



The Value of Soil Wetness Measurements for Regional Landslide Early Warning Systems

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Abstract

Current regional landslide Early Warning Systems (LEWS) are typically based on rainfall data and rarely use soil wetness information in spite of the direct relationship between soil wetness and landslide triggering. This is partly due to the limited availability of soil moisture measurement networks and the lack of experience in interpreting such data. Here we show how soil wetness measurements could be exploited for LEWS in a region (or country) with variable topography and soil composition. In particular, we highlight the relevance of (steep) topography for the soil wetness observations and its significance for the interpretation in regard to landslide criticality. To this end, a field study has been set up and is currently running in a landslide-susceptible region of central Switzerland (Emmental) where different soil wetness measurement methods are compared on a flat and a steep meadow site. First results suggest that in spite of noticeable topographical effects on soil drying and wetting the informative value of these data for LEWS is not very different for sloped and flat locations. Based on these findings and a comprehensive analysis of the co-occurrence between soil wetness indicators and shallow landslides across Switzerland we attribute soil wetness measurements a significant value for landslide early warning and encourage a wider incorporation of such data in existing warning systems.

Keywords

Soil moisture • Landslide early warning • Monitoring systems

Introduction

In mountainous regions, landslides are a serious hazard for people and infrastructures. In Switzerland, they have caused a total financial damage of 520 million Euros in the period from 1972 to 2007 (Hilker et al. 2009) and the death of 74 people between 1946 and 2015 (Badoux et al. 2016). Shallow landslides are particularly dangerous due to the short interval time between activation and failure and their widespread occurrence.

Regional landslide early warning systems (LEWS) have proven to be a valuable and efficient tool to issue warnings to the public in order to move people and goods at risks to safety (Stähli et al. 2015). Existing LEWS have been mostly based on rainfall exceedance thresholds that empirically relate precipitation characteristics to the occurrence of landslides (e.g. Guzzetti et al. 2007). While precipitation measurements are widely available, rainfall exceedance thresholds bear specific limitations such as the non-representation of antecedent wetness conditions and soil wetness distribution at depth (Godt et al. 2009), or a high spatial and temporal variability of critical threshold values (Aleotti 2004; Baum and Godt 2010).

To overcome these limitations, the need for hydrological-based thresholds has been stated (e.g. Berne et al. 2013; Devoli 2017). In addition, it has been postulated that including information on antecedent saturation conditions could effectively reduce both false and missed alarms (Bogaard and Greco 2018). In fact, recent studies have demonstrated an improvement of the forecast quality of rainfall-based LEWS after the inclusion of soil wetness information derived from measurements (Mirus et al. 2018a, b; Comegna et al. 2016) or models (Segoni et al. 2018).

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Measuring Soil Wetness for Landslide Prediction

Shallow landslides are typically triggered after the infiltration of rainfall or snow melt water and the consequent rise of the water saturation and perched groundwater tables. The resulting increase in pore water pressure and decrease in matric suction may reach critical values at which point the slope eventually fails (Crozier 1986; Wieczorek 1996). Measurements of soil wetness have thus long been suggested to be valuable for assessing the landslide danger (e.g. Springman et al. 2003; Lu et al. 2010).

Soil wetness is commonly expressed as the volume of pores that is filled with water divided by the total soil volume (volumetric water content, VWC, θ) or as the pressure at which water is bounded to the particles (matric potential). It can be measured or indirectly estimated at different spatial and temporal scales.

At the scale of soil profiles, soil moisture probes (time-domain reflectometry, TDR, or capacitance based) are used to estimate permittivity by electromagnetic sensors. The permittivity values can then be related to the VWC using a specific calibration function (Topp et al. 1980). The matric potential can be measured with tensiometers consisting of a porous cup on a rigid tube which is filled with water and connected to a vacuum gauge that measures pressure levels (Livingston 1908). Both sensor types allow for continuous soil wetness monitoring. While they are representative for a specific measurement volume, multiple probes are usually integrated in depth profiles.

Electrical resistivity tomography (ERT) allows for a distributed 2-D VWC estimation along hill-slope transects of several meters length. Between pairs of equally spaced electrodes, the potential difference is measured, and by variation of the electrode geometry, the 2-D distribution of apparent resistivity is assessed. Specific resistivities are then deducted by the application of an inversion algorithm (e.g. Kneisel and Hauck 2008). While single measurements depend largely on the lithology, resistivity changes can be related to changes in the soil water content (Robinson et al. 2009). This type of measurement allows for a 2-D VWC estimation and is non-invasive, however the longer acquisition time results in a lower temporal resolution.

