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# Avalanche situation in Turkey and back-calculation of selected events

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Received: 24 December 2013 – Accepted: 8 January 2014 – Published: 21 January 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Abstract

In Turkey, an average of 24 people dies in snow avalanches every year, mainly in the eastern part of Anatolia and in the eastern Black Sea Region where high mountain ranges are close to the sea. The proportion of people killed in buildings is very high (87%), especially in comparison to other European and American countries. In this paper we discuss avalanche occurrence, the climatic situation and historical avalanche events in Turkey; in addition, we identify bottlenecks and suggest solutions to tackle avalanche problems. Furthermore, we have applied the numerical avalanche simulation software RAMMS combined with a Digital Elevation Model (DEM)-based potential release zone identification algorithm to analyze the catastrophic avalanche events in the villages of Üzengili (Bayburt province) in 1993 and Yaylaönü (Trabzon province) in 1981. The results demonstrate the value of such an approach for regions with poor avalanche databases, enabling the calculation of different scenarios and the estimation of run-out distances, flow velocities, impact pressure and flow height.

## 1 Introduction

Mountain ranges can provide valuable resources such as minerals, recreational services, wood for fuel and building material, and special agricultural products (Kräuchi et al., 2000). They are also an important source of water (Viviroli et al., 2007). However, mountain environments, due to their harsh topography and climatic conditions, are subject to natural hazards such as landslides, debris flows, rockfalls, flash floods and snow avalanches. Mountain areas occupy about one-fourth of the total land surface on Earth and are home to about one-tenth of all human beings (Ives et al., 1997; Price and Butt, 2000). Seventy-eight percent of Turkey's land surface consists of mountains, with 33.4 million people (about 47% of the country's total population) living in these regions (EEA, 2010).

**NHESSD**

2, 581–611, 2014

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Turkey in general is comprised of two peninsulas, Thrace and Anatolia, with a 2-D-area of 769 471 km<sup>2</sup>, excluding lakes (Elibüyük and Yılmaz, 2010). This present landform was created by the convergence of Tethys sea sediments located among the African, Eurasian and Arabian plates. Thus, Alpine orogeny began with this convergence and has continued up to present day (Bozkurt, 2001). Therefore, Turkey has been tectonically active, and this has directly affected the character of its landforms and determined its aspect, slope and elevation features. Mountain ranges run in a west-east direction, parallel to the Black Sea in the north and to the Mediterranean Sea in the south. Comparatively high mountains (e.g. the Ağrı Mountain at 5165 m and the Reşko summit of Cilo Mountain at 4168 m) and plains (e.g. the Doğu Beyazıt plateau at 2000 m and the Erzurum plateau at 1900 m) exist at the eastern part of the Anatolian peninsula (Fig. 1). According to a recent study (Elibüyük and Yılmaz, 2010) the mean altitude of Turkey is 1141 m a.s.l., more than three times higher than that of Europe (300 m a.s.l.), with a mean slope angle of 10°. Altitudes higher than 1500 m with slopes greater than 27° cover 5.1 % of the total area. These values dramatically increase in the eastern Black Sea Region, which has been identified as a hot-spot for avalanches. The average altitude and average slope of the eastern Black Sea area are 1662 m a.s.l. and 19°, respectively. The elevation of 66 % of the total land surface is higher than 1500 m a.s.l. and 22.6 % of all the slopes are steeper than 27° (Elibüyük and Yılmaz, 2010). Altitudes higher than 1500 m with slopes greater than 27° cover 12 % of the total eastern Black Sea Region (Erkan Yılmaz, 2012 personal communication, see Fig. 1).

Even though avalanches are a serious issue in Turkey, the management of snow avalanches has not yet attracted the necessary attention. According to a new regulation, the office of “Mountainous Areas Management (MAM)”, organized under the Turkish Forest Service, was established in 2011. This new office is mainly responsible for the prevention of floods, snow avalanches and landslides, and for preparing hazard and risk maps. Before the establishment of this office, the Avalanche Team (AT) of the General Directorate of Disaster Affairs (GDDA) was responsible for this task. The AT was established after the destructive 1992/1993 avalanche cycle in Turkey and had

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
⏪	⏩
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

undertaken various national and international projects (Gürer, 1998). Because of the recent reorganization, this team was abolished and all staff members were transferred to various other departments. This discontinuity has been a big drawback to setting up an institutional memory and years of accumulated experience have been lost. Due to the vagueness of the duties and responsibilities of the MAM, no avalanche events have been recorded since the AT was abolished in 2009. The MAM office is located in central Ankara and as of yet has no branch offices in local avalanche-prone areas. When avalanches occur, there is at present no one responsible for recording and documenting the events, drawing outlines or making necessary measurements and analyses. Therefore, only a few recorded events are available, and there is no updated avalanche database in place today in Turkey.

Snow and avalanche mitigation profits substantially from research and development (R&D) organizations such as the WSL Institute for Snow and Avalanche Research SLF in Switzerland and the National Research Institute of Science and Technology for Environment and Agriculture (IRSTEA, formerly CEMAGREF) in France. Continuity in research, determining the needs and gaps in research and practice, and increasing the quality of practical measures are some of the main aims of such institutions. In Turkey there are no such research institutes, resulting in a lack of support for practitioners and capacity building in the country.

Even though the MAM is responsible for the hazard and risk mapping of natural hazards in Turkey, no guidelines or regulations exist to define the process of hazard and risk mapping; therefore, there are no restrictions on land use. As a result, buildings, tourism facilities and traffic infrastructures are still being constructed in high-risk avalanche zones in Turkey.

