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MAMODIS – a universal, cost-effective debris flow detection system based on infrasound and seismic signals

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Abstract. The automatic detection of sediment related disasters like landslides, debris flows and debris floods, gets increasing importance for hazard mitigation and early warning. Past studies showed that such processes induce characteristic seismic signals and acoustic signals in the infrasonic spectrum which can be used for event detection. The presented system MAMODIS (MAss MOvement Detection and Identification System) is a detection system for debris flows, debris floods and avalanches based on a combination of infrasound and seismic signals. The detection system consists of one infrasound sensor, one geophone and a microcontroller, where a specially designed detection algorithm is executed. This algorithm reliably detects events in real time directly at the sensor site. The setup can be easily installed beside a torrent or an avalanche path and therefore can be used as a low-cost and practicable solution for early warning. In addition, this system offers first information of the process-type and a rough estimation of the peak discharge and the total volume for debris flows and debris floods. These values are calculated from the infrasound and seismic signals. Currently the system is installed on several sites in Austria, Switzerland and Italy.

Key words: *debris flows, avalanches, detection system; infrasound; seismic signals*

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MAMODIS – универсальная, экономически эффективная система обнаружения селевых потоков на основе инфразвуковых и сейсмических сигналов

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Аннотация. Автоматическое обнаружение бедствий, связанных с осадками, таких как оползни, селевые потоки и селевые потоки, приобретает все большее значение для смягчения последствий опасностей и раннего оповещения. Прошлые исследования показали, что такие процессы вызывают характерные сейсмические сигналы и акустические сигналы в инфразвуковом спектре, которые могут использоваться для обнаружения событий. Представленная система MAMODIS (MAss MOvement Detection and Identification System) представляет собой систему обнаружения селевых потоков, селевых потоков и лавин, основанную на сочетании инфразвуковых и сейсмических сигналов. Система обнаружения состоит из одного инфразвукового датчика, одного геофона и микроконтроллера, в котором выполняется специально разработанный алгоритм обнаружения. Этот алгоритм надежно обнаруживает события в реальном времени непосредственно на месте расположения датчика. Установка может быть легко установлена рядом с потоком или траекторией схода лавины и, следовательно, может использоваться в качестве недорогого и практичного решения для раннего оповещения. Кроме того, эта система предоставляет первую информацию о типе процесса и грубую оценку пикового расхода и общего объема селевых потоков и селевых потоков. Эти значения рассчитываются на основе инфразвуковых и сейсмических сигналов. В настоящее время система установлена на нескольких объектах в Австрии, Швейцарии и Италии.

Ключевые слова: *селевые потоки, лавины, система обнаружения; инфразвук; сейсмические сигналы*

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Introduction

Automatic detection of alpine mass movements is an important tool for protecting people and property in the fast socio-economic developing mountain areas. Although different warning systems like wire sensors, radar, ultrasonic sensors (flow depth) etc. already exist, most of the present methods need sensors placed in or above the process itself, which leads to expensive structures and continuous maintenance to ensure steadiness and stability.

Alpine mass movements like debris flows and debris floods or avalanches induce waves in the low-frequency infrasonic spectrum (e.g. [*Kogelnig et al., 2014*]) and characteristically seismic waves (e.g. [*Burtin et al., 2016*]). These infrasound and seismic waves produced by the mass movement can be used for detecting events before a surge passes the sensor location and to monitor mass movements from a remote location unaffected by the process.

There have already been several approaches for automatic detection of debris flows based on seismic signals (e.g. [*Walter et al., 2017*]) and also infrasound signals are commonly used for detecting avalanches or debris flows (e.g. [*Marchetti et al., 2019*]). Seismic and infrasound waves have different advantages and disadvantages, so a combination of both technologies can increase detection probability and reduce false alarms (e.g. [*Hübl et al., 2013*]).