Soil wetness can also be sensed remotely from space e.g. using satellite-based measurements of passive or active microwave emission of the soil surface (Reichle et al. 2017). However, the spatial resolution of this information is very coarse, the temporal resolution reduced compared to in-situ measurements, and the depth of the represented soil wetness shallow, which strongly limits the potential for LEWS in mountainous landscapes (Thomas et al. 2019).

Dependence of Soil Wetness on Topography

It is well known that the spatial distribution of soil wetness is heavily influenced by topography. There are topographical zones where water accumulates, and such where water can drain (laterally) relatively quickly. In hydrology, a topographic wetness index (TWI; Sørensen et al. 2006) is typically used for discerning these areas.

But not only the lateral water flow in the soil, also soil evaporation or snow cover distribution is significantly influenced by the topography, which in turn can lead to variations in soil wetness.

For LEWS, the question arises to what extent these topographical effects on soil wetness must be taken into account, especially since available measurement networks are often located at flat sites.

Soil Wetness Measurements at a Landslide Prone Site

In order to assess the representativeness of flat measurement sites for critical hydrological conditions at hillslopes, a specific soil wetness observatory has been set up in a landslide prone area of central Switzerland (Emmental, Swiss prealps, Fig. 1). A flat and a sloped location (30° slope angle) were equipped with various soil wetness measurement sensors in spring 2019. To analyse the potential of the different measurement techniques for the use in a LEWS, they were compared in their ability to identify critically saturated conditions in the upper soil layer.

Monitoring Setup

Capacitance-based soil moisture probes (ECH2O 5TE, Meter, Germany) and tensiometers (T8, Meter, Germany)



Fig. 1 Soil moisture site (sloped location) in the Napf area (Switzerland)

were installed in soil pits at three different depths (15, 50 and 100 cm). Perched ground-water levels are measured using a piezometer. Additional measurements include air and ground temperature (temperature probes) as well as precipitation (tipping bucket).

For comparison, the absolute soil moisture measurements are normalized for each sensor by the respective maximum of the time series. Both soil moisture and matric potential records are integrated to depth profiles by calculating the profile mean.

To further assess the 2-D distribution of temporal soil moisture dynamics, an ERT profile line was installed at the sloped site. It consists of 48 electrodes at an 0.25 m electrode spacing, which is small enough to capture small scale hydrological processes. Automated measurements were conducted during precipitation events at hourly time scale, and a time-lapse tomography inversion scheme was applied to relate the resistivity changes to changes in soil water content.

Summer 2019 Results

First results of the soil moisture measurements from April to November 2019 suggest that differences between the flat and the sloped measurement site are generally small (Fig. 2). Differences are smallest near the saturated and the dry end, and they become larger at intermediately saturated conditions and inhibit an S-shaped relationship between the flat and the sloped site.

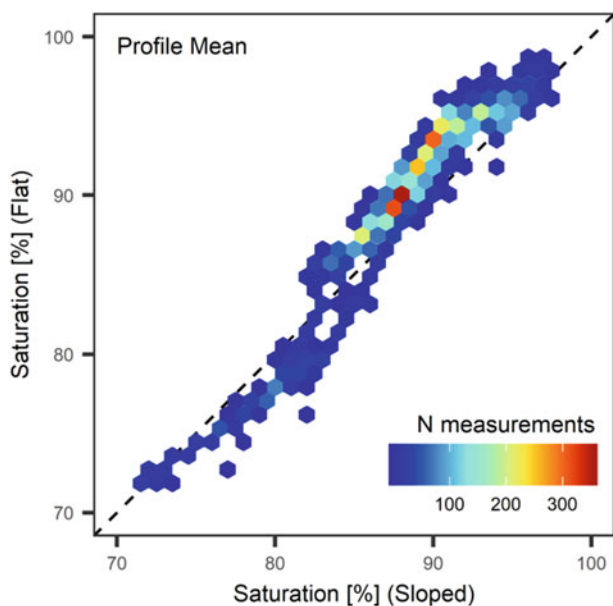


Fig. 2 Profile mean saturation at the sloped site vs. the flat site for the period of April to November 2019

This indicates that during conditions of higher saturation, the sloped site drains faster (more quickly) but saturates slower, which can be explained by the larger gravitational potential (quicker desaturation) and higher surface runoff rates (slower saturation) due to the slope degree. Conversely, during drier conditions, the sloped site dries out slower but saturates faster (more quickly), which we relate to lower evaporation rates due to the SE exposition and shading by trees (slower drying rates) and higher infiltration capacity (quicker saturation).

