WATER-RELATED NATURAL DISASTERS: STRATEGIES TO DEAL WITH DEBRIS FLOWS: THE CASE OF TSCHENGLS, ITALY*

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Abstract: The chapter reports on a case study of how people and public administrations dealt in the past and currently deal with the danger of debris flow. After a brief description of main debris flow features, the time series of debris flow events and the history of training works at the Tschengls torrent are reported. Finally, a modern approach based on a theoretical background of debris flow research is described. The integral analysis allows us to assess the debris flow activity and intensity in satisfactory detail and therefore allows us to derive recommendations for structural and nonstructural measures.

Keywords: debris flow, mitigation of debris flow hazards, time series analysis

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1. INTRODUCTION

Water resources play a key role for humanity. Without water, no life is possible; however, at the same time water, can represent a major threat for mankind. Floods cause huge damages and loss of human life.

Through the centuries, people in mountainous regions have had to face different features of floods. Clear water floods do not occur only in the wide plains closed to the outflows of the rivers into the ocean, but also in the main mountain valleys where large rivers flow. Flooding becomes hazardous when great depths of water or strong currents occur in the flooded region. Manfreda, this volume, describes examples of practical research and explains how the scientific community and public administrations deal with the problem.

In addition to clear water floods, mountainous regions, where slopes are steep and loose material potential are pronounced, are affected also by the phenomenon of debris flows. Compared to ordinary floods, debris flows may mobilize and transport significantly larger volumes of solids, thus causing severe damage mainly in the deposition areas, i.e., on the fans of the torrents.

A close observation of debris flow events seems to indicate that there are three regions where debris flows are more prevalent: (1) semi-arid regions, (2) alpine regions and (3) volcanic regions (Mainali and Rajaratnam 1991). Thus, the province of Tyrol, situated in the heart of the Alps, is subjected to this phenomenon.

In earlier periods, because large rivers were not yet managed and floodplains were often marshy and inhospitable, our ancestors tended to settle in elevated locations on the alluvial fans. By constructing buildings and infrastructure on these fans, a large potential for damage was created over the course of time.

The village of Tschengls, situated in the province of South Tyrol in Italy, represents a typical example of the struggle between people and nature. The village is situated on the fan of the Tschengls torrent and has been affected several times by debris flow events. Since then, the inhabitants of the village have faced the torrent with great respect. Downstream of the village, for instance, there is an almost untouched alluvial forest which has been reserved for debris flow deposition. The existence of this forest in the middle of cultivated land is a testament to wise land use planning.

This chapter first describes the general characteristics of debris flows. After presenting the watershed of the Tschengls torrent, the time series of debris flow events is illustrated. Then, several strategies that people have developed to deal with debris flows in the Tschengls torrent are described.

Finally, an integrated approach, based on the essential processes of debris flow formation, propagation and deposition, is presented. The example shows how increased understanding of the processes of debris flow contributes to optimize mitigation measures.

2. CHARACTERISTICS OF DEBRIS FLOW

2.1. General Aspects

A typical debris flow occurs in one or several pulses. The flow consists of a small percentage of water mixed with a much larger percentage of solids (clay, silt, sand, gravel, boulders, and wood). Typically three distinct zones (Figure 1) may be distinguished along the path of a debris flow (1) The initiation zone where the debris flow starts, (2) the transition zone where erosion and/or deposition may occur, but often balance each other, (3) the deposition zone where the debris flow stops and the material is deposited.

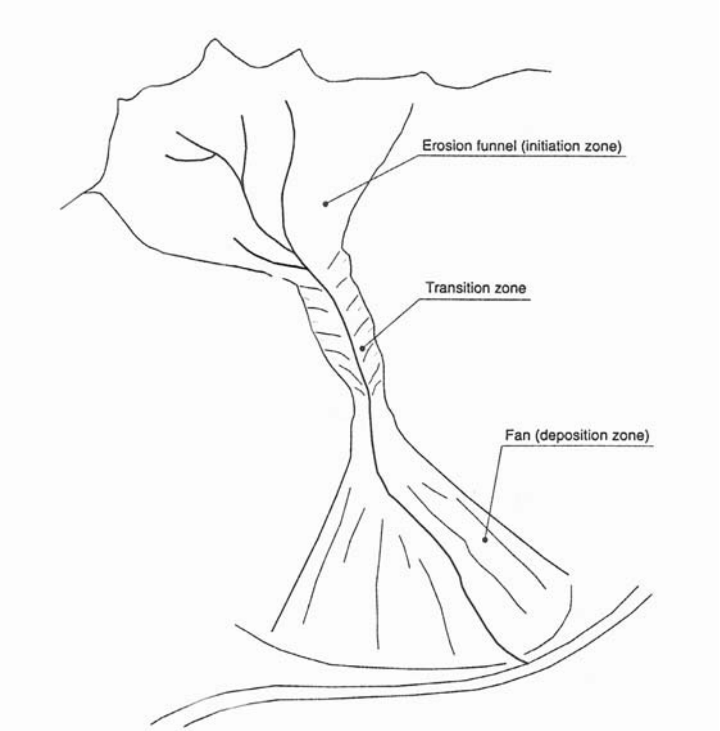


Figure 1: Definition of Erosion Zone, Transition Zone, and Deposition Zone (Bezzola 2000).