In Turkey weather stations are operated by the State Meteorological Office (SMO). All stations are located in city centers, which do not represent the high mountain ranges or places far from the cities where the avalanches occur. Furthermore, the total amount of snow and rainfall precipitation as measured by the gauges is not differentiated. The



quality and scarcity of this meteorological data make them nearly meritless for analyzing avalanche events.

The aim of present paper is to describe the meteorological and avalanche situation in Turkey and to assess the applicability of a dynamic avalanche simulation model (RAMMS) to back-calculate two well documented events.

## 2 Climatic situation

In winter, Turkey is usually under the effect of polar air masses, classified as maritime polar (mP) and continental polar (cP). Maritime polar air masses originate in the Atlantic Ocean and pass over Europe from NW to SE (Fig. 2). They bring rainfall to the Black Sea coast and snow to the inland region. Continental polar air masses originate in Siberia and are very cold and dry. When they pass over the Black Sea, they become moister and can cause orographic rainfall in the Black Sea coastal zone. When cP air masses reach the Mediterranean region, they get warmer and gain moisture, resulting in thunderstorms. The Mediterranean and Black Sea mountain ranges run parallel to the coasts. This topography causes significant differences in climate from one region to another. While coastal areas have a milder climate, the high mountain hinterlands of the coasts receive high amounts (2 to 3 m) of snowfall (Gürer and Naaim, 1993), and the inland Anatolian plateau experiences cold winters with limited precipitation e.g. 443 mm in Bayburt and 407.5 mm in Erzurum (Sensoy, 2004; Akçar and Schlüchter, 2005; Bekereci et al., 2010). The orographic effects in both the Taurus and Black Sea mountains are dominant. For instance, in the eastern Black Sea Region, rainfall sharply decreases from coastal Rize, with a mean annual precipitation of 2200 mm, to the inland eastern Anatolian city of Erzurum, 130 km to the south, with mean annual precipitation of 407.5 mm. Both cities are situated north of the Mediterranean climate boundary (Akçar and Schlüchter, 2005).

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

### 3 Avalanche history

Historically, avalanches have occurred mainly in the eastern Black Sea Region, in eastern Anatolia, in the mountainous part of the south-eastern region of Anatolia, and last, but not least, in high and/or steep-sloped mountainous areas in the rest of the country (Fig. 3). Avalanche fatalities are high in Turkey, with an average of 24 lives lost per year. Between 1951 and 2006, 676 avalanches were recorded in the Turkish avalanche archives, with a total of 1325 fatalities and 365 injured (GDDA, 2009). Most of these accidents took place in the eastern and south-eastern parts of the Anatolian peninsula (Fig. 3). Out of the 1325 deaths, 120 (9%) were soldiers, 27 (2%) were hunters, 18 (1.4%) were skiers and climbers, 12 (0.9%) were buried in cars on highways, one (0.08%) was a worker; the remaining 1147 (86.6%) were local inhabitants trapped in their houses. About one-third of all recorded avalanches occurred in villages in the Trabzon, Rize and Bayburt provinces of the eastern Black Sea Region of Turkey (see Fig. 1). During field visits to the eastern Anatolian and eastern Black Sea Regions of Turkey, and after interviewing local people, we realized that the numbers in the archives seem to be significantly lower than the real numbers in terms of both, casualties and avalanche occurrences. Avalanche statistics demonstrate that avalanches in Turkey mainly affect settlements. In contrast, in the European Alps and in North America, most casualties result from winter sport activities (Schweizer and Lütshg, 2001; Zweifel et al., 2012; Atkins, 2010). In recent years winter tourism has also gained importance in Turkey, and the casualties have been increasing accordingly. As an example, on 25 January 2009, an avalanche in Zigana pass in Trabzon Province in Turkey's eastern Black Sea Region buried 17 mountaineers, 10 of whom lost their lives. Similarly, on 11 February 2006, 14 mountaineers were buried by an avalanche at Demirkazik summit in the Aladağlar Mountains of the Central Anatolian Region with four fatalities. During very extreme winter conditions, avalanches can occur at new locations where no avalanches have been observed before. On 25 and 30 December 1992, in two events in the Kastamonu province of Western Black Sea Region of Turkey, 13 people were killed, two

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



injured and 17 houses damaged (Gürer et al., 1995). The altitude of the starting zone of one of these avalanches (Kayaarkası avalanche) was located as low as approximately 900 m a.s.l. (Köse et al., 2010). Due to scarcity of avalanche data and the unavailability of an avalanche database in Turkey, we selected only the two best documented and studied avalanche events, in order to back-calculate them with avalanche dynamic simulation model of RAMMS. Thus, the 1993 Üzengili (Bayburt Province) avalanche, documented in several publications (Gürer and Naaim, 1993; Gürer et al., 1993), and the 1981 Yaylaönü (Trabzon Province) avalanche, where data was collected in the field and affected people interviewed by two of the authors, were selected for this study. Furthermore, these cases are located in the Bayburt–Rize–Trabzon triangle, a site accounting for one-third of all recorded avalanches in Turkey.

#### 4 Study area

This study was conducted in two different survey areas (Üzengili and Yaylaönü) in order to back-calculate the observed and documented avalanche events. Üzengili village is located at 40°23′00″ E–40°29′30″ N and is 41 km north of the Bayburt city center (Fig. 1). The village is located in the lee direction of the Soğanlı Mountains in the eastern Black Sea Region of Turkey. The altitude of the village is 1950 m a.s.l. and it is in a downstream area of bowl-shaped slopes. Yaylaönü village is located at 40°18′00″ E–40°35′15″ N and 105 km south-east of the Trabzon city center (Fig. 1). The village is located in the northern part of the Soğanlı Mountains in the eastern Black Sea Region of Turkey at an altitude of 1700–1900 m a.s.l., at the edge of the central section of an avalanche track.

