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A modified tank model including snowmelt and infiltration time lags for deep-seated landslides in Alpine Environments (Aggenalm, Germany)

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Abstract

Deep-seated landslides are an important and widespread natural hazard within alpine regions, and can have a massive impact on infrastructure. Pore water pressure plays an important role in determining the stability of hydro-triggered deep-seated landslides. We improve current methods of groundwater level prediction by introducing a means to account for time lags associated with groundwater supply caused by snow accumulation, snowmelt, and infiltration in deep-seated landslides. In this study, we demonstrate a simple method to improve the estimation of these time lags using a modified tank model to calculate groundwater levels. In a deep-seated landslide in Bavaria, Germany, our results predict daily changes in pore water pressure ranging from -1 to 1.6 kPa depending on daily rainfall and snowmelt. The inclusion of time lags improves the results of standard tank models by ~36% (linear correlation with measurement) after heavy rainfall and, respectively, by ~82% following snowmelt in a 1-2 day period. For the modified tank model, we introduced a representation of snow accumulation and snowmelt, based on a temperature index and an equivalent infiltration method, i.e. the melted snow water equivalent. This compares well to the in situ measurement for the same time interval which reflect changes of pore water pressure with 0-8% relative error in rainfall season (standard tank model: 2-16% relative error) and with 0-7% relative error in snowmelt season (standard tank model: 2-45% relative error). Here we demonstrate a modified tank model for deep-seated landslides that includes snow and infiltration effects and can effectively predict changes in pore water pressure in alpine environments.

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Nomenclature

a	related coefficient between equivalent infiltration and increased ground water table, 1	q_i	drainage of i^{th} day, mm
a'	related coefficient between equivalent infiltration and increased pore water pressure, kPa/mm	PWP_i	pore water pressure of i^{th} day, kPa
b	average value of pore water pressure changed by drainage and ground water supply, kPa.	$\Delta PWP_{(g+q)i}$	*PWP* changed by drainage combined groundwater supply, kPa
a	related coefficient between pore water pressure of i^{th} day and $i+1^{th}$ day without infiltration, kPa.	ΔPWP_i	change of pore water pressure of i^{th} day, kPa
b	related coefficient between pore water pressure of i^{th} day and $i+1^{th}$ day without infiltration, 1	$R_i^{(n)}$	part of rainfall of i^{th} day to changed pore water pressure of i^{th} day, mm
ER_i	equivalent rainfall of i^{th} day, mm	RH	relative humidity, 1
ES_i	equivalent snowmelt of i^{th} day, mm	RH_t	threshold of relative humidity, 1
f_m	degree-day factor for snowmelt rate, mm/°C	M	time about effect of infiltration reducing to 50%, 1
F	canopy covers percent, 1	R_i	rainfall of i^{th} day, mm
g_i	ground water supply of i^{th} day, mm	$S_i^{(n)}$	part of snowmelt of i^{th} day to changed pore water pressure of i^{th} day, mm
h_i	ground water table height the i^{th} day, mm	S_i	rainfall of i^{th} day, mm
H	base water table, mm	T_d	daily average temperature, °C
M'	daily snowmelt, mm		

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1 Introduction

Deep-seated landslides in the eastern European Alps pose a certain hazard to people and infrastructure (Mayer et al., 2002; Madritsch and Millen, 2007; Agliardi et al., 2009). It has long been recognized that pore water pressure (PWP) changes by precipitation play a critical role in hydrologically triggered deep-seated landslide activation. The rise in PWP causes a drop of effective normal stress on potential sliding surfaces (Bromhead, 1978; Iverson, 2000; Wang and Sassa, 2003; Rahardjo et al., 2010). The estimation of pore water pressure is of great significance for anticipating deep-seated landslide stability. In past years, geotechnical monitoring systems have revealed PWP change related to rainfall and snowmelt events (Angeli et al., 1988; Simoni et al., 2004; Hong et al., 2005; Rahardjo et al., 2008; Huang et al., 2010). The Green and Ampt Model and the Richards Equation are generally used to describe groundwater infiltration and water table changes (producing PWP) in saturated homogeneous material (Chen and Young, 2006; Weill et al., 2009). The Van Genuchten Equation (Schaap and Van Genuchten, 2006) and the Fredlund and Xing (1994) method show better performance in the evaluation of infiltration and groundwater table but require many parameters which cannot be measured easily. Tank models typically describe infiltration and evaporation in shallow soil materials (Ishihara and Kobatake, 1979). They are based on the water balance theory, which means they account for flows into and out of a particular drainage area. Multi-tank models involving two or three tank elements have been developed to better estimate groundwater fluctuations within shallow landslides induced by heavy rainfall (Michiue, 1985; Ohtsu et al., 2003; Takahashi, 2004; Takahashi et al., 2008; Xiong et al., 2009). However, multi-tank models do often not predict groundwater changes well in deep-seated landslides as they (i) require too many parameters to track groundwater flow supplies in complicated geological structures and (ii) are presently not developed to replicate time lags of increased infiltration, e.g., following snowmelt (Iverson, 2000; Sidle, 2006; Nishii and Matsuoka, 2010)

In this study, we introduce a simple method to estimate time lags by a modified standard tank model which predicts changes in pore water pressure. We apply our mode to a case study on the Aggenalm landslide, Bavaria, Germany, where predicted PWP changes can be verified against monitoring data. The monitoring network design and installation, as well as detailed monitoring data, and the introduction of monitoring devices have been described periviously

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in detail (THURO et al., 2009; Thuro et al., 2011a; Thuro et al., 2011b; Festl et al., 2012; Thuro et al., 2013).