Debris flows can be distinguished from clear water flows by the following characteristics:

1. Debris flows generally mobilize much more solid material than clear water floods with bed load transport. Due to its erosion capacity, a single debris flow event can bring about larger changes in the landscape than can longer periods of continuous geomorphologic activity, particularly in the erosion and deposition zones.
2. The solid concentration of debris flows is impressively high. According to O'Brien (2001) the solid concentration of a debris flow surge can reach 40 – 50 percent, whereas Coussot (1996) reports solid concentrations larger than 80 percent. In clear water floods, solid concentrations usually do not exceed 10 percent.
3. The maximum discharge from debris flows far exceeds the maximum discharge of clear water floods in watersheds of the same size. Therefore, maximum flow depths and velocities are also generally higher. Furthermore, the density of debris flows can reach values of up to 2.200 kg/m^3. The high velocity and high density of debris flows are thus responsible for the enormous destructive potential of such flows. Debris flow waves have been reported to be up to 6 m high, moving at velocities of up to 15 m/s. Coussot (1996) gives a summary of observed maximum flow depths, velocities, volumes and solid concentrations for a large number of debris flow events.
4. In clear water flow with sediment transport, grains move in response to the gravity-driven flow of water past them. In this case, the velocity of the water is around 2.5 times as large as the velocity of the solids (Coussot 1996). In a debris flow, water and solids move with almost the same velocity and all components are subject gravity, which maintains the flow. There is no significant segregation of components, so water and grains of all sizes are more or less uniformly distributed throughout the flow depth.
5. Debris flows are non-Newtonian fluids: in order to be initiated, a certain yield stress is needed, and this yield stress again leads to the deposition of the solid matter. Furthermore, debris flows usually are characterized by a shear thinning, or shear thickening flow, depending on the type of the debris flow. Numerous constitutive approaches to describe the behavior of debris flows exist. Comprehensive reviews can be found for example in Takahashi (1991), Mainali and Rajaratnam (1991), Jan and Shen (1993), Iverson (1997), and Iverson and Vallance (2001).

2.2. Flow Profile of Debris Flows

Within a typical debris flow surge, three parts can be defined (Figure 2). The first part is the front where usually the largest flow depths can be observed. Occasionally the front is almost dry or only partially saturated, since at the front water often infiltrates in the underground (Tognacca 1999) and large boulders accumulate at the front.

A clear distinction between the front and the debris flow body, which follows the front, often is not possible, as there is a continuous exchange of material between the front part and the body of a debris flow.

In the debris flow body, the concentration of solids usually diminishes. However, concentration and grain size distribution may vary according to the specific local conditions.

The third part is the more fluid tail, where discharge and sediment concentration usually are considerably lower. Larger grains concentrate in the vicinity of the bed and the debris flow changes into a hyperconcentrated flow.

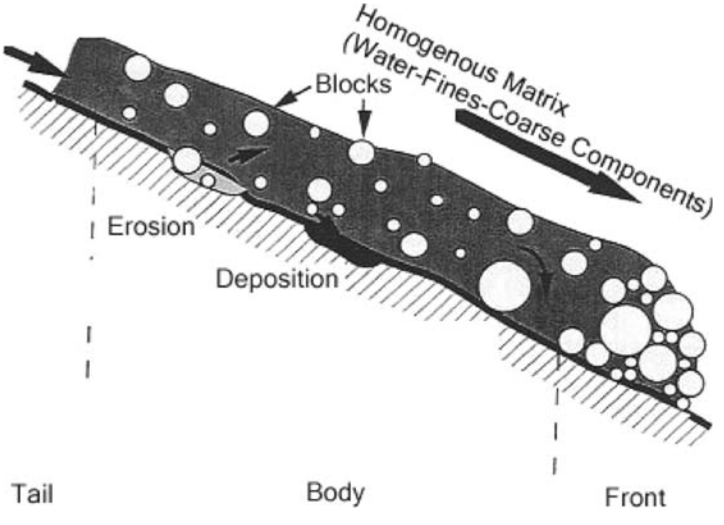


Figure 2: Conceptual Scheme of the Flow Profile of a Debris Flow Pulse (Coussot 1996).

2.3. Conditions for the Occurrence of Debris Flow

For the occurrence of debris flows in a watershed, two conditions must exist: debris sources and a minimum torrent slope. According to Kienholz (1995), the presence of these conditions represents the basic disposition (long-term tendency) of a torrent to show debris flow activity.