For this study, we generated DEM datasets from 10 m contour interval and 1 : 25 000 scaled topographical maps. We generated raster data of the study area with a grid resolution of 10 m as input for the numerical simulations with RAMMS. Reference information on the events was obtained by interviewing affected people and, consulting photographs, newspaper articles and archives of official institutions.

### Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 4.1 The 1993 Üzengili avalanche

The Üzengili avalanche path consists of an open bowl in the upper part, a channeled track and an open run-out zone with slopes of  $7^{\circ}$  to  $10^{\circ}$  (Fig. 6). Both, the release and the run-out zones were sparsely vegetated with small bushes. The 1993 avalanche stopped about 500 m before the bottom of the valley. A brief description of the Üzengili avalanche and information on deposition height (at the center of the debris about 8–10 m) can be found in Gürer and Naaim (1993). A sketch (Fig. 9) by the GDDA describing the location of damaged buildings and mosque were given and it is assumed that this sketch shows the boundary of the avalanche. Information on building damage and a collection of observations from local people were taken from GDDA archives. All residential structures were constructed from bricks and wooden material. Only mosque was constructed of masonry. Release depth estimation was done based on Gürer and Naaim (1993) and villagers' statements and finally we use 160 cm for the model.

The avalanche mass started from the high part of the mountain on 18 January 1993 at 7.30 a.m. and buried 85 houses, 72 of which were completely destroyed or transported to the far end of the run-out zone (Fig. 4). Fifty-nine people were killed and 21 injured. Prior to the avalanche release, new snow had fallen continuously for a period of three days, with heavy northern winds which brought 70 cm of fresh and dry snow; the air temperature had consistently remained at well below zero (Gürer and Naaim, 1993). The villagers inferred that the first avalanche had come from the slope on the orographic left hand side (the release zone of this avalanche is visible for the villager), filling the channel with snow deposits. Just a few minutes later, a second avalanche came from the slope on the right hand side (this release zone is invisible for the villager) and flowed over the previously filled channel, destroying large parts of the village. People mentioned a past avalanche which had occurred around 1890, in which 10 houses disappeared. Other than this information, no one living there could remember any other avalanche.

NHESSD

2, 581–611, 2014

### Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion







specific events (Bartelt et al., 2012; Christen et al., 2010b; Bühler et al., 2009). The software is commercially available and is used by avalanche experts and engineering offices to plan hazard mitigation projects around the world. Currently, a module for snow avalanche and one for debris flow simulations are available; modules for shallow landslides and rock falls are under development (<http://ramms.slf.ch>).

## 6 DEM-based release zone identification

Release zones for the Üzengili case were determined using a Geographical Information Systems (GIS)-based digital elevation model DEM analysis. No snow-pack or meteorological parameters are included in this analysis. Slope, planar curvature, roughness and size are the main parameters which are derived from the DEM in this procedure (Bühler et al., 2013). It is a further expansion of the algorithm developed by Maggioni and Gruber (2003) and works with high spatial resolution DEM datasets (10 m resolution and better). In this study, a DEM resolution of 10 m, a slope range of 28–60° a curvature threshold of 3 and a ruggedness threshold of 0.03 were used. After a final plausibility check by an avalanche expert and a correction procedure the release zones were used as input for the numerical simulation software RAMMS. Such an approach has the potential to be used for large-scale hazard mapping (Gruber and Bartelt, 2007).

We identified 10 potential release zones in the first step using the DEM-based algorithm, see Fig. 6. In the second step, we checked the release zones manually and selected and corrected the polygons, based on expert knowledge. Strong winds from the north and 70 cm of freshly fallen snow (over 10–20 cm of old snow) had been observed by the villagers just before the event. The release zones were located significantly higher than the Üzengili village. Therefore, based on the Swiss Guidelines (Salm et al., 1990), we used a snow depth of 160 cm and included 50 cm of wind accumulation to calculate the release depths.

For Yaylaönü event all information was collected in the field by interviewing villagers and observers. During the avalanche, strong winds from the south and more than 24 h

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of continuous snowfall (90 to 100 cm) were reported. Three main release zones were identified. Based on this information, the release depth was estimated to be around 160 cm (Fig. 7).

## 7 Results and discussion

### 7.1 Applied scenarios

In Üzengili, the avalanche occurred at 7.30 a.m. and according to villagers' observations came from the left-hand side slope (in the flow direction) and filled the track with a deposit of snow. Just a few minutes later a second avalanche came from the slope on the right hand side, causing the damage, so we know that the two avalanches came just one after another. In order to corroborate the villagers' statements with numerical avalanche simulations, we used six different elaborated scenarios (Table 1). RAMMS allows DEM modifications, for example, updating the track with a previous avalanche deposit. For scenarios 2 to 6 we made the DEM adaptation after releasing zone number 1. Then we released the other zones over the adapted DEM to see the effect of filling the track by the first avalanche. We applied six different probable scenarios, but only scenario 3 was able to cause an event as big as had been observed; the results of scenario 3 are presented in the following sections.

At the Yaylaönü site, the avalanche occurred at 09.00 a.m., so the eyewitnesses were clearly able to identify the release zone. The 1981 avalanche originated from release zone number 1, see Fig. 7. Release zone number 1 was leeward of the strong south to north winds and the snow had accumulated heavily. Release zones number 2 and 3 were located at the windward side and the wind caused the snow to drift from there to behind the northern ridge. Thus, only the avalanche release zone number 1 scenario was applied; the results are reported in the following sections.

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 7.2 Friction parameters

In RAMMS friction parameters can be specified as constant (for the whole calculation domain) or variable. Constant values are recommended for a first attempt to quickly analyze the problem (Christen et al., 2010b). Variable friction parameters for the entire calculation domain are automatically calculated using GIS-based terrain analysis for different return periods and avalanche volume classes (RAMMS Manual, 2010).