2 Site descriptions

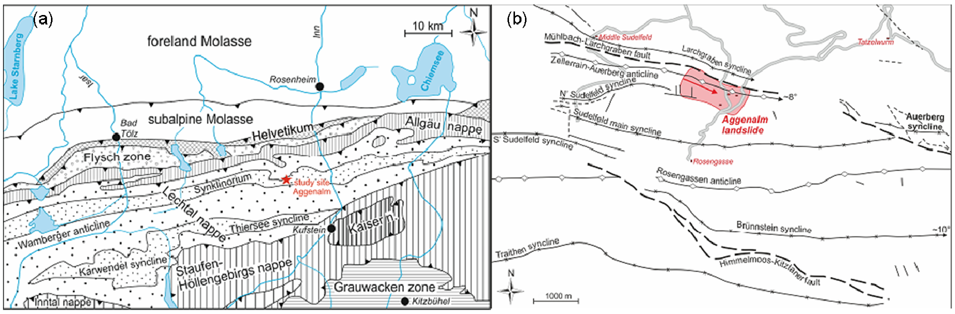

Figure 1 (a) Tectonic map of the Northern Calcareous Alps between Lake Starnberg and Chiemsee. The Aggenalm Landslide is situated in the Lechtal Nappe within the Synklinorium, a major syncline–anticline–syncline fold belt, which can be traced through the whole region. (b) Detailed tectonic map showing the main tectonic features in the Aggenalm landslide area. Here the Synklinorium has a complex structure with several additional minor syn- and anticlines, of which the eastward dipping of the Zellerrain-Auerberg Anticline is responsible for the nearly slope parallel orientation of the rock mass within the Sudelfeld landslide (modified from Festl 2014).

The Aggenalm Landslide is situated in the Bavarian Alps in the Sudelfeld region near Bayrischzell (Fig. 1). During the Alpine orogeny, the rock mass was faulted and folded into several large east-west oriented synclines, of which the Audorfer Syclinorium is responsible for the nearly slope-parallel bedding orientation of the rock mass in the area of the Aggenalm Landslide (Fig. 2). The Aggenalm Landslide is underlain by Late Triassic well-bedded limestones (Plattenkalk, predominantly Nor), overlain by Kössen Layers (Rhät, predominantly marly basin facies) and the often more massive Oberrhät Limestones and Dolomites (Rhät) (Fig. 2). The marls of the Kössen Layers are assumed to provide primary sliding surfaces and are very sensitive to weathering as they decompose over time to a clay-rich residual mass (Nickmann et al., 2006). The landslide mechanism can be classified as a complex landslide dominated by deep-seated sliding with earth flow and lateral rock spreading components (Singer et al., 2009). A major activation of the landslide occurred in 1935, destroying three bridges and a local road. Slow slope deformation and secondary debris flow activity has been ongoing since this time.

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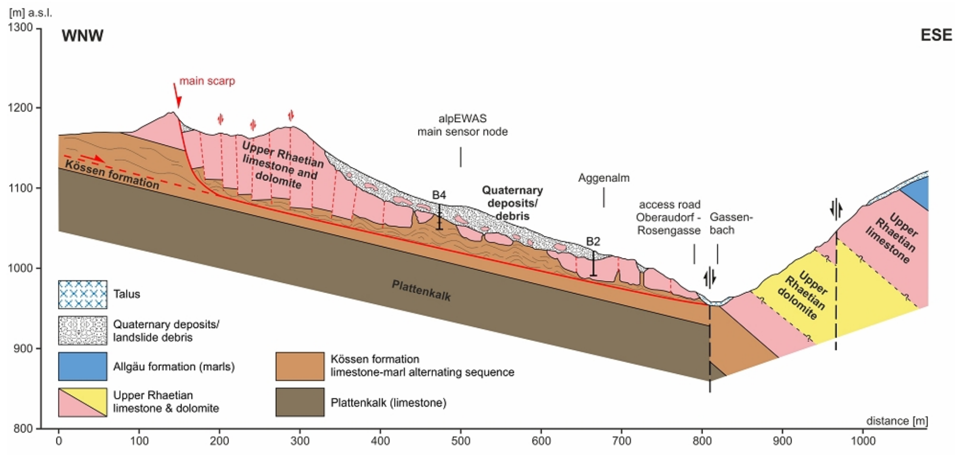

Figure 2 Geological profile of the Aggenalm Landslide (modified from Festl, 2014)

3 Data and Methods

3.1 Monitoring data

Monitoring data for this study is derived from a rain gauge and humidity sensor (alpEWAS central station), and a pore water pressure sensor (PWP) installed in boreholes close to the assumed shear zone (B4, 29.4 meter deep) (Fig. 2) (Singer et al., 2009; Festl, 2014). A heated precipitation gauge provides data on the snow-water equivalent of snowfall. Short term noise in raw data was filtered. PWP, temperature, and humidity are averaged over a 24-hour period (Festl, 2014). The monitoring period lasts almost from February 2009 to December 2011. Considering data loss in some months, we have approximately 24 months of valid data. We use data from the 13 months (May 2009 to June 2009; September 2009 to December 2009; February 2010 to August 2010) to parametrize the modified tank model. The 55 days of rainfall (July 2009 to August 2009) and 44 days of snowmelt (March 2009 to April 2009) are used to validate the modified tank model. In addition, simulation of two years PWP levels are compared to the whole two years of monitoring data of PWP levels bridging the data gaps.