However, up to date no system has been designed which uses a combination of low-cost seismic and infrasound sensors for an automatic detection of sediment related disasters of different types. So, this work aims to develop a reliable universal detection system for alpine mass movements, which is based on one infrasound and one seismic sensor and can detect different processes in real time directly at the sensor site [*Schimmel et al. 2017, 2018*]. The benefits of these methods include independence from weather conditions regarding visibility, no structural need for sustainability, same system for different kinds of mass movements and monitoring from a remote location unaffected by the process. Further, this approach can also offer a first estimate of the peak discharge, and the total volume of debris flows and debris floods based on the infrasound and seismic signals.

Methods

System setup

The MAMODIS system (MAss MOvement Detection and Identification System) is based on a modular setup to offer an inexpensive and practical solution for different applications.

The infrasound sensor used for the MAMODIS system is a modified differential pressure sensor with a measurement range from -50 to 500 Pa. As seismic sensors, we use the SM-6 with a sensitivity of 28.8 V/m/s and a natural frequency of 4.5 Hz. The system offers the possibility for a second geophone input, which can be used for estimation of the mass movement velocity. The process velocity is calculated via cross-correlation of booth seismic signals [*Schimmel et al. 2022*].

The sensor signals have to be adapted for the input of the microcontroller, which is done by a non-inverting OPV circuit and band pass filtering. These input signals are sampled by the microcontroller ADC (analog-to-digital converter) with a sample rate of 100 Hz.

A STMicroelectronics development board with the microcontroller STM32L4R9AI (former version: Texas Instruments, TM4C129X) is used for data processing and as data-logger. The software for the microcontroller is based on the open-source runtime system FreeRTOS. The development board has a 12-bit ADC module, five UARTs (Universal Asynchronous Receiver Transmitters), several GPIOs (General Purpose Input/output), which can be used as alarm outputs, and a 1.2" AMOLED display with touch-screen function. The data can be stored on a micro-SD card where sizes of 8 GB, 16 GB or 32 GB can be used, and up to eight months (32 GB, one geophone) of data can be recorded continuously.

Besides the input of the sensor signals, the free ADC channels offer the possibility to log the flow height measured by a radar or ultrasonic gauge (input 4–20 mA), which can be used for event verification. In addition, the power supply voltage is monitored to check for low power and an input for a second infrasound sensor is available. Communication of the system can be conducted via a GSM module or a WIFI module. The system is designed to send a status message to a server every hour using MQTT. In case of an event a MQTT message is sent at detection and at the end of the event a summary including detection time, duration, type, and magnitude estimation is sent to the server. This server creates e-mail alerts and summaries in case of an event. The status and event data of all stations can be viewed on a Grafan platform and additional on a webserver (http://mamodis.ddns.net/).

The time synchronization of the station is done by either a connection with a time server via GSM or WIFI module, or by a GPS module, which is also connected via UART. The alarm output can be done by Relays or via a radio link with a LoRA RF-Module. An overview of the hardware components and the inputs and outputs of the system is given in Fig. 1.