In RAMMS, the dry coulomb friction  $\mu$  and the velocity dependent turbulent friction  $\xi$  depend on the avalanche volume, the return period and the terrain. We used values based on the calibration with avalanche events within the SLF real scale test site Val-  
lée de la Sionne, in Switzerland. Because both events can be considered as extreme and the volumes have been large ( $> 60\,000\text{ m}^3$ ) we have chosen corresponding friction values. The aim of this study was not to calibrate the friction parameters for Turkish avalanches. Thus, for both study areas constant values of  $\mu$  and  $\xi$  were used for the entire calculation domain. For the Üzengili avalanche site  $\mu=0.19$  and  $\xi = 2100\text{ ms}^{-2}$  were selected, respectively. Because we had a channeled avalanche track at the Yay-laönü avalanche site, the parameters were selected as  $\mu = 0.24$  and  $\xi = 1500\text{ ms}^{-2}$ , as suggested in the Swiss Guidelines (Salm et al., 1990). The Swiss Guidelines were developed for the analytical Voellmy–Salm model. These values were adapted for numerical simulation with AVAL-1D (Christen et al., 2002) and RAMMS. These adaptations are based on the back calculation of numerous large scale avalanches in a dissertation at SLF (Gruber et al., 1998; Gruber 1998, Gruber and Bartelt, 2007). The adapted  $\mu$  and  $\xi$  values are listed in Bartelt et al. (2010).

## 7.3 Flow heights, velocities and impact pressures

### Üzengili avalanche site

At the Üzengili avalanche site, according to the statements of eyewitnesses, the deposition height was about 7–8 m. This value may have occurred in some places due to the

**NHESSD**

2, 581–611, 2014

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

obstacle effect of buildings. When considering the comparably wide run-out zone, a deposition height of 3–5 m at the center part was thought to be reasonable. However, at the eastern part of the deposition zone much less deposition height simulated which is higher in the real situation. Contrary, at the most down part of the deposition zone even no deposition observed a little bit deposition simulated (Fig. 8). A sketch (Fig. 9) by the GDDA describing the location of damaged buildings by the avalanche is included and it is assumed that this sketch shows the boundary of the avalanche. Since no detailed information on flow velocity or impact pressure was available, the simulation result could not be verified. However, a pressure of 10–20 kPa has been estimated at the mosque by visual interpretation on photographs which shows structural damages (Fig. 4), and corresponds well with the simulated avalanche results (M. Schaer, personal communication, 2012, SLF). Flow velocity and impact pressure for the entire avalanche track are given in Fig. 8. Furthermore, the impact pressure forces calculated at the mosque location are shown in Fig. 10.

### Yaylaönü avalanche site

At the Yaylaönü avalanche site, the villagers' statements about a deposition height of 6–7 m seemed to be realistic. Due to a narrow, channeled run-out zone, simulation results also showed deposition to be around 7 m at the deposition zone, which complies with the villagers' statements (Fig. 11). In 1981 the avalanche damaged the school building by breaking doors and windows and uplifting roof, but it was not completely destroyed. Maybe the damages at the building were caused by a powder cloud. A pressure of dense part of avalanche less than 1–2 kPa could have been seen at the edge of the school building and seems to be acceptable. The simulation results support this argument. A sketch based on villagers' statements drawing the outline of the 1981 avalanche (Fig. 7) corresponds to the outline of the modelled avalanche (compare Fig. 7 and Fig. 11). Impact pressure for the entire avalanche track are given in Fig. 11; impact pressure forces calculated at the damaged school location are shown in Fig. 12.

## 8 Conclusions

Turkey is a fast developing country, with more than 78% of its territory in mountainous areas. According to information from Ministry of Transportation, 15 700 km of new double-lane highways have been constructed over the last ten years and there are plans to build another 15 000 km of new railway lines by the year 2023. Furthermore, winter sport activities have been increasing in Turkey during the last decade. It can be inferred that the importance of avalanches as a major natural hazards in Turkey will increase substantially.

In Turkey, the proportion of avalanche fatalities who die in their homes is very high (87%) compared with European and North American countries; for example in Switzerland and in the United States less than 5% of the people who die in avalanches are killed in their houses. This is the result of the long history of great efforts in avalanche research, hazard mapping and mitigation measures established in this regions.

Avalanche mitigation requires a multidisciplinary approach. Thus in Turkey, a multidisciplinary organizational structure which includes foresters, GIS experts, civil engineers and geographers at the central and local offices of avalanche-prone areas are needed to improve the situation. Legislation gaps must be filled in order to outline a concrete definition of organizational duties and responsibilities. Avalanche mitigation needs the support of a strong R&D department. Unfortunately, in Turkey not many scientists or researchers are involved in avalanche studies. Establishing an independent research institute would ensure success in meeting the needs of operational branches and in the training of research staff. Furthermore, it is necessary to obtain sufficient meteorological data reflecting high mountain conditions. This could be achieved by setting up an organized alpine weather station network.

The Üzengili (Bayburt) and Yaylaönü (Trabzon) avalanches were selected to test the feasibility of using RAMMS in such cases. Even without meteorological data and the lack of exact release area information of the Üzengili avalanche, RAMMS produced realistic results. The DEM-based release generation is a big help but requires expert

**NHESSD**

2, 581–611, 2014

### **Avalanche situation in Turkey and back-calculation of selected events**

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



knowledge; using the generated release zones directly as input of RAMMS can be deceptive and cause unrealistic results.