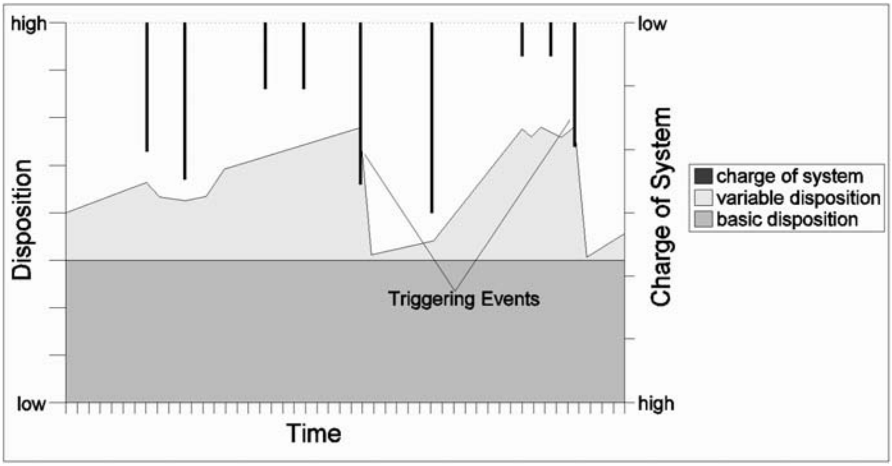


Figure 3: Link between Basic Disposition, Variable Disposition and Triggering Events (Kienholz 1995).

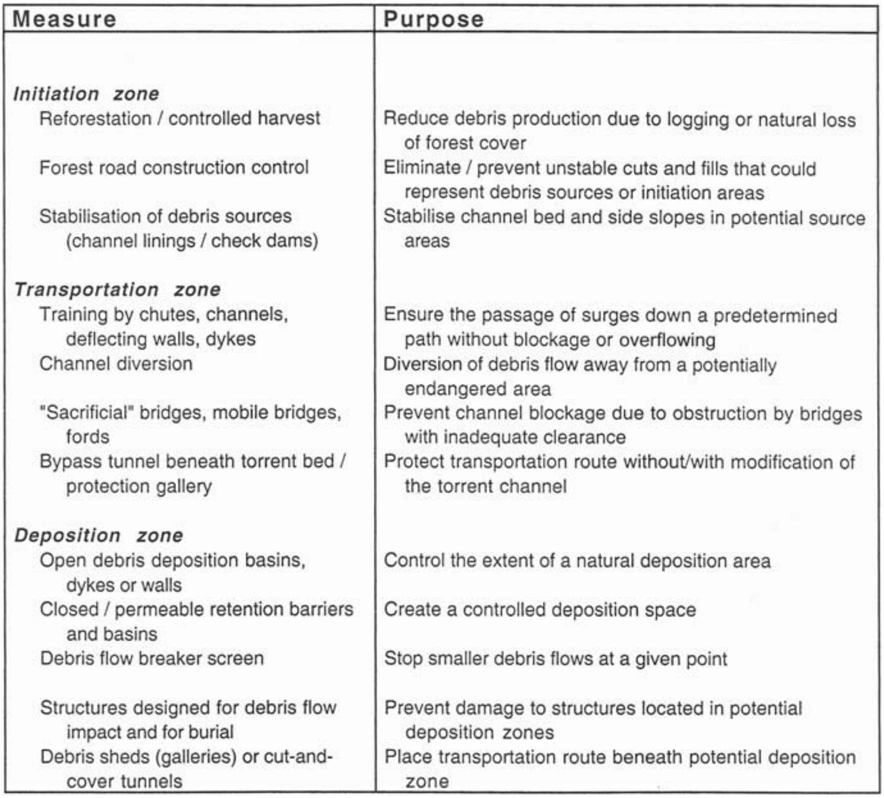
The variable disposition represents the short-term readiness for a debris flow event, for example, the saturation of the underground material or the accumulation of loose materials on the torrent bed (due to continuous sediment delivery or due to a sudden event, for example, a landslide).

The initiation of a debris flow finally is caused by a triggering event. In the Alps, these events are primarily intense precipitations. Alternatively, catastrophic flows can be originated by the collapse of a glacial moraine, by dam failures, by strong snow melting, or even by soil liquefaction caused by seismic events. As shown in Figure 3, the triggering intensity required to initiate an event is not constant in time and is directly related to the total disposition, i.e., the sum of basic and variable disposition, in the torrent at the moment of the triggering event.

2.4. Mitigation of Debris Flow Hazards

When dealing with mitigation of debris flow hazards, generally three types of measures can be distinguished: (1) structural measures, (2) nonstructural measures, (3) emergency planning.

Structural measures can be undertaken in the initiation zone, in the transition zone and in the deposition zone of the torrent. The most important structural measures are listed in Figure 4.