Potential of an Existing In-situ SWC Network for LEWS

Soil moisture measurements are becoming more frequent within operational monitoring networks. To assess the potential of existing in-situ VWC measurements for regional landslide early warning, a comprehensive soil moisture data base was compiled from existing soil moisture monitoring networks in Switzerland (Fig. 3). In a recent study (Wicki et al. 2020), the temporal variation of the soil moisture measurements was compared to the occurrence of landslides that were recorded in a national landslide inventory (Swiss flood and landslide damage database, WSL, Fig. 3).

Methodology

VWC time series were first homogenized, normalized by the minimum and maximum of each time series, and then integrated to ensembles of sensors at each site. At the ensemble mean time series, the onset and end of individual *infiltration events* (i.e. continuous periods of saturation increase) were identified and various event properties were quantified.

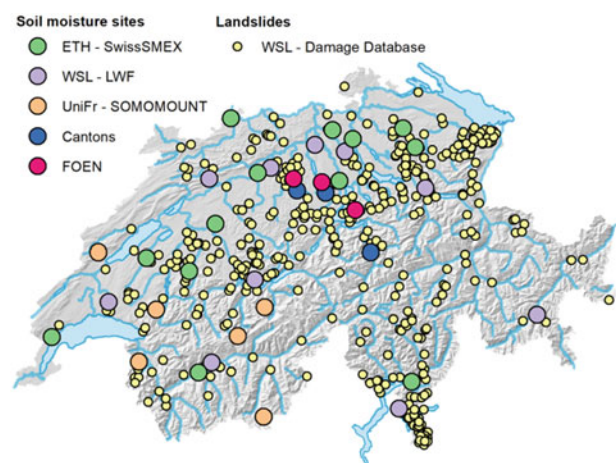


Fig. 3 Map of Switzerland showing all included soil moisture sites and landslide records

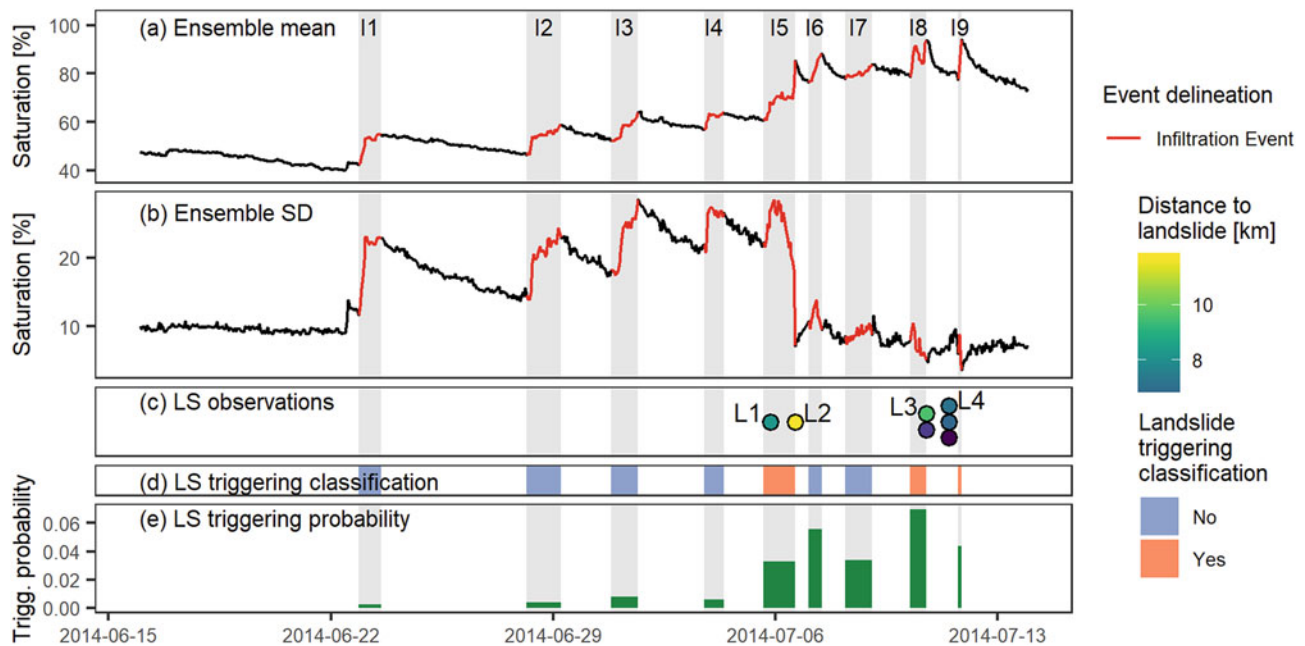


Fig. 4 Temporal evolution for a sample time period at the SwissSMEX Site Plaffeien of **a** the ensemble mean and **b** ensemble standard deviation with infiltration events highlighted in red, **c** recorded landslides within 15 km distance from the site, **d** the respective