We used default friction values with little modification in the Üzengili avalanche simulations, as recommended by the Gruber et al. (1998), Gruber (1998), Gruber and Bartelt (2007) and Bartelt et al. (2012). For the Yaylaönü avalanche site, we used the parameters for channeled avalanches which are recommended by the RAMMS Manual (Bartelt et al., 2010). Even though, RAMMS is calibrated for large scale avalanches in Switzerland. It is very important to see that this model works also well in a climatically completely different regions such as Turkey with realistic results for our cases. This indicates the robustness and reliability of the Voellmy–Salm approach for avalanche simulation to improve hazard mapping and hazard zonation where such simulations are missing for other areas than for the European Alps. But users should be very careful in using and keep in mind some main limitation of dynamic models such as calibrating parameters, sensitivity analysis, problems originated from event documentation and so on (Jamieson et al., 2008).

Although villagers in Üzengili claimed that the second avalanche had come from the right hand side slope (in flow direction), simulation results did not agree with this statement. We concluded that the second avalanche originated from release zones number 3–5 of the left hand side slope (see Fig. 6 and Table 1).

This study shows that based on the observations and estimations made in this paper we assume that RAMMS can be help for hazard mitigation planning. The impact forces predicted by RAMMS at the mosque (Üzengili avalanche) and the school location (Yaylaönü avalanche) are in good agreement with the observed situation. Although generalization is not recommended, using RAMMS with expert knowledge for sparsely-documented events can yield valuable information. Many countries with alpine regions exist, where no or very sparse historic avalanche information exists. It is interesting to read for them how the tools developed elsewhere can be applied and what limitations and problems occur. Besides, Hazard mapping in remote regions is a demanding task. However to do nothing is not an option in many regions. The application of numerical

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



simulations can therefore be a big help by keeping in mind their limitations, necessity of good event documentation and expert opinions. This papers show how such a tool can be applied.

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## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

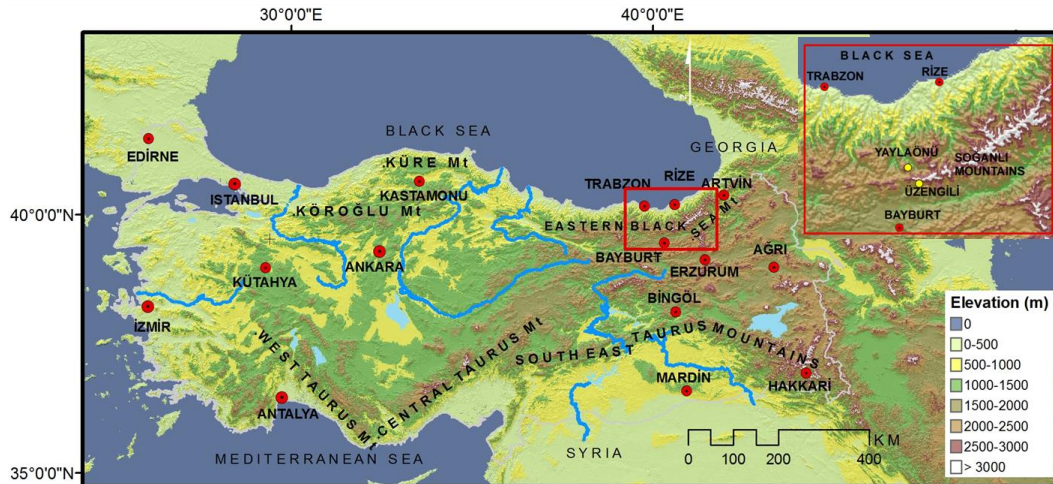
Interactive Discussion

**Table 1.** Applied scenarios (See Fig. 6).

Scenarios	Release Zones		Remarks
	First	Second	
S1	–	–	All released individually
S2	1	2–5	DEM adaptation procedures applied
S3	1	3–5	DEM adaptation procedures applied
S4	1–2	3–5	DEM adaptation procedures applied
S5	1	6–7	DEM adaptation procedures applied
S6	1	8–10	DEM adaptation procedures applied

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

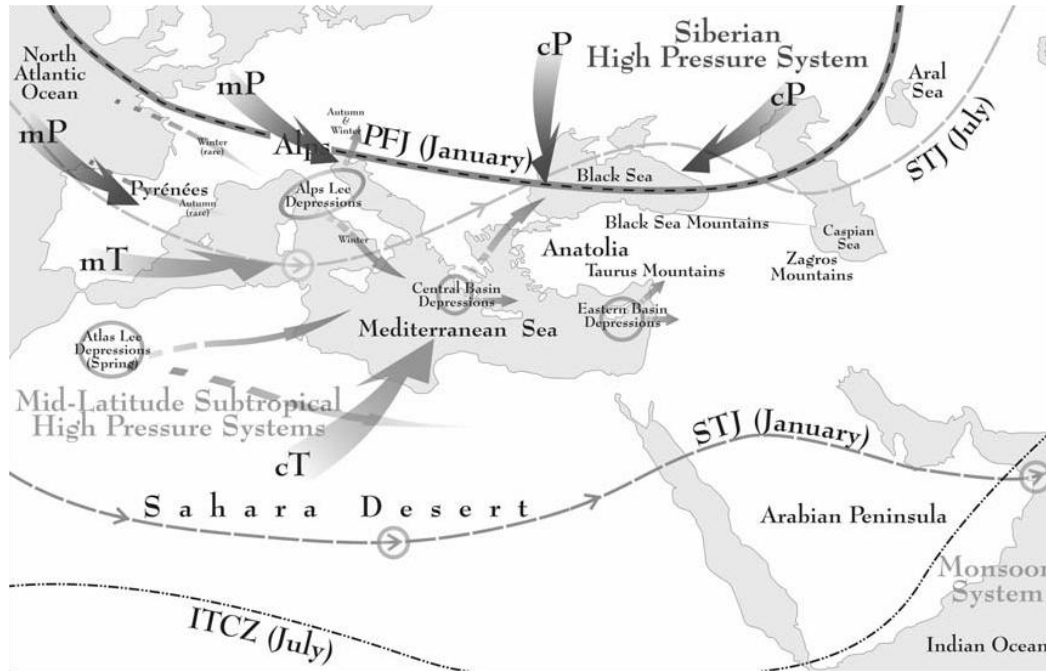


**Fig. 1.** Physical map of Turkey showing the most important mountain ranges and study areas (upper right corner).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
⏪	⏩
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