Measure	Purpose
Initiation zone	
Reforestation / controlled harvest	Reduce debris production due to logging or natural loss of forest cover
Forest road construction control	Eliminate / prevent unstable cuts and fills that could represent debris sources or initiation areas
Stabilisation of debris sources (channel linings / check dams)	Stabilise channel bed and side slopes in potential source areas
Transportation zone	
Training by chutes, channels, deflecting walls, dykes	Ensure the passage of surges down a predetermined path without blockage or overflowing
Channel diversion	Diversion of debris flow away from a potentially endangered area
"Sacrificial" bridges, mobile bridges, fords	Prevent channel blockage due to obstruction by bridges with inadequate clearance
Bypass tunnel beneath torrent bed / protection gallery	Protect transportation route without/with modification of the torrent channel
Deposition zone	
Open debris deposition basins, dykes or walls	Control the extent of a natural deposition area
Closed / permeable retention barriers and basins	Create a controlled deposition space
Debris flow breaker screen	Stop smaller debris flows at a given point
Structures designed for debris flow impact and for burial	Prevent damage to structures located in potential deposition zones
Debris sheds (galleries) or cut-and-cover tunnels	Place transportation route beneath potential deposition zone

Figure 4: List of the Most Important Structural Measures against Debris Flows (Bezzola 2000).

Nonstructural measures for the most part comprise hazard and risk zone assessment and consequent spatial planning. By identifying and classifying the concerned areas, suitable land use can be accordingly planned in order to manage the further development of these areas with respect of the existing natural hazards.

Emergency planning includes the installation of warning devices, the implementation of evacuation plans and the organization of measures such as the temporary closure of openings with stop-logs or sandbags. It should be noted that emergency planning must be done properly in advance —a difficult task as warning time generally is very short. In the case of the Tschengls torrent, for example, the span between the initiation of a debris flow and its arrival in the village is around 30 minutes.

3. THE CASE STUDY OF TSCHENGLS

3.1. The Tschengls Torrent Watershed

The Tschengls torrent has a catchment area of 10.6 km^2 and is a tributary of the Etsch, the river with the second largest catchment area of Italy. The highest point of the watershed is at an altitude of 3,375 m a.s.l., the lowest point is at 875 m a.s.l. The main reach of the torrent has a length of 7.1 km with a mean slope of 34 percent.

Geologically, the Tschengls watershed is located in the schist zone of the Vinschgau valley with presence mainly of mica schist and gneiss. In the upper area of the watershed, amphibolites can be found.

The Tschengls torrent is a typical alpine mountain torrent. The main debris sources are in the upper basin area and have a total surface area of around 0.75 km^2. Several secondary creeks run through the debris sources and, after having passed a rocky portion with cascades, they join and form the main reach of the Tschengls torrent. Both the steep slope and the large volume of available debris in the upper basin area contribute to a high likelihood of the occurrence of debris flows in the Tschengls torrent.

The upper basin area of the Tschengls torrent is surrounded by very steep rocky walls that provoke thunderstorm cells to burst, resulting in intensive precipitation, which is an important triggering condition for the initiation of debris flows (Figure 5). Therefore the upper basin area is characterized by a high debris flow activity.

Downstream from the cascades, the transition zone begins. Observations of past events show that the material balance in this reach is almost neutral: i.e., the amount of erosion and deposition during a single debris flow event, as well as over longer periods of time, balance each other, as the reach has been trained with a series of check dams. In the lower part of the transition zone, there are two debris retention basins. Deposition of solid material in these two basins reduces the volume of debris flows. The basins are regularly cleared.

At the end of the transition zone, the Tschengls torrent enters the main valley of the Etsch where the village of Tschengls is located and where deposition processes occur. Since the last ice age, the Tschengls torrent has formed an impressive debris fan with a volume of around $11 \cdot 10^6$ m^3.

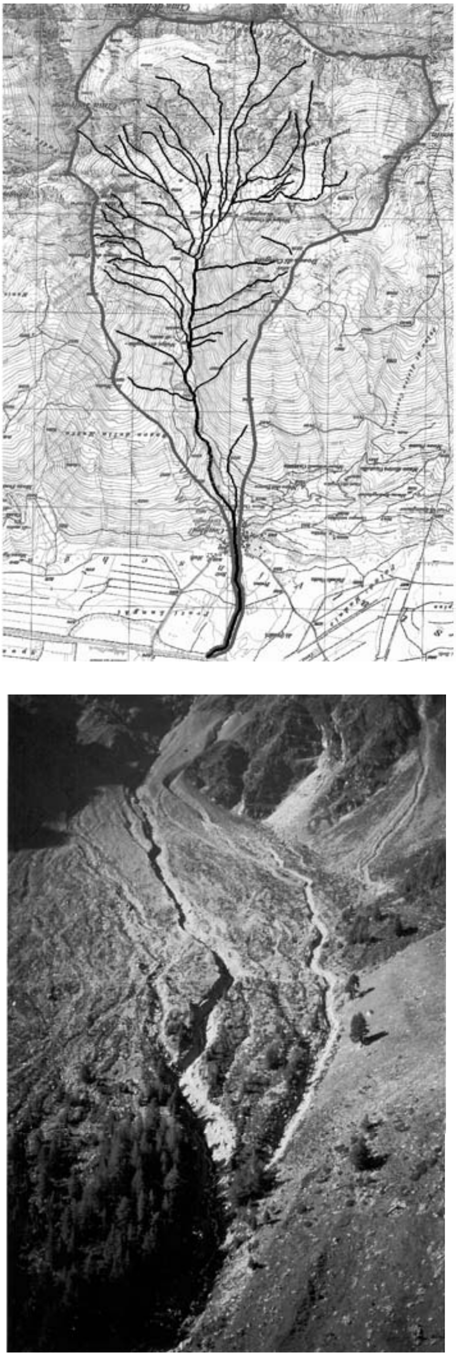


Figure 5: The Watershed and the Upper Basin Area of the Tschengls Torrent.