landslide triggering classification, and **e** the resulting landslide triggering probability from one model fit (all event properties, all sensors, all sites, 15 km forecast distance)

Further, infiltration events were classified as *landslide triggering* or *landslide non-triggering* based on the coincident occurrence of landslides within a specific distance from the site (referred to as the *forecast distance*). To assess the distance sensitivity of the model, the forecast distance was varied in 5 km steps from 5 to 40 km.

Finally, a multiple logistic regression (MLR) function was fit to the infiltration event set to statistically reproduce the landslide probability as a function of the infiltration event properties. To assess the forecast quality of a specific model fit and to compare different model fits, receiver operating characteristics (ROC) analysis was performed.

Results

The components of one specific model fit are illustrated in Fig. 4 for a time period extract from June to July 2014 and at a sample site (SwissSMEX site Plaffeien, Canton of Fribourg, Northern pre-Alps). During this period, a series of rainfall events caused widespread landslide activity in all Switzerland and specifically in the region of Fribourg. The measurements show a continuous increase in the soil saturation (Fig. 4a). It is accompanied by a initial increase of the standard deviation which suddenly decreases at I5 (Fig. 4b),

indicating that the soil profile is homogeneously saturated from then on. It was also during I5 and in the following days that several landslide events were observed (Fig. 4c). This elevated landslide danger was reproduced by the MLR model as a sudden landslide probability increase from I5 onwards (Fig. 4e).

Comparison of the different model fits revealed a strong distance dependence of the forecast goodness which increases with short distances between site and landslide. We explain this distance dependence to be mainly driven by variations in precipitation (phase, intensity, duration) that determine the amount of water infiltration, and by variations of irradiance, wind or humidity that mostly drive the drying up of the soil. Some forecast skill persists even at a forecast distance of 40 km. We relate this to spatial persistence of relative soil moisture anomalies as opposed to absolute soil moisture differences, which was found in a previous study for the SwissSMEX sites for much of Switzerland (Mittelbach and Seneviratne 2012).

Main model drivers were identified to be the antecedent saturation (saturation at the onset of an infiltration event), the two-week preceding maximum saturation and the saturation change during an infiltration event. Using a model fit that includes only the antecedent saturation and the saturation change resulted in almost the same forecast goodness as if all

event properties are considered. This demonstrates the importance of describing both the medium-term antecedent conditions as well as the short-term event dynamics, as previously proposed by Bogaard and Greco (2016).

Considerable differences were found between landslides triggered by long-lasting precipitation events compared to landslides due to thunderstorms. If only the first are considered, the forecast goodness improves significantly and event properties that describe the antecedent conditions become more important. If the latter are included in the modelling only, the forecast goodness decreases significantly and event properties that describe the event dynamics become more important.

Finally, improvements of the forecast goodness could be achieved if seasons were considered individually and if the soil moisture sites were grouped by texture. However, the analysis was limited by the size of the dataset. Further, it was shown that most variability could be explained by considering the uppermost sensors (≤ 30 cm depth) only.

Conclusions and Outlook

Our experiences from this work so far suggests that in-situ soil moisture measurements contain specific information on the regional landslide activity and can be effectively used for landslide early warning. Most important soil-wetness information pointing to the imminence of shallow landslides are the antecedent saturation and the saturation change during an infiltration event.

The forecast goodness strongly depends on the distance between the measurement site and the location of the landslide, which is explained to be driven mainly by meteorological variations. The presence of forecast skill at large distance underlines the value of focusing on relative changes as opposed to using absolute soil moisture variations. Finally, the topographic influence is small if the top 1 m is considered only. This supports the use of already existing soil moisture monitoring networks.

Open questions remain about the value of other soil wetness measurement techniques (tensiometers, ERT). Also, in our future work we will test to what degree soil wetness data from measurement networks can be replaced by numerical soil moisture simulations.

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