3.2 The modified tank model including snowmelt and infiltration

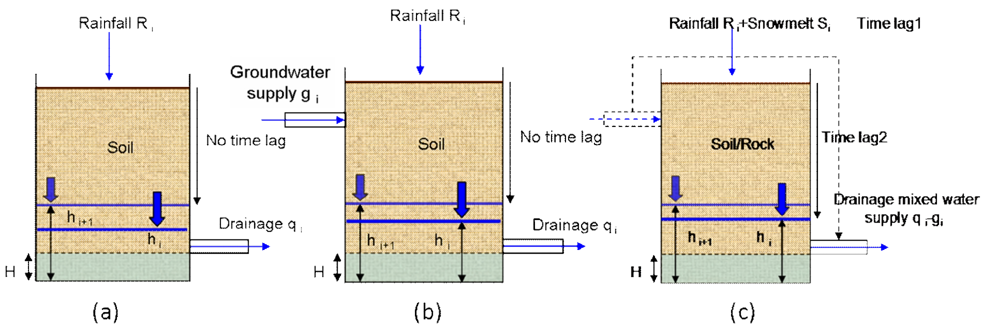

Figure 3 Generation of the modified tank model. (a) Original tank model considering the vertical infiltration and drain affecting water table. (b) Considering both vertical infiltration and horizontal water flow. (c) Modified tank model including water supply and two time lags (snowmelt and infiltration).

Figure 3 demonstrates the changes from the original tank model (Ishihara and Kobatake, 1979; Michiue, 1985; Ohtsu et al., 2003; Uchimura et al., 2010) to our modified model. Fig. 3a shows the basic concept of the original tank model, the daily change in the groundwater table height h_{i+1} - h_i is

$$h_{i+1} - h_i = R_i - q_i \ . \qquad (1)$$

where R_i is the rainfall and q_i is the drainage of the i^{th} day. h_i is groundwater table height the i^{th} day.

Concepts illustrated in Fig. 3b are now incorporated in the water flow supply tank model including groundwater supply. The daily change in groundwater table height h_{i+1} - h_i is

$$h_{i+1} - h_i = R_i - (q_i - g_i)\,, \qquad (2)$$

where g_i is groundwater supply of the i^{th} day from the upper slope.

Another aspect, snowmelt also plays an important role in producing groundwater supply in Fig. 3c. Thus, the equation (3) should be written as

$$h_{i+1} - h_i = R_i + S_i - (q_i - g_i)\,, \qquad (3)$$

where, S_i is the snowmelt of the i^{th} day.

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More importantly, snow accumulation and snowmelt produces our first time lag (*time lag 1*) as a result of the effects of ambient temperature on snowmelt. Both the groundwater response snowmelt and rainfall are compounded by long infiltration paths as, for example, water infiltration often takes one or more days to reach the water table in deep-seated landslide masses (*time lag 2*) (Fig. 3c). This can be described: the infiltration in i^{th} day does not only affect the groundwater table in i^{th} day but also the groundwater table over the following n days if the *time lag2* (n days) is considered (n>1). In other words, R_i and S_i are divided into n parts ($R_i = \sum_{n=1}^{N} R_i^{(n)}$ and $S_i = \sum_{n=1}^{N} S_i^{(n)}, i, n \geq 1$). Each component ($R_i^{(n)}$ and $S_i^{(n)}$) contributes to daily changes in the groundwater table (h_{i+n}-h_{i+n-1}). Thus, for example, total daily variations (h_{i+2}-h_{i+1}) in response to rainfall and snowmelt can be described by $R_{i-1}^{(3)} + S_{i-1}^{(3)}$, $R_i^{(2)} + S_i^{(2)}$, $R_{i+1}^{(1)} + S_{i+1}^{(1)}$ when time lag is 2 days as shown in Fig. 4. (Considering that the groundwater table in $i+1^{th}$ day is not only affected by the infiltration today but also the infiltration of previous two days)

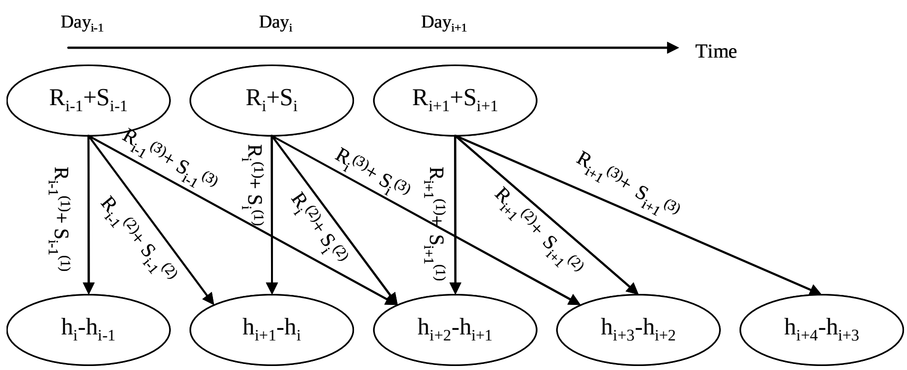

Figure 4 Schematic diagram of water infiltration from the surface to the groundwater table producing *time lag 2* (time lag is 2 days)

Groundwater changes on a given day (Day_{i+1}) result from infiltration over the previous three days (Day_{i-1}, Day_i, and Day_{i+1}).

Antecedent Precipitation Index (API) can reduce this *time lag 2* by estimating the current water content of the ground affected by previous precipitation (Chow, 1964). This is equivalent to the infiltration calculations of (Suzuki and Kobashi, 1981; Matsuura et al., 2003; Sumio Matsuura et al., 2008) who define equivalent infiltration as

$$ER_i + ES_i = (0.5)^{1/M} R_i + (0.5)^{1/M} ER_{i-1} + (0.5)^{1/M} S_i + (0.5)^{1/M} ES_{i-1}. \quad (4)$$

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where ER_{i-1} and ES_{i-1} represent the equivalent rainfall and snowmelt of ***i-1**th* days, respectively; R_i and S_i mean the rainfall and snowmelt of i^{th} day; $(0.5)^M$ means the effect of infiltration reduces to 50% in *M* days (where M is determined from field observations). Therefore, the whole modified tank model with an equivalent infiltration method could substitute both, ***time lag 1*** by integrating snow accumulation and snowmelt (section 2.4) and ***time lag 2***.