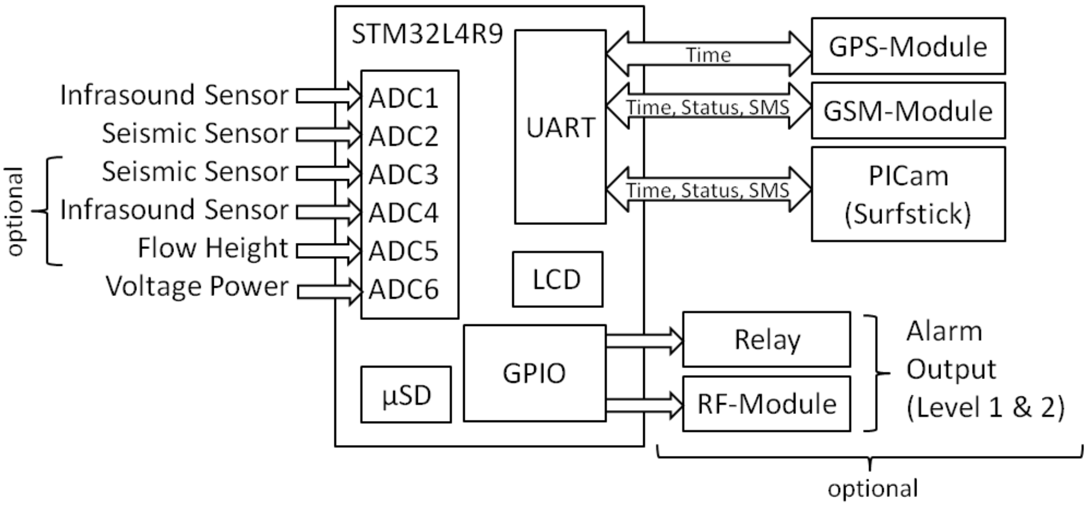

Fig. 1. Overview system setup and components

The system operates at a voltage of 5 V, provided by a DC–DC converter, which needs a power connection at a voltage range from 6.5 to 32 V. The system has power consumption between 0.6 to 1 W (depending on the equipment), which makes this system very suitable for stand-alone stations using a solar power supply, as is typically used. A typical system setup is shown in Fig. 2.

The MAMODIS System is currently installed on 11 sites in the Alps (Fig. 3; blue dots: snow avalanches, red dots: debris flow). Data and further information on these sites are available at: http://mamodis.ddns.net.

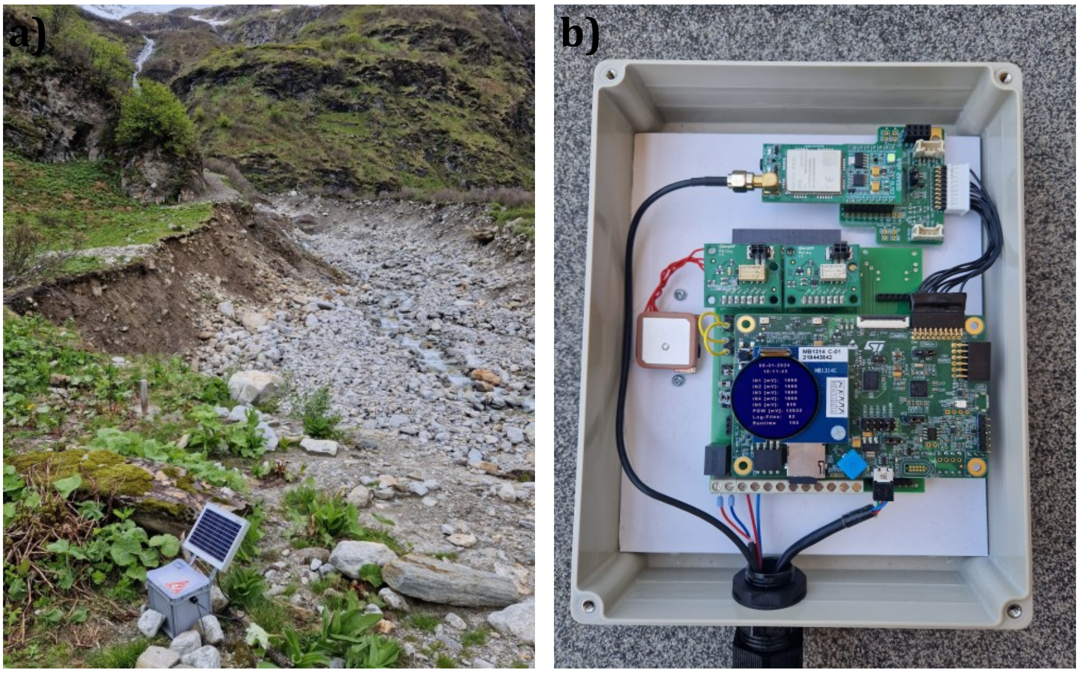

Fig. 2. System setup at the site Pilatuskar (a) and closer view of the microcontroller unit (b)

Fig. 3. Systems installed in 2025 (blue dots: snow avalanches, red dots: debris flow).

Detection algorithm

The principle of the detection algorithm is already presented in [*Schimmel et al., 2018*] so only a short summary is given below. For the automatic detection of debris flows based on seismic and infrasound data, a detection algorithm had to be developed, which identifies events as early as possible, without false alarms, in a simple way, so that the algorithm can be used in real time directly at the sensor location without extensive requirements on computing effort (on a resource limited microcontroller).