3.2. Time Series of Debris Flows in the Tschengls Torrent

The debris fan is a clear and evident index for the debris flow activity of the Tschengls torrent. Physical evidence is corroborated by written sources recording debris flows that date back to the eighteenth century.

Table 1 reports the time series of recorded debris flow events. The following sources have been used: (1) records of the village chronologist (Raffeiner 1990), (2) documentation of catastrophic natural events in Tyrol

Table 1: History of Debris Flows in the Tschengls Torrent.

Year	Description of event	Source
1719	Flood with debris flow in Tschengls	1,2
1768	Flood with debris flow in Tschengls	1,2
1784	Flood with debris flow in Tschengls	1,2
1850	June 18th floods in whole valley, debris flow event in Tschengls	2
1865	April 10th debris flow event in Tschengls and neighboring villages	2
1868	July 23rd after 5 days of rainfall, debris flow event in Tschengls and in the neighboring torrents	2
1887	September 8th debris flow event in Tschengls; inhabitants blame authorities for slow execution of structural measures at the torrent. The longitudinal protection walls in the village are destroyed over a length of 80 m	1,2
1889	Debris flow with partial destruction of the protection works	1
1902	Debris flow with partial destruction of the protection works	1
1911	Debris flow with large damage in meadows downstream of village. Structural protection measures withstand the event	1
1929	Debris flow with destruction of the two bridges across the river in the village	1
1931	Debris flow event in Tschengls	1
1933	Debris flow with new destruction of bridges	1
1948	Debris flow again with destruction of bridges	1
1956	On August 21st flood (supposed debris flow event) with damage of the protection walls in the village	3
1971	August 28th debris flow event with obstruction of the first bridge in the village. Subsequently the debris flow leaves the torrent bed and floods village on both sides of the torrent	1,3,4
1999	August 16th debris flow event. Maximum discharge almost reaches the structure of the bridges. In the alluvial forest downstream from the village, the debris flow deposits over an area with a surface of 13 ha.	4
1999	September 20th a smaller debris flow event occurs, exactly one day after the debris retention basins had been cleaned	4

(Fliri 1998), (3) technical reports of the Department for Hydraulic Structures of South Tyrol, (4) eyewitnesses.

Assuming that the time series is complete, in the past 280 years 18 debris flows reaching the village of Tschengls occurred, 15 of them during the last 150 years. This activity corresponds to an average occurrence of debris flow events reaching the village of Tschengls every 10−15 years.

However, as shown in Table 1 and Figure 6, debris flow activity on the Tschengls torrent is rather erratic. Frequently after big debris flow events, a series of smaller events occurs (for example after the events in the years 1865, 1887, 1929, and 1999). This observation leads to the hypothesis that the zone where debris flows develop is destabilized by the first event, encouraging the development of subsequent smaller debris flows.

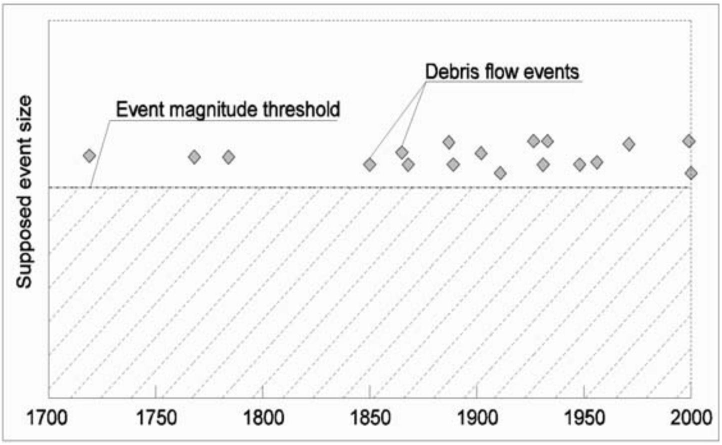


Figure 6: Time Series of Debris Flow Events at the Tschengls Torrent.[1]

Figures 7 and 8 show the initiation zone and deposition zone respectively of the debris flow events in 1999, whose main characteristics could be reconstructed quite well from field evidence, a video recording and eyewitnesses accounts.

The total volume of the two debris flows was estimated by comparing the volume of channel erosion with the volume of the deposits. Both debris flows together mobilized a volume of 70,000 to 100,000 m³. Based on their duration, velocity, and depth, as observed by eyewitnesses, the volume of the first event was estimated to be twice the volume of the second event.

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[1] The graph shows the debris flow that exceeded the threshold of event magnitude which is necessary to reach the village of Tschengls (according to Ouarda et al. 2002). Beneath the threshold other events that did not reach the village might have occurred.