The relationship between infiltration and water table is often proportional in slopes (Matsuura et al., 2008; Schulz et al., 2009; Thuro et al., 2010; Yin et al., 2010;). Therefore, the conceptual equation of changed water table should be like:

$$\Delta h_i = h_{i+1} - h_i = a\,(ER_i + ES_i) - (q_i - g_i)\,. \tag{5}$$

where a is a proportional coefficient (only for ideal tank model, a is one).

Assuming seepage forces are negligible, PWP can be linearly correlated to groundwater levels such that:

$$\Delta PWP_i = a^{'}(ER_i + ES_i) - \Delta PWP_{(g+q)i}\,. \tag{6}$$

where, $\Delta PWP_{(g+q)i}$ is the *PWP* changed by subsurface inflows and outflows on the i^{th} day This allows us to evaluate changes in *PWP* resulting from infiltration, drainage, and groundwater supply. The workflow chart of our modified tank model for change of PWP_i is indicated in Fig. 5.

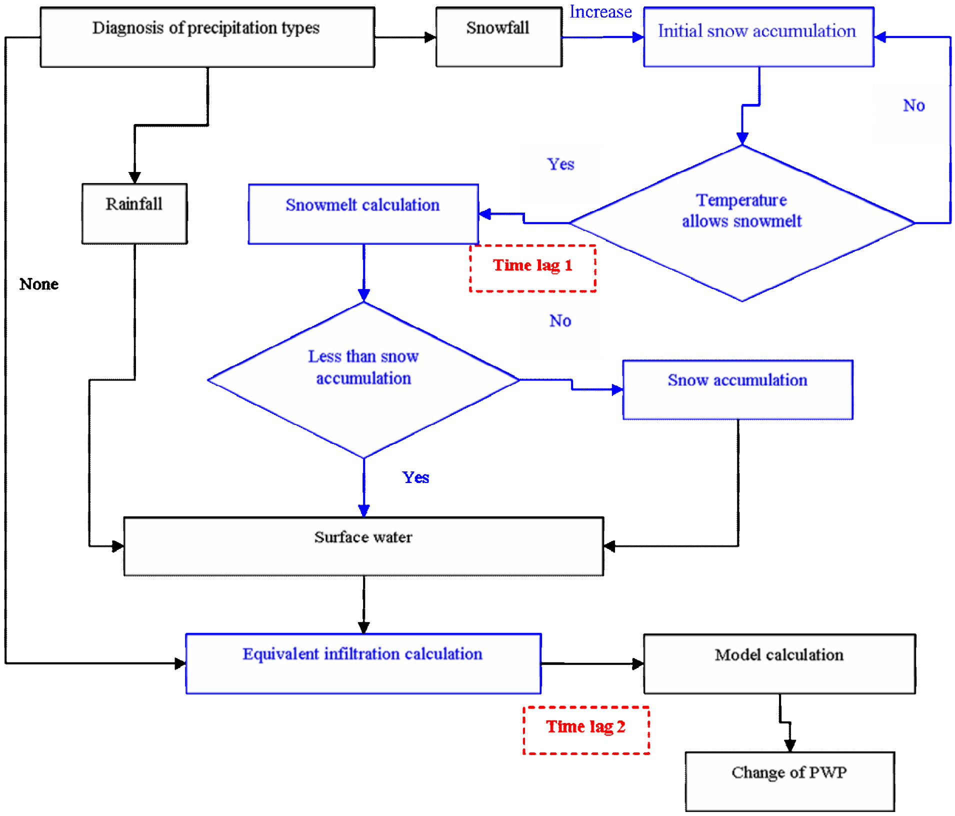

Figure 5 Workflow chart of the modified tank model with respect to the original model are highlighted in blue including time lags from snow accumulation/snowmelt and infiltration.

3.3 Determining the parameter of PWP calculation in the modified tank model

In order to determine an appropriate value of a' for the monitoring location on the Aggenalm Landslide, we use 13 months data as training data to fit the relationship between equivalent rainfall and ΔPWP (Fig. 6 and Fig. 7).

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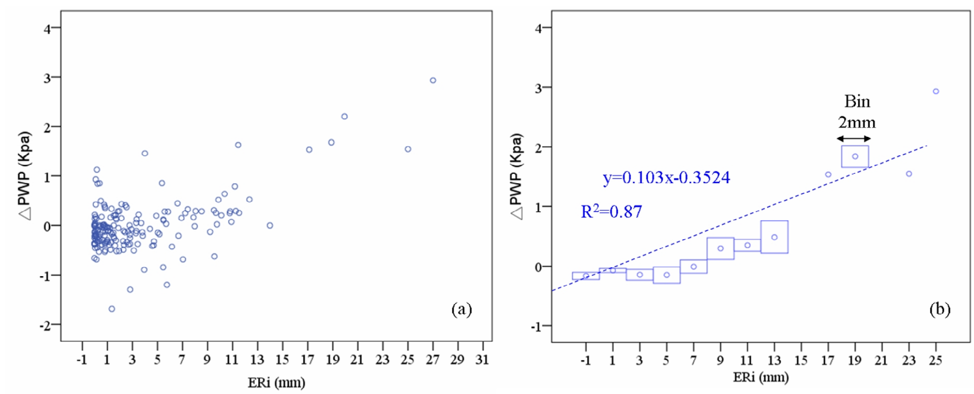

Figure 6 (a) Daily equivalent rainfall ER_i versus daily change of pore water pressure $\triangle PWP_i$ in absolute values for 13 months (Sep.2009-Feb.2010 and May.2010-Nov.2010). (b) $\triangle PWP_i$ has been aggregated in bins of mean values for discrete steps of daily equivalent rainfall (mean+1 sigma error).