The developed detection algorithm analyses the evolution in time of the frequency content from the infrasonic and seismic mass movement signals. Different frequency bands are used to analyse the infrasound signal, whereby a 3 to 15 Hz band characterises debris flows, and a 15 to 45 Hz band is used for debris floods. For snow avalanches a 2 to10 Hz band is used for powder avalanches and a band from 11 to 40 Hz is used for wet snow avalanches. For the seismic signals a frequency band from 10 to 30 Hz is used for sediment related mass movements and a frequency band from 5 to 25 Hz is used for avalanches [*Kogelnig et al. 2012*]. Three criteria must be fulfilled for a specified Detection-Time (20 s for debris flow and debris flood; 8 s for snow avalanches) to identify events:

1. The average infrasound and seismic amplitudes of the debris flow/debris flood or avalanche frequency bands must exceed a certain threshold (to distinguish between different event sizes, two limits are used: Level 1 (L1) and Level 2 (L2)).
2. The average infrasound amplitudes of the debris flow/debris flood or avalanche frequency band have to be at least above a third (for debris flows and powder avalanches) or a fourth (for debris floods or wet snow avalanches) of the amplitudes of the frequency band below. These criteria can avoid false alarms due to wind that dominates this low-frequency band.
3. The variance of the seismic and infrasound amplitudes has to be under a limit (to avoid false alarms from artificial sources, since this variance in the amplitudes of the broad-banded debris flow or debris flood signals is low, compared to narrow-banded signals from artificial sources).
4. Because bedload transport processes as well as debris flows and debris floods can be detected, a further criterion is needed to enable identification of event type. For debris flow/debris flood detection, the seismic amplitude must rise at least beyond the threshold used for the amplitude criterion during the detection time.

Using the combination of seismic and infrasound signals, we achieve a high detection ratio and a strong reduction in the frequency of false alarms.

Results and discussion

Detection example

Since 2015 the system is installed at the Illgraben, near Leuk in the canton Vallis in Switzerland. The catchment area of 9.5 km^2 extends from the summit of the Illhorn at 2716 m a.s.l. down to the Rhône valley at 610 m a.s.l. and is one of the most active debris flow catchments in the Alps. The debris flow used as detection example was recorded on 07.08.2021 with a peak discharge of 41 m^3/s and a total volume of 39.738 m^3 [*de Haas et al., 2022*].

The event was detected at sec. 2337 for Level 1 and at 2479 s for Level 2. So, the time between detection and passing of the first surge at the sensor site (2561 s) was 224 s for Level 1 and 82 s for Level 2 which is an adequate time for early warning. The total volume calculated based on the infrasound and seismic signal was 15.445 m^3 which underestimate the measured total volume, but the estimation of the peak discharge of 50 m^3/s fits very well with the measured peak discharge.

In total, 43 Level 1 events and 77 Level 2 events (debris flows, debris floods as well as high discharge with sediment transport) have been detected since 2015 on all debris flow sites listed in the map at Fig. 2. A total of 22 events were not detected on the Illgraben and Gadria sites because there were temporary problems with the power supply or with the infrasound sensor and a broken geophone cable. At the stations Gadria and Lattenbach a series of false alarms occurred, which were all caused by construction work in the channel close to the station (construction of riprap, work on protection structures or clearing of retention basins). However, since this work can be delimited in time, it is possible to clearly identify these false alarms, and they can be avoided by temporarily increasing the threshold values of the detection algorithm. No false alarms occurred at the other stations during the entire runtime.