**Avalanche situation  
in Turkey and  
back-calculation of  
selected events**

A. Aydın et al.

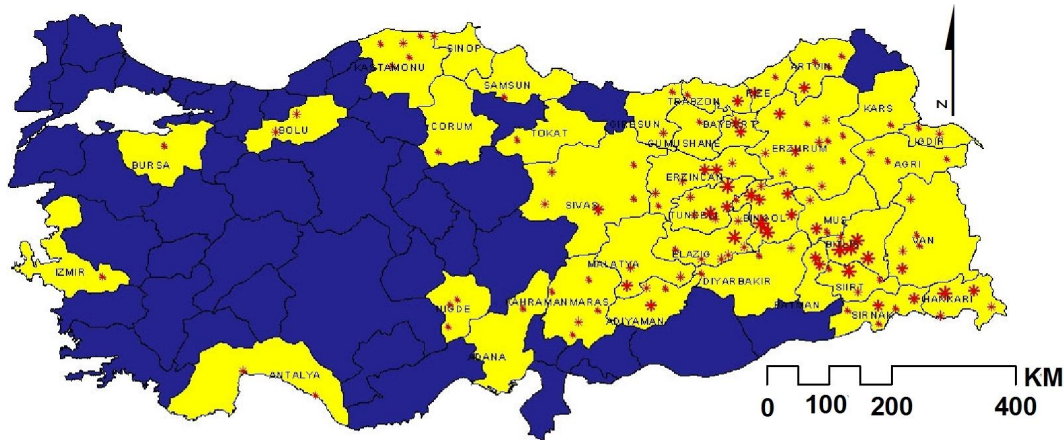


**Fig. 2.** Air masses affecting Turkey (Akçar and Schlüchter, 2005).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.



**Fig. 3.** Avalanche record map of Turkey (Yellow color refers avalanche observed cities and red star refers recorded avalanche locations, Source: GDDA).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 4.** Destroyed mosque due to 1993 avalanche event in Üzengili village.

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Avalanche situation  
in Turkey and  
back-calculation of  
selected events**

A. Aydın et al.



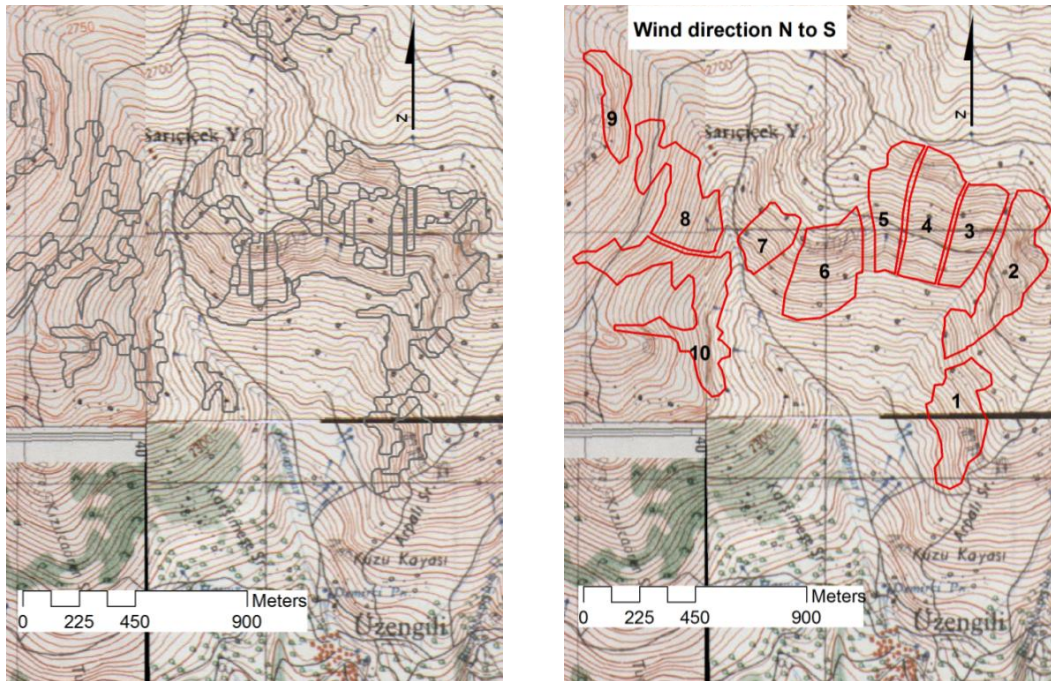
**Fig. 5.** Damaged school building (red ellipse) and houses (black ellipse) due to the 1981 – house indicated in blue circle constructed in 2004.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.