The linear relationship between daily change of pore water pressure (ΔPWP_i) and daily equivalent rainfall (ER_i) for absolute data is shown in Fig. 6a. However, this does not produce a functional link between ΔPWP_i and ER_i. We consider using the mean value of daily change of pore water pressure given for certain daily equivalent rainfall such as in ***Bin*** (Fig. 6b) to replace the data of the same width (Fig. 6a) (Freedman et al., 1998). The result shows change of PWP_i as

$$\Delta PWP_i = a^{'} ER_i - b \ . \tag{7}$$

where, $a^{'}$ [kPa/mm] is 0.103, thus relates rainfall to pore pressure increase and b (-0.3524) [kPa] is the average decrease of pore water pressure by drainage (Thus at a day without infiltration by snowmelt and rainfall the pore water pressure drops by 0.35 kPa, i.e. the water column drops by 35mm). According to the tank model theory, b, as a constant, is quite rough. The original tank theory demonstrates that the decrease of pore water pressure rate depends on the current pore water pressure (Michiue 1985; Ohtsu et al. 2003; Takahashi 2004; Takahashi et al., 2008; Xiong et al., 2009; Uchimura et al., 2010). In reality, the relationship can only be calculated by monitoring an extended period without infiltration. As shown in Fig. 7a, the observation of ***PWP*** is within 48 days without rainfall input which means these processes only include the information of drainage combined with groundwater supply for

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this test point. The relation between PWP_{i+1} and PWP_i without rainfall infiltration is shown in Fig. 7b and equation (8).

$$PWP_{i+1} = ae^{bPWP_i} \quad (8)$$

where a (13.4) and b (0.02664) are fitted coefficients.

Thus, ΔPWP_i calculation could be rewritten as:

$$\Delta PWP_i = a^{'}(ER_i + ES_i) - (PWP_i - ae^{bPWP_i}) \quad (9)$$

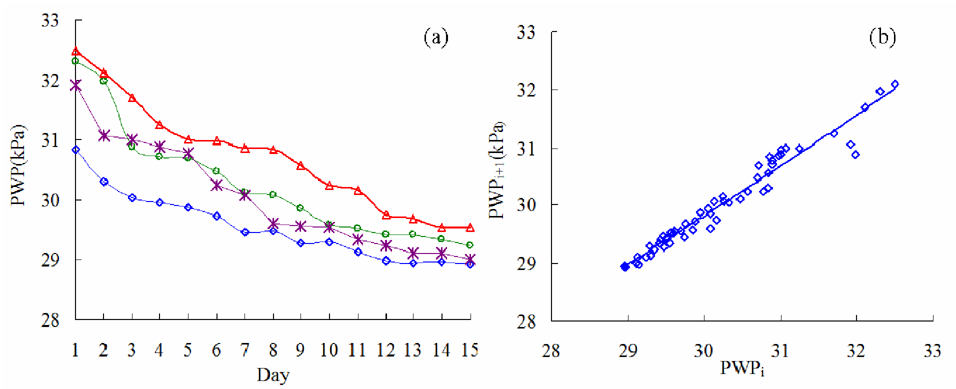

Figure 7 (a) Observation of *PWP* vs. time for four fifteen-day-long periods without rainfall or snowmelt. (Number of samples: n=48) (b) PWP_i vs. PWP_{i+1} (i^{th} day of *PWP* correlates to $i+1^{th}$ day of *PWP* for four fifteen-day-long periods without rainfall or snowmelt (Number of samples: n=48).

3.4 Snowmelt calculations in modified tank model

3.4.1 Diagnosis of precipitation types

A threshold temperature under which the precipitation falls as snow solid is a key factor for a snow accumulation model. However, diagnosis of precipitation is difficult, and there are no parameters with which the type of precipitation can be determined for certainty (Wagner, 1957; Koolwine, 1975; Bocchieri, 1980; Czys et al., 1996; Ahrens, 2007). Until now, the most common approach is still to derive statistical relationships between some predictors and different precipitation types (Bourgouin, 2000). We therefore select a statistical model based on hundreds of observation samples in Wajima Japan, between 1975 and 1978 to estimate precipitation types (Matsuo and Sasyo, 1981). The threshold of relative humidity calculated by T_d (daily average temperature) is as follows:

$$RH_t = 124.9e^{-0.0698T_d} \quad (10)$$

If the real relative humidity RH is smaller than RH_t, the precipitation is usually snowfall (Häggmark and Ivarsson, 1997).

3.4.2 Snowmelt model

One of the most popular methods employed to forecast snowmelt is to correlate air temperature with snowmelt data. Such a relation was first used for an Alpine glacier by Finsterwalder and Schunk (1887) and has since then been extensively applied and further refined (Kustas et al., 1994; Rango and Martinec, 1995; Hock, 1999, 2003). Recently, the most widely accepted temperature-index model is that of Hock (2003). The approach of daily melt assumes the form:

$$M' = f_m(T_d - T_0) \quad (11)$$

where T_0 is a threshold temperature beyond which melt is assumed to occur (typically 0°C), and f_m is a degree-day factor. Widely used empirical f_m is suggested here (e.g., Gottlieb, 1980; Lang, 1986; Braun et al., 1994; Hock, 2003), which is decided according to canopy cover of one area in percent, beginning time of snowmelt, etc., In this study, the degree-day factor is calculated by

$$f_m = 2.92 - 0.0164F \quad (12)$$

where F is canopy covers of Aggenalm Landslide area in percent (Esko, 1980).