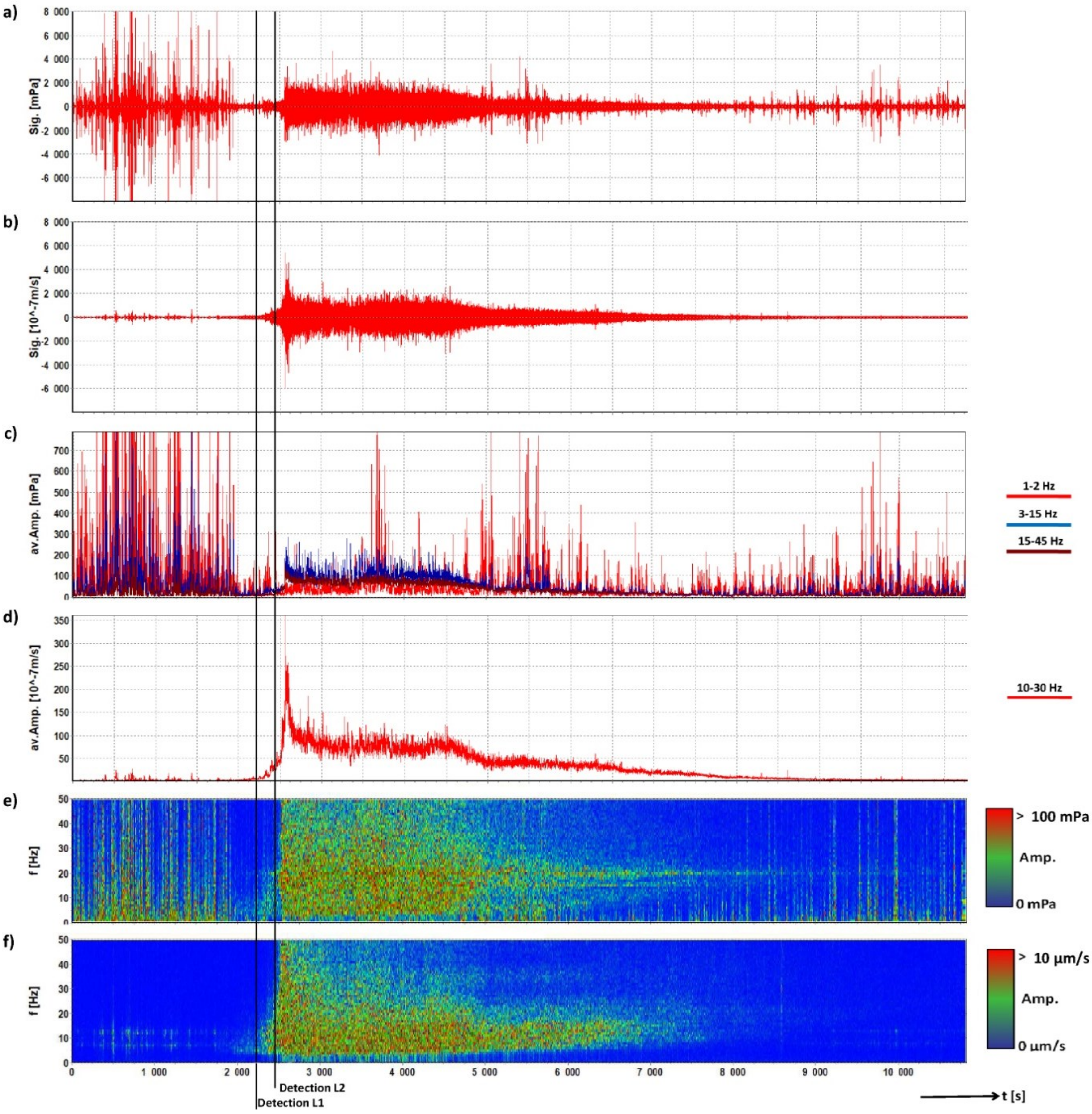

Fig. 1. Debris Flow at Illgraben (07.08.2021): (a) Infrasound time series; (b) Seismogram; (c) Average amplitude of the three frequency bands of the infrasound signal; (d) Average amplitude of the frequency band of the seismic signal; (e) Running spectrum of the infrasound signal; (f) Running spectrum of the seismic signal; Lines: time of detection for Level 1 and Level 2. Signals are represented with a common base of time.

Magnitude estimation

The system also offers a first estimation of the event size of debris flows or debris floods based on the infrasound and seismic data. The infrasound and seismic energy correlates passably with the discharge of an event (e.g., [*Coviello et al., 2019*]), so we compared the maximum infrasound and seismic amplitudes with the peak discharge of an event (Fig. 5).