Figure 7: Erosion Channel in the Initiation Zone of Debris Flow Events in 1999.

Figure 8: Deposition Zone of Debris Flow Events in 1999.

The maximum discharge was observed during the first event and was seen to decrease along the flow path. An estimation of the maximum discharge was possible as the traces of the event, corresponding to the maximum flow depths were still visible on the torrent embankments. In the upper basin area, the discharge was around 160 m³/s, in the transition zone around 100 m³/s and in the urbanized area about 70 m³/s.

3.3. History of Hazard Management in the Tschengls Torrent

After a debris flow event, public administrations and affected populations generally intensify their efforts to undertake protection measures. This being said, planning and execution of structural measures are closely related to public funds, which are not always available. The history of hazard management in the Tschengls torrent must be seen in this light.

Written sources (Raffeiner 1990) reveal that in 1747 a municipality law required the inhabitants of Tschengls to come to the channel during floods or debris flows in order to prevent an outburst. If a citizen protected only his own property, he could expect punishment.

After the debris flow event of 1768, the population of the village envisaged construction of protective structures. As the village could not raise the money for it, the works were not undertaken.

The systematic training of the Tschengls torrent began in the nineteenth century. Longitudinal protection walls with a total length of 380 m on both sides of the torrent bed were constructed through the village. The year of completion has been found engraved on the left wall.

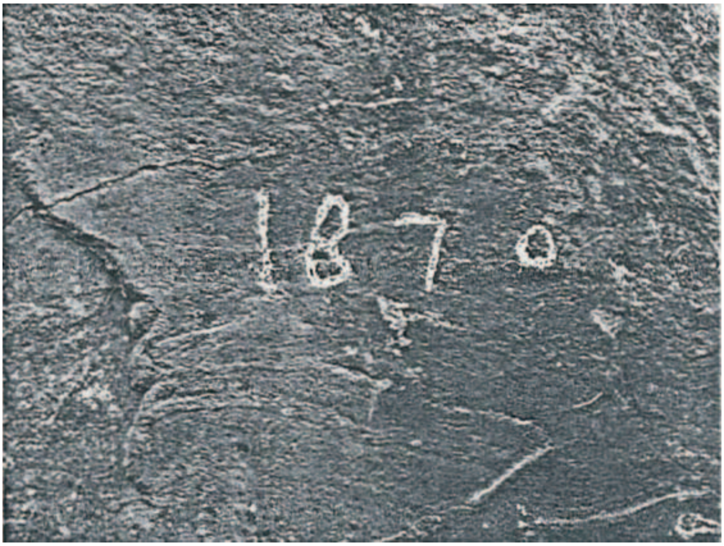

Figure 9: Year of Construction, Engraved on the Protection Wall (Raffeiner 1990).

Table 2: History of Training Works at the Tschengls Torrent.

Year	Description of work	Position of work	Source
1870	Longitudinal protection walls in village (total length 380 m, maximum height 3 m)	Lower reach	1
1882–1883	Extension of protection walls at the downstream side	Lower reach	1
1882–1883	Construction of 130 small check dams (main channel and secondary creeks)	Middle and Upper reach	1
1904	Construction of a debris retention dam (“Kohlstattl”)	Middle reach	2, 3
1908–1909	Protection works	Lower and Middle reach	1
1934–1935	Construction of 4 check dams	Lower reach	1, 3
1935	Paving of discharge section in the village	Lower reach	1
1938–1939	Construction of 6 check dams	Middle reach	3
1951	Construction of 3 check dams	Middle reach	3
1957	Rehabilitation of 2 check dams and protection walls	Lower reach	3
1966	Rehabilitation of 3 check dams	Middle reach	3
1972	Construction of a check dam series (9 dams) and rehabilitation of 3 check dams	Middle reach	3
1973	Construction of 4 check dams in main channel and 5 metal gabions in lateral creeks	Middle reach	3
1973	Construction of a debris retention dam (maximum height 14.4 m)	Lower reach	3
1974	Construction of 1 check dam and of a paved trapezoidal profile in the village (length 260 m), reconstruction of 2 bridges	Lower reach	3
1975	Continuation of the paved trapezoidal profile at the downstream end (length 250 m)	Lower reach	3
1982	Rehabilitation of check dam and heightening of debris retention dam “Kohlstattl”	Middle reach	3
1984	Construction of 1 check dam	Middle reach	3
1990	Construction of protection wall (length 30 m)	Lower reach	3

The first intensive period of structural measures to contain the Tschengls torrent coincided with a rash of other similar efforts undertaken in South Tyrol between 1883 and 1893. After some works had been carried out in 1908 and 1909, activities stopped during World War I. They were reinitiated following the events of 1929, 1931, and 1933. During World War II, work again ceased, to be reinitiated only after 1950. The period between 1972 and 1975 was characterized by intense training works following the catastrophic event of 1971. After the completion of these works, public opinion was satisfied that the protection objectives had been fulfilled and the residual risk lowered to an acceptable level. Nevertheless, the debris flow events of 1999 raised the question of whether the protection strategy should be revised and additional measures should be planned.