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4 Results

4.1 Performance of modified tank model in heavy rainfall season

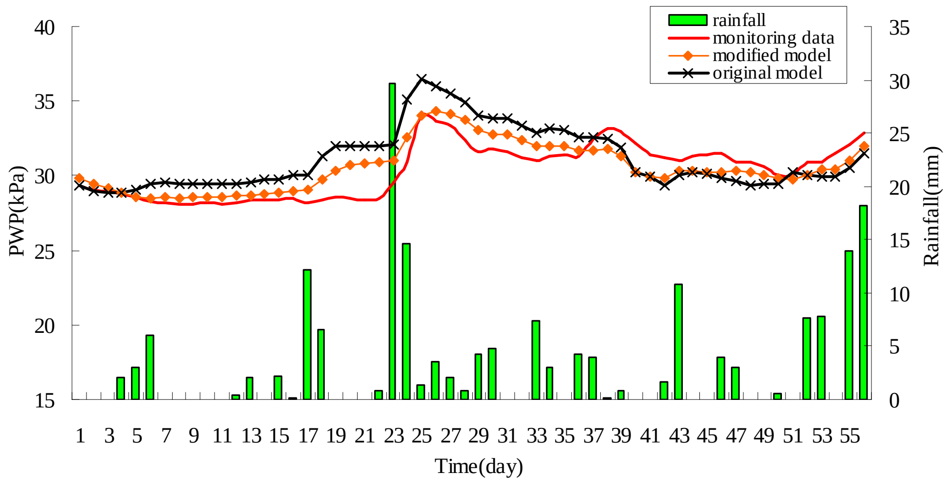

Figure 8 Estimation of change of *PWP* using our modified tank model (snowmelt + time lag 1+2) and the original tank model during summer (snow free) (07.07.2009-31.08.2009).

As shown in Fig. 8, our modified tank model and original tank model considering no time lag are used to estimate the change of *PWP* in summer. Both the original and modified tank model do a reasonably good job at estimating changes in PWP during summer.. The original model, however, generally overestimates the *PWP* curve. The modified model matches the measurement curve better due to the infiltration *time lag 2*. Error analysis in Fig. 10 quantifies the model‘s performance.

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4.2 Performance of modified tank model in snowmelt season

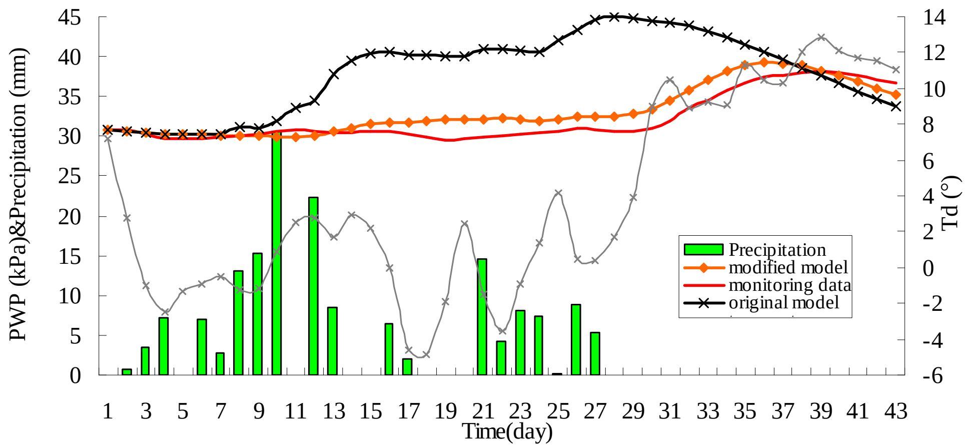

Figure 9 Estimation of change of PWP using our modified tank model (snowmelt + time lag 1+2) and original tank model in snowmelt season (04.03.2009-15.04.2009).

The original model without snow accumulation and snowmelt does a poor job at estimating PWP during spring, as the change of *PWP* missing the accumulation *time lag 1* caused by the original model to overestimate *PWP* from the day 12-33. The modified tank model much better reflects the peak of snowmelt (33th-37th day) and matches the measurement curve well in consideration of *time lag 1*. The deviation derives from the naturally limited accuracy of snow accumulation and snowmelt models. The Fig.10 indicates evaluation index of original and modified tank model including correlation, root mean square error (RMSE), and relative error. As shown in Fig. 11, modified tank model simulated the *PWP* levels in whole monitoring period.

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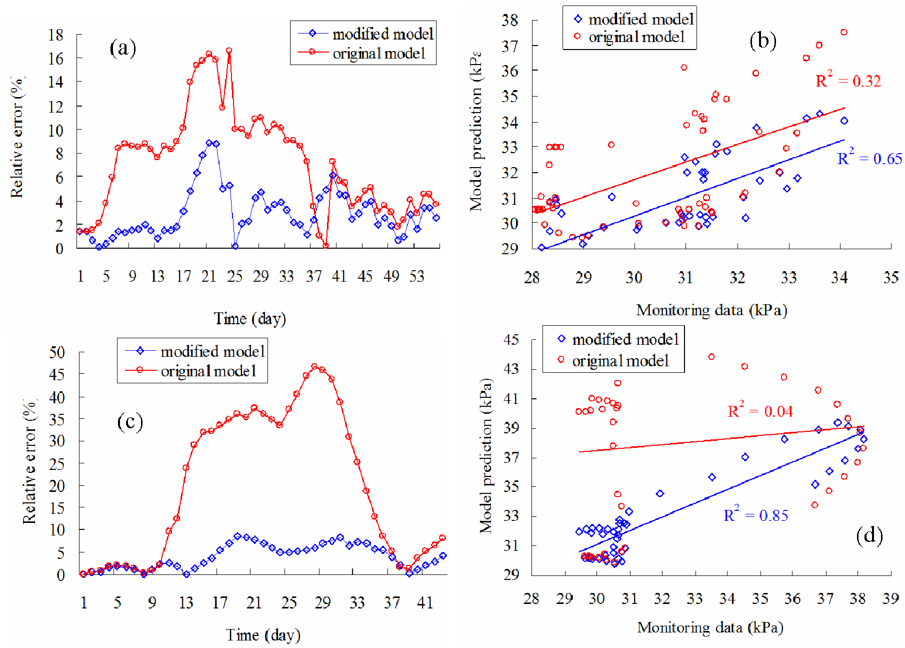

Figure 10 Evaluation of original and modified tank model (a) Correlation between measurements and original/modified tank model during a 54-day rainfall period (n=54) Root mean square errors (RMSE) for the original and modified models are 1.9 and 0.97 respectively. (b) Correlation between measurements and original/modified tank model in snowmelt period (n=47). Root mean square error (RMSE): Original model 5.4/Modified model 1.3. (c) Relative error of original and modified tank model in summer (n=54). (d) Relative error of original and modified tank model during spring (n=47).