The values for peak discharge and total volume used for this analysis are from Level 2 events at the Lattenbach, Gadria and Illgraben test sites (Table 1) and are calculated based on flow height measurements and velocity estimations. Since all monitoring stations used for this study are rather close to the channel (between 10 and 20 m) and the distances are nearly the same at every test site, we neglected attenuation of the signals in the air or in the ground, geometric spreading and the influence of topography or geology.

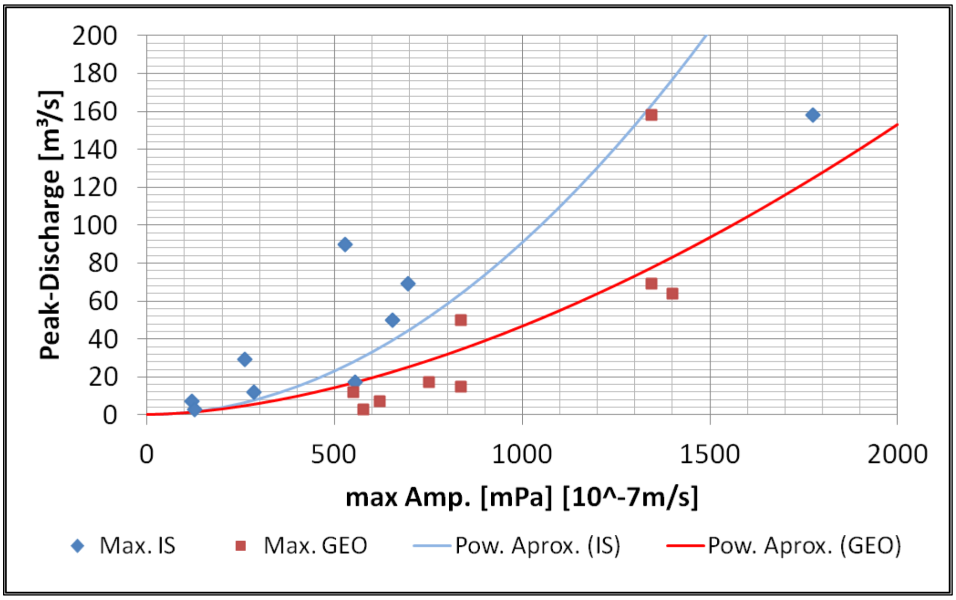

Fig. 5. Peak discharge over maximum seismic (Max GEO) and infrasound amplitudes (Max IS) and the approximation based on infrasound data (Pow. Approx. (IS)) and seismic data (Pow. Approx. (GEO))

Table 1. Peak discharge and total volume of used events.

Site	Event-Date	Peak discharge [m^3/s]	Total volume [m^3]
Lattenbach	09.08.2015	50	11500
	10.08.2015	69	18500
	16.08.2015	12	5000
	10.09.2016	158	46000
Gadria	15.07.2014	na	10500
	08.06.2015	na	9850
	12.07.2016	na	1500
Illgraben	22.07.2015	17	8700
	10.08.2015	7	6100
	14.08.2015	7	25000
	15.08.2015	3	2000
	12.07.2016	15	10000
	22.07.2016	50-90	>10000
	09.08.2016	29	<10000

This analysis shows that, for peak discharge, a power curve fitting offers a good approach to find an initial relationship between the recorded signals and this event parameter. This curve fitting provides a R^2 of 0.76 for peak discharge based on infrasound data and a R^2 of 0.65 for the seismic data. The approximation for peak discharge Q_{peak} (in m^3/s) can be calculated based on the maximum infrasound amplitudes $A_{IS(max)}$ (in mPa) and the maximum seismic amplitudes $A_{GEO(max)}$ (in 10^{-7} m/s) according to Equation (1).

$$Q_{peak} = \frac{1}{2}\left(0.0001019598\, A_{IS(max)}{}^{1.982999} + 0.000332\, A_{GEO(max)}{}^{1.715603}\right) \quad (1)$$

The peak discharge is calculated as the means of both relations, and this overall calculation offers a R^2 of 0.967. For an estimation of the total volume, we integrate the discharge calculated with the relationship for peak discharge (equation (1)) over the entire detection time of an event. Fig. 6 compares the calculated values (vertical axis) for peak discharge and total volume to the observed values (horizontal axis). The line represents the one-to-one relationship.