Table 2 presents the most important training works at the Tschengls torrent. The sources are: (1) Raffeiner (1990), (2) Stacul (1979) and (3) technical reports of the Public Department for Hydraulic Structures of South Tyrol. The Figures 10–12 show the most important structural measures at the Tschengls torrent.

Figure 10: Check Dam Series in the Transition Zone of the Torrent (construction: 1972−1973).

Figure 11: Debris Retention Basin Immediately Upstream of the Village (construction: 1973)

Figure 12: Trapezoidal Channel through the Village (construction: 1974−1975).

3.4. A Modern Approach for Debris Flow Assessment

3.4.1. Methodology

The 1999 events raised the question of whether the protection strategy should be revised and which additional measures should be planned. In order to answer these questions, the Public Authority for Hydraulic Structures of South Tyrol financed a study in which an integrated approach has been proposed (Gostner et al. 2003).

The methodology used for the integrated analysis of debris flow hazards at the Tschengls torrent is based on the theoretical background of debris flow research and assesses the applicability of recent laboratory

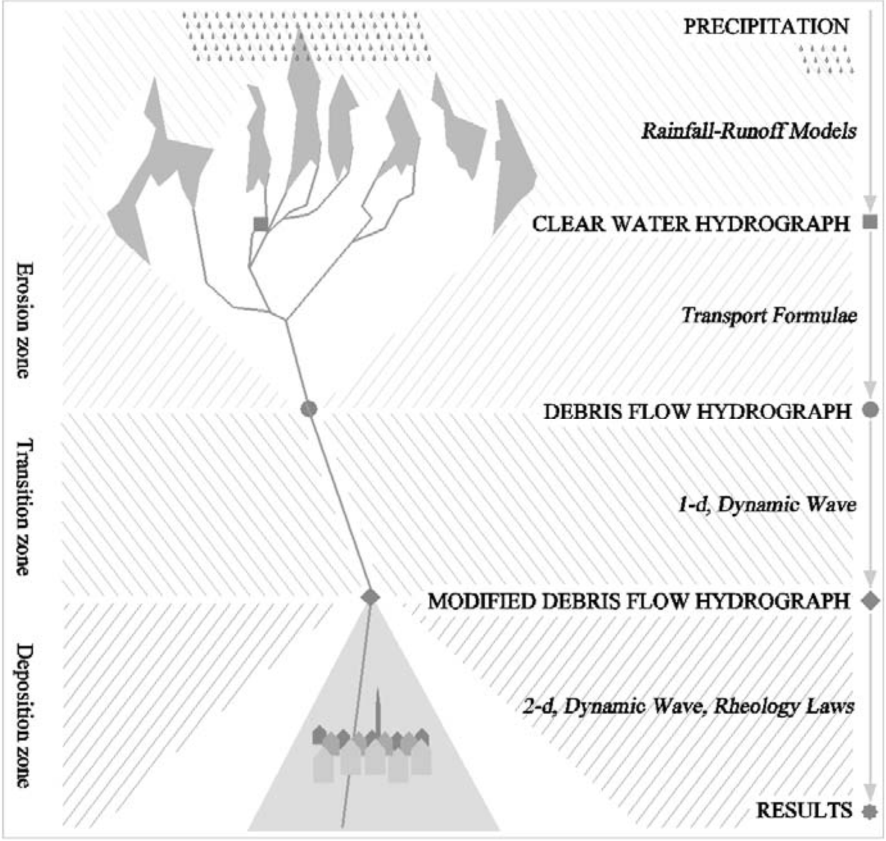

Figure 13: Flowchart of the Adopted Methodology That Takes into Account Debris Flow Initiation, Transport, and Deposition.

results. By means of extensive analysis, intensive field work and interviews with eyewitnesses, it has been possible to recognize essential characteristics of the Tschengls torrent, to assess its debris flow activity in a satisfactory detail and therefore to give recommendations for structural and nonstructural measures.

Figure 13 presents a flowchart of the adopted methodology. The modular and gradual structure of the physically based approach includes the formation, transportation and deposition of debris flows.

Analysis begins with a rainfall-runoff model. Precipitation data based on the local meteorological conditions are combined with the hydrological characteristics of the watershed to define clear water hydrographs at different points of interest.

Clear water hydrographs serve as input data for the next step of the analysis where debris flow hydrographs are developed, using different sediment transport formulae.

Debris flow hydrographs are routed through the transition zone using a 1D numerical model. Debris retention basins are considered in a simplified way.

The modified debris flow hydrographs represent the input for the 2D numerical model of the urbanized area. The simulation of different scenarios provides a series of results that allow to the proposal of mitigation measures.

A detailed description of the entire procedure can be found in Gostner (2002) and Gostner et al. (2003).

3.4.2. Situation in the Urbanized Area

In the numerical model (Figure 14), the depositions of a simulated debris flow event are shown. In the photo a portion of the deposits of the 1999 events can be seen.