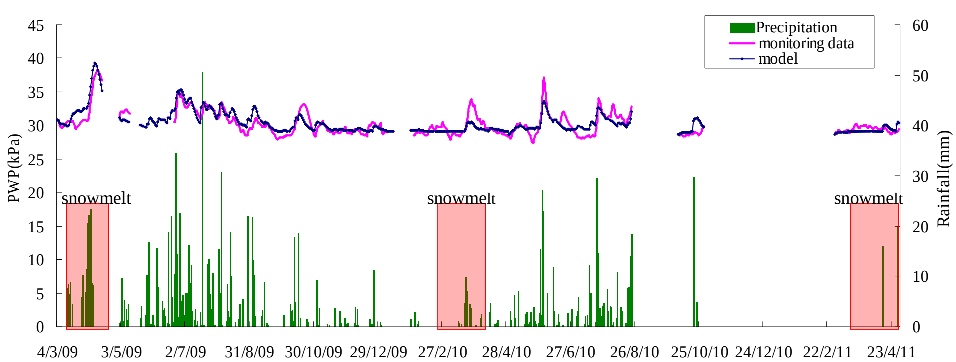

Figure 11 Simulation of *PWP* using the modified tank model throughout the monitoring

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period (04.03.2009-23.04.2011).

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In order to evaluate the performance of the modified tank model with respect to heavy rainfall and snowmelt, the two most important forces for accelerating slope movement.

5.1 Performance of modified tank model in heavy rainfall season

The modified tank model describes the fluctuation of *PWP* reasonably well, especially during heavy rainfall days such as 23th to 26th day (43 mm) and 51th to 55th day (45 mm) (Fig. 8). The relative errors in Fig.10a are less than 3% and 4% during these days. Dry periods (such as 2nd to 7th day and 17th to 21st) agree with *PWP* measurement, with a relative error of 2-9% as shown in Fig. 10a. The low water content of the landslide materials during the dry season appears to reduce the infiltration rates (Fredlund and Xing, 1994; Schaap and Van Genuchten, 2006). And *PWP* levels increase very slowly or not at all during these periods. As a result, the relative error of our modified model is slightly higher than that during wetter intervals. Compared with the original model, our model better represents PWP monitoring data. Fig.10b indicates a higher linear correlation between measurements and modified tank model with 0.65 (RMSE -0.97) than the original tank model with 0.29 (RMSE -1.9).

5.2 Performance of modified tank model in snowmelt season

We found a better correlation between measurements and our modified tank model with 0.86 (RMSE -0.97) than the original tank model in which all precipitation was assumed to be rainfall and snowmelt was not considered with 0.04 (RMSE -5.4) during snowmelt period. It has to be pointed out that the snowmelt estimation is still not very precise, as the temperature-index model is relatively simple (Garen and Marks, 2005; Herrero et al., 2009; Lakhankar et al., 2013). Also, we do not consider surface runoff due to the high permeability of surface deposits. Our modified tank model, however, provides a useful estimation of increased *PWP* in creeping landslide masses several 10's of meters deep.

5.3 Highlights of our modified model

Compared to the traditional permeability-based on methods (Fredlund and Xing, 1994; Chen and Young, 2006; Schaap and Van Genuchten, 2006; Weill et al., 2009), our modified tank model just needs historical monitoring data and doesn't need to consider uncertainties of

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material properties. Compared to the recent multi-tank model researches (Ohtsu et al., 2003; Takahashi, 2004; Takahashi et al., 2008; Xiong et al., 2009), our modified tank model does not require complicated algorithms and several observation boreholes to optimize the parameters. It is a straightforward approach. The model integrates the snow accumulation/-melt model which is few considered in other tank model researches. We present a flexible approach since the model can simulate groundwater table at least two years continuously without obvious accumulative error unlike permeability-based numerical models or optimization parameter-based models needing refreshment at times (Takahashi et al., 2008; Xiong et al., 2009).

6 Conclusions

Pore water pressure is one of the important dynamic factors in deep-seated slope destabilization and our modified tank model could help to anticipate critical states of deep-seated landslide stability a few days in advance by predicting changes in pore water pressure. In this paper, we proposed a modified tank model for estimation of increased pore water pressure induced by rainfall or snowmelt events in a deep-seated landslide. Compared to the original tank model, we simulate the fluctuation of *PWP* more accurately by reducing the time lag effects induced by snowmelt and infiltration into a long path of deep-seated landslide. In this modified model, a statistical method based on temperature and humidity is used for diagnosis of precipitation types and a snowmelt model based on temperature index is integrated into it, also included an equivalent infiltration method which can describe the infiltration relative reliably is in the modified model to reduce their time lag effect.

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References

Agliardi, F., Crosta, G. B., Zanchi, A., and Ravazzi, C.: Onset and timing of deep-seated gravitational slope deformations in the eastern Alps, Italy. Geomorphology, 103 (1), 113-129, 2009.

Ahrens, C. D.: Meteorology today: an introduction to weather, climate, and the environment. Cengage Learning. 2007.

Angeli, M. G., Gasparetto, P., Silano, S., Tonnetti, G.: An automatic recording system to detect critical stability conditions in slopes. Proc. of the 5th ISL, Vol. 1. Lausanne, 375–378, 1988.

Bromhead, E. N.: Large landslides in London Clay at Herne Bay, Kent. Quarterly Journal of Engineering Geology and Hydrogeology, 11(4), 291-304, 1978.