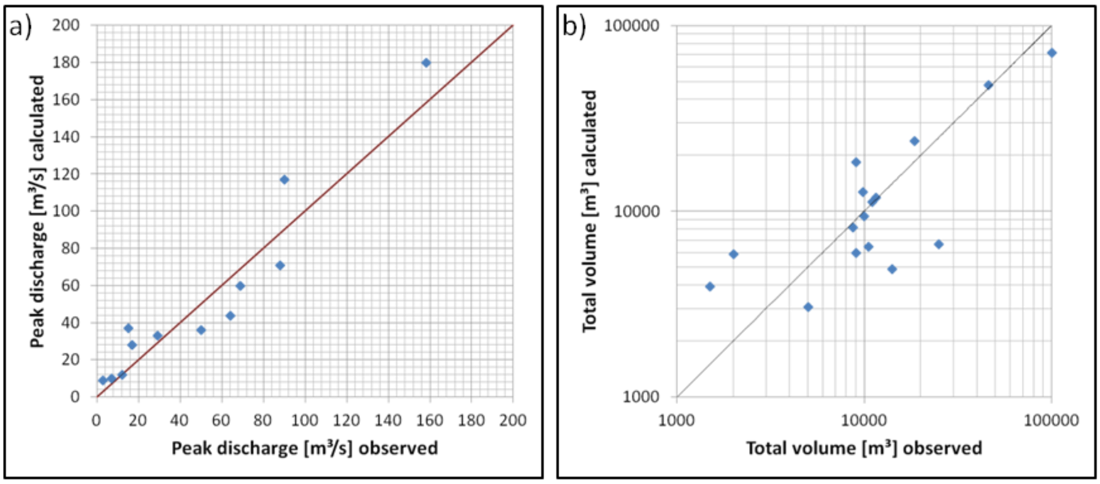

Fig. 6. Comparison of the calculated peak discharge to the observed values (a); comparison of the calculated total volume to the observed volume (b)

Both diagrams suggest that it is possible to obtain first-order estimates of the peak discharge and the total volume for debris flows and debris floods at different sites based on the infrasound and seismic amplitudes. The calculation of the peak discharge based on a combination of infrasound and seismic data offers a good approximation ($R^2 = 0.912$), for the total volume, this method shows a larger variance ($R^2 = 0.880$).

In fact, beside the magnitude, flow velocity and the sediment concentration have also a large influence on the seismic and infrasound amplitudes of a debris flow, so including them in a next step in the magnitude estimation could lead to more accurate results.

Conclusions

This paper presents an approach of a debris flow/debris flood and avalanche detection system based on a combination of seismic and infrasound sensors. The combination of both sensor technologies increases the detection probability and minimizes false alarms. So with these complementary technologies it is possible to build up a reliable warning system which can detect avalanches as well as debris flows/debris floods in real time directly at the sensor site and comes along with only one seismic and one infrasound sensor (co-located). The use of a microcontroller for the calculation of the detection algorithm makes the system very flexible, low energy consuming and cost-efficient and opens the possibility for several applications. So applications of this system are protection of infrastructure like traffic lines by controlling a traffic light, information about events to check the status of technical protection measure (e.g. fill level of a retention basin or debris-flow net), protection of construction sites inside the channel (e.g. for cleaning up a basin after an event), or at regions where a temporary protection is sufficient. Since the material cost of such a system is low and the installation is very easy, this setup may be used especially at sites, where the necessary founding for expensive torrent and avalanche barriers are not available, or where immediate protection measure are necessary.

However, the application of seismic and infrasound sensors for monitoring and detection of alpine mass movements is not a straightforward task. Understanding the propagation and attenuation mechanisms of seismic and infrasonic waves and the background noise characteristics in the study conditions is crucial for the interpretation of the recorded seismic and infrasonic signals and the development of a detection algorithm. The equipment and the placement of the sensors have to be chosen carefully.

In summary this work shows that the combination of one infrasound and one seismic sensor and the use of a microcontroller can offer a good basis for an easy to install, and inexpensive warning system for different kind of alpine mass movements.

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