**Fig. 6.** Identified release zones by DEM-Based release zone generation approach (left); corrected release zones to use in simulations at Üzengili (right) with a DEM resample of 10 m, a curvature threshold of 3 and a roughness threshold of 0.03.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

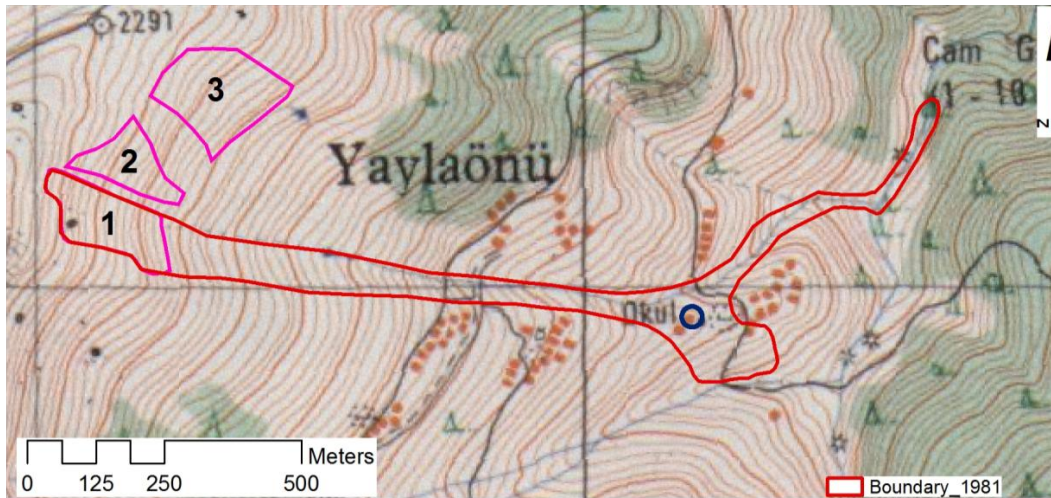
Back

Close

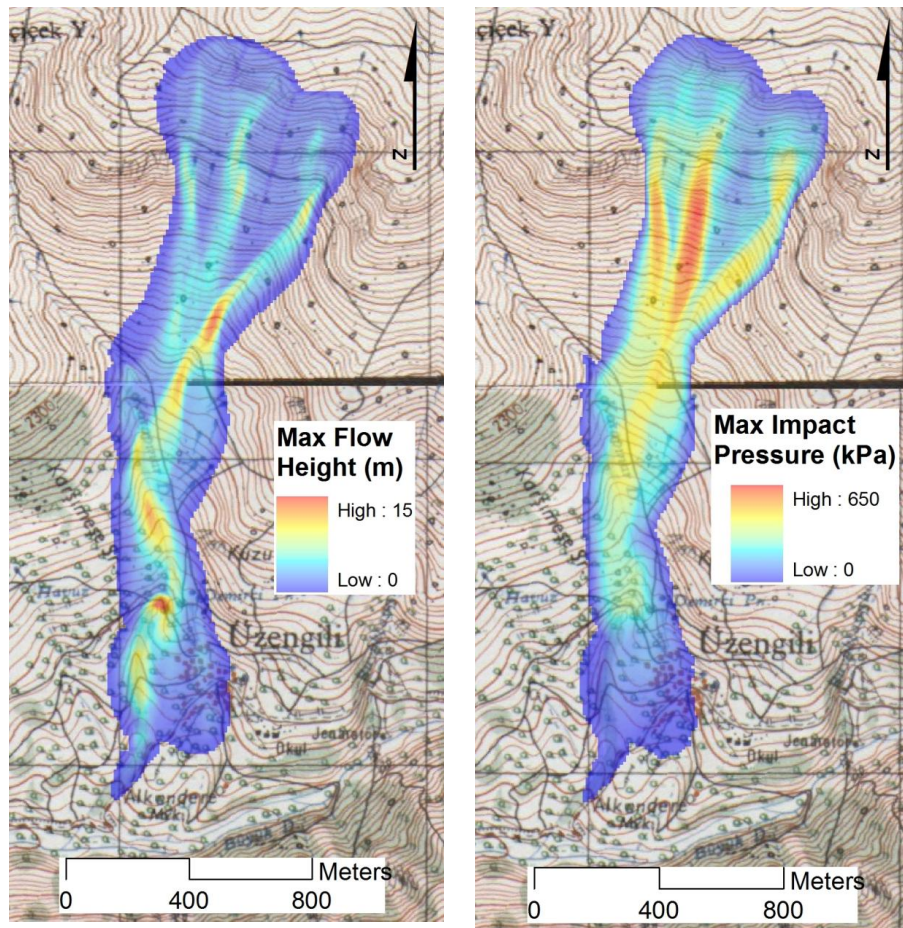
Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 7.** Outlines of the 1981 avalanche event and potential release zones (damaged school indicated in blue circle, see Fig. 5).



**Fig. 8.** Maximum flow height (left), maximum flow velocity (middle) and maximum impact pressure (right).

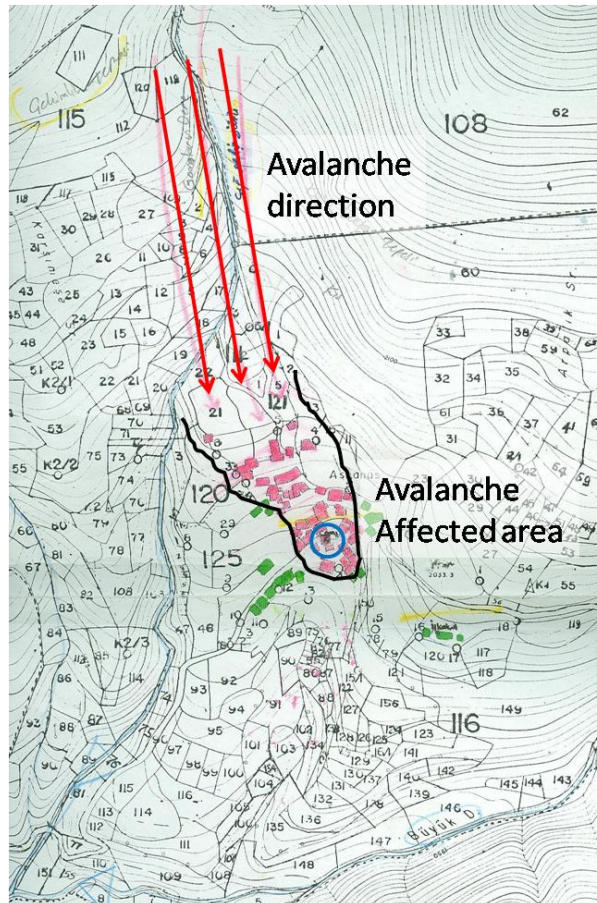
**Avalanche situation  
in Turkey and  
back-calculation of  
selected events**