For the investigation of the discharge capacity of the trapezoidal channel and of the deposition processes in the village and downstream, the numerical model FLO-2D (O'Brien et al. 1993 and O'Brien 2001) is used. FLO-2D is a two-dimensional flood routing model and allows the use of both clear water hydrographs and debris flows. The main results can be summarized as following:

1. The debris flows of 1999 can be reconstructed with the adopted methodology. Results of the modelling correspond well with reports

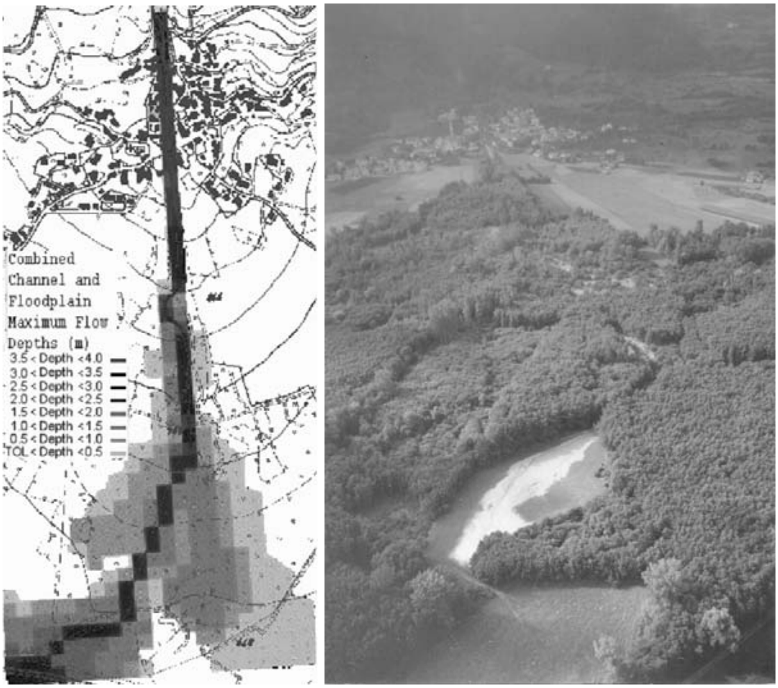

Figure 14: Numerical Model and Photo of the Deposition Zone with the Village of Tschengls (Upper Part) and the Alluvial Forest (Lower Part).

from eyewitnesses and field evidence. The first of the 1999 events corresponds to a debris flow with a high to medium probability of occurrence (return period between 30 and 100 years).

2. Maximum flow depths do not vary significantly and are enclosed in a narrow spectrum. However, the rheological behaviour of a debris flow is the determining factor for the maximum flow depth and not, as for clear water flow, the maximum discharge.
3. In general, the trapezoidal channel has a high discharge capacity due to the low roughness and the rather high slope of around 11 percent. The protection walls on both sides of the trapezoidal section contribute to the discharge capacity. Exceptions are two bridges that cross the torrent in the village. They restrict the discharge capacity of the torrent, and in several debris flow scenarios the maximum flow depth reaches the structure of the bridges.
4. The open area downstream of the village of Tschengls is sufficiently large for the deposition of debris flows, if the debris flow is routed across the village.

3.4.3. Proposal of Mitigation Measures

There are several measures that could mitigate the hydraulic risk of the Tschengls torrent; the most effective ones are briefly discussed in the following:

1. The side walls on both sides of the trapezoidal channel contribute significantly to the discharge capacity of the torrent. They confine the flow and allow it to pass through the village. Therefore it is necessary to examine their condition since they are around 130 years old and seem weakened in some places.
2. The study has shown that two bridges are the weak points in the village protection strategy since they restrict the channel capacity. The construction of mobile bridges would be an efficient measure. During a debris flow event they could be opened, enabling the debris flow to pass through. Mobile bridges exist in other countries and have already proven their effectiveness (Vischer and Bezzola 2000).
3. Emergency planning. Even if protection measures are well planned and executed, a residual risk remains. Thus it is of primary importance to plan for emergencies using temporary measures (for example, stop-logs at the openings of the side walls), warning devices and evacuation plans to prevent major damage in the case of catastrophic events.
4. Mapping of hazard zones should be done to prevent increased damage potential due to the urbanisation of the depositional area. This measure is very useful as there is still a large free surface available for the activity of the Tschengls torrent. In the village, the discharge section has to be maintained and the deposition zone should be utilized only extensively.

4. CONCLUSIONS

The case study of Tschengls presents an example of the way to deal with the natural danger of debris flows. The time series of debris flow events and the history of hazard management at the Tschengls torrent show the direct link between catastrophic events and subsequent protection works. Their realization was and is, of course, dependent on the availability of financial resources. In former times, protection measures were mainly based on empirical knowledge. The integrated analysis of the Tschengls torrent shows how modern research and better understanding of the physical processes involved in a debris flow event allow us to assess the debris flow activity of a torrent in satisfactory detail. Thus, it is possible to define more and more precise recommendations and to design structural and nonstructural measures. However, in order to provide reliable and useful results an integrated analysis based on scientific approaches must take advantage of all available sources including eyewitness accounts, written resources, field evidence, and event history.