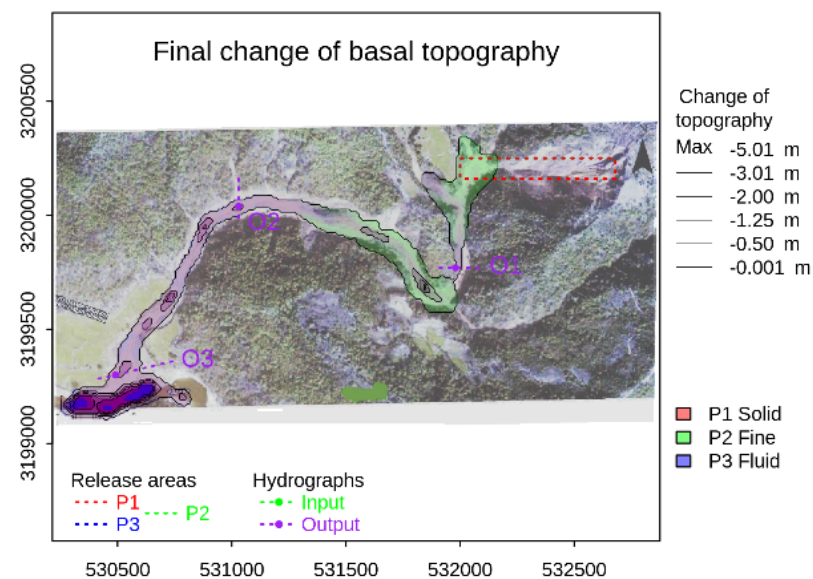


Figure 18. The final deposition of probable future debris flow based on a moderate-water-content model.

6. Conclusions

The present study focuses on a field study of recurring landslides and debris flows in the Kalli village in Achham District in Nepal. It shows that rainfall is the primary triggering factor for such gravity-driven mass wasting events. The poor underlying geological conditions that feature interbedding of shale and sandstone are a major cause. It is observed that debris flows may occur in two different stages. In the first stage, when the rainfall is not extremely high, smaller landslides occur and the runout distance of the debris generated is quite modest, approximately only a few hundred meters away from the landslide crown due to insufficient fluid in the debris mass. The second stage may occur during extreme rainfall when the debris mass contains a very high water content. A combination of the debris from the fresh landslides and the debris from the earlier landslides may flow to the

Karnali river that is located around over three kilometers from the original landslide crown area. The field study shows that debris deposition follows a unique pattern, where the larger particles tend to travel farther from the initiation area while the finer particles are deposited closer to the initiation area.

Numerical simulations based on a multi-phase computational framework are conducted to quantitatively analyze the characteristics of the debris flows in motion. The deposition profile and runout distance in both stages are simulated. In the first stage, the debris is largely accumulated at the toe of the hill and spread laterally along the slope. In the second stage, the debris flow travels over a very long distance to reach the Karnali river; large deposition is concentrated at the fan area and along the Karnali riverbank. Overall, the major trends from the numerical simulations are reasonably consistent with the field observations. At present in the field there are still large blocks separated by tension cracks that are rampant in the landslide crown area; which pose a considerable hazard for future landslides and debris flows. Additional numerical simulations are performed to predict the fate of an estimated volume of 200,000 m³ of potential debris material present in the field. The numerical results show that the characteristics of such future events would be very similar to past incidents. Depending on the availability of water content, affected by the rainfall conditions, a potentially very destructive debris flow scenario is likely, as it may travel over the entire Dogade stream and reach Kolimara village and the Karnali river.

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