A. Aydın et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.



**Fig. 9.** Avalanche affected houses (red); non affected houses (green); mosque indicated in blue circle, see Fig. 4 (Source: GDDA).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

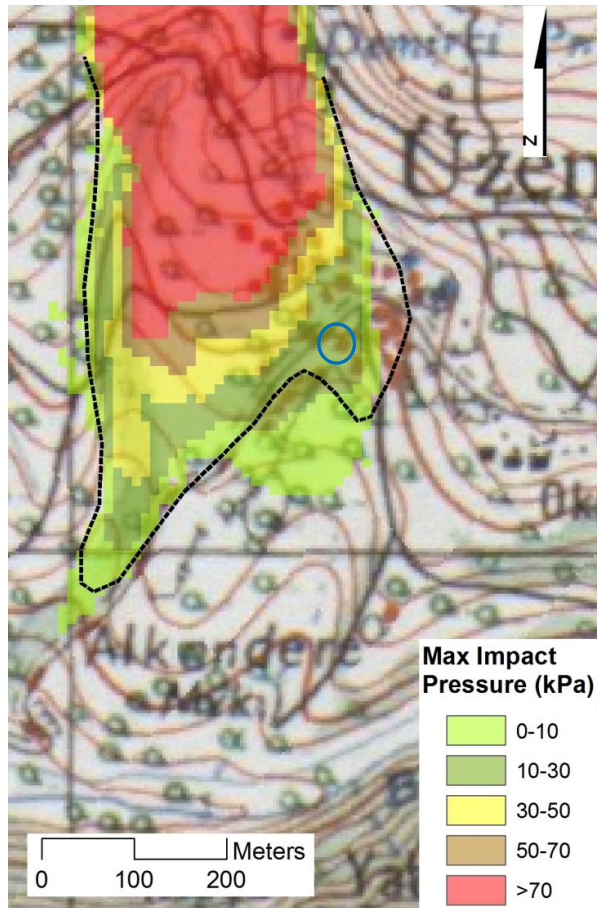
Back

Close

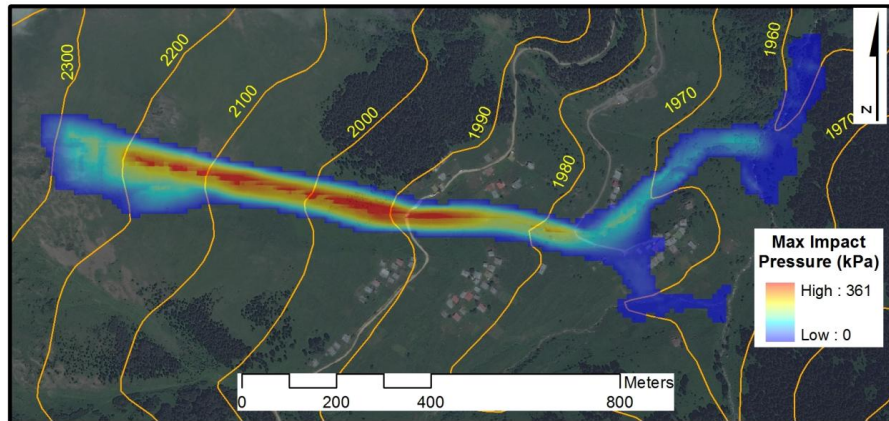
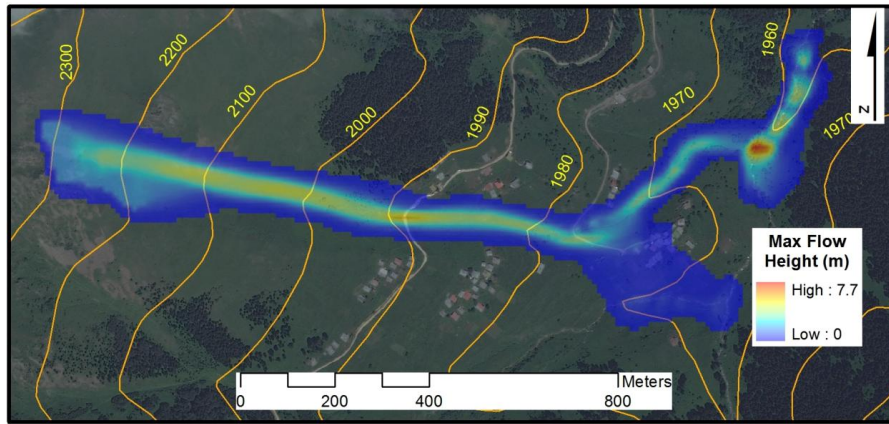
Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 10.** Avalanche impact pressure at damaged mosque area (mosque indicated in blue circle – see Fig. 4, dashed black line indicate the outline of observed avalanche).



**Fig. 11.** Simulation result of Yaylaönü project area: maximum flow height (top) and maximum impact pressure (bottom).

## Avalanche situation in Turkey and back-calculation of selected events

A. Aydın et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Avalanche situation  
in Turkey and  
back-calculation of  
selected events**

A. Aydın et al.



**Fig. 12.** Damaged school during 1981 avalanche; impact pressure forces of around 1–2 kPa.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)