Braun, L. N., Aellen, M., Funk, M., Hock, R., Rohrer, M. B., Steinegger, U., Kappenberger, G., and Müller-Lemans, H.: Measurement and simulation of high alpine water balance components in the Linth-Limmern head watershed (Northeastern Switzerland). Z. Gletscherkd. Glazialgeol, 30, 161–185, 1994.

Bourgouin, P.: A method to determine precipitation types. Weather and forecasting, 15 (5), 583-592, 2000.

Bocchieri, J. R.: The objective use of upper air sounding to specify precipitation type. Mon. Wea. Rev., 108, 596–603, 1980.

Chow, Ven. Te.: Runoff, Handbook of Applied Hydrology. Mc Graw Hill Book Comp, pp. 14.5-14.8. In Chow Ven Te (ed) 1964.

Czys, R. R., Scott, R.W., Tang, K. C., Przybylinski, R. W., and Sabones, M. E.: A physically based, nondimensional parameter for discriminating between locations of freezing rain and ice pellets. Wea. Forecasting, 11, 591–598, 1996.

Chen, L. and Young, M. H.: Green-Ampt infiltration model for sloping surfaces. Water resources research, 42 (7), W07420, doi:10.1029/2005WR004468, 2006.

Cruden, D. M. and Varnes, D. J.: Landslide types and processes. In: Turner, A. K. and Schuster, R. L. (ed.). Landslides: Investigation and Mitigation. Transportation Research

Board National Research Council. Special Report 247, 36-75, Washington, National Academy Press. 1996.

Esko, K.: On the values and variability of degree-day melting factor in Finland. Nordic hydrology, 11 (5), 235-242, 1980.

Freedman, D., Pisani, R., and Purves, R.: Statistics (3rd ed). Norton & Company. 113, 1998.

Finsterwalder, S. and Schunk, H.: Der Suldenferner. Zeitschrift des Deutschen und Oesterreichischen Alpenvereins 18, 72–89, 1887.

Festl, J., Singer, J. & Thuro, K. (2012): The Aggenalm landslide – first findings of the monitoring data. – In: Eberhardt, E., Froese, C., Turner, A. K. & Leroueil, S. [eds.] (2012): Landslides and Engineered Slopes: Protecting society through improved understanding. – 1995 p., 11. International & 2nd National North American Symposium on Landslides, Banff, Alberta, Canada, June, 3rd – 8th 2012, London (Balkema), 907-912.

Festl, J.: Analysis and Evaluation of the Geosensor Network's Data at the Aggenalm Landslide, Bayerischzell, Germany. PhD thesis, Technical University Munich, Munich, Germany, 2014.

Fredlund, D. G., and Xing, A.: Equations for the soil-water characteristic curve. Canadian Geotechnical Journal. Vol. 31, 521-532, 1994.

Gottlieb, L.: Development and applications of a run off model for snow covered and glacierized basins. Nord. Hydrol. 11, 255–284, 1980.

Garen, D. C. and Marks, D.: Spatially distributed energy balance snowmelt modelling in a mountainous river basin: estimation of meteorological inputs and verification of model results, J. Hydrol., 315, 126–153, 2005.

Hock, R.: A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. J. Glaciol. 45, 101–111, 1999.

Hock, R.: Temperature index melt modelling in mountain areas. J. Hydrol. 282, 104–115, 2003.

Häggmark, L. and Ivarsson, K. I.: MESAN Mesoskalig analys, SMHI RMK Nr. 75, 21-28, 1997.

Huang, A. B., Lee, J. T., Ho, Y. T., and Chiu, Y. F.: Stability monitoring of rainfall-induced deep landslides through pore pressure profile measurements. Soils and Foundations, 52 (4): 737-747, 2012.

Herrero, J., Polo, M. J., Moñino, A., and Losada, M. A.: An energy balance snowmelt model in a Mediterranean site, J. Hydrol., 371, 98–107, 2009.

Hong, Y., Hiura, H., Shino, K., Sassa, K. and Fukuoka, H.: Quantitative assessment of the influence of heavy rainfall on a crystalline schist landslide by monitoring system—a case study of the Zentoku landslide, Japan. Landslides 2, 31–41, 2005.

Iverson, R. M.: Landslide triggering by rain infiltration. Water resources research, 36 (7): 1897-1910, 2000.

Ishihara, Y., and Kobatake, S.: Runoff model for flood forecasting. Bulletin of the Disaster Prevention Research Institute 29 (1), 27-43, 1979.

Kustas, W. P., Rango, A., and Uijlenhoet, R.: A simple energy budget algorithm for the snowmelt runoff model. Water Resour. Res. 30 (5), 1515–1527, 1994.

Koolwine, T.: Freezing rain. M.S. thesis, Dept. of Physics, University of Toronto, 92 pp. 1975. [Available from University of Toronto Libraries, 27 King's College Circle, Toronto, ON M5S1A1, Canada.]

Lang, H.: Forecasting meltwater runoff from snow-covered areas and from glacier basins. In: Kraijenhoff, D.A. and Moll, J.R. (Eds.), River Flow Modelling and Forecasting, D. Reidel publishing company, pp. 99–127, Chapter 5, 1986.

Lakhankar, T. Y., Muñoz, J., Romanov, P., Powell, A. M., Krakauer, N. Y., Rossow, W. B., and Khanbilvardi, R. M.: CREST-Snow Field Experiment: analysis of snowpack properties using multifrequency microwave remote sensing data, Hydrol. Earth Syst. Sci., 17, 783–793, doi:10.5194/hess-17-783-2013.

Linzer, H. G., Ratschbacher, L., and Frisch, W.: Transpressional collision structures in the upper crust: the fold-thrust belt of the Northern Calcareous Alps. Tectonophysics, 242 (1): 41-61, 1995.

Lodge, G. M. and Brennan, M. A.: Rainfall and soil water content at a native pasture site near Barraba, NSW. In: Boschma, S.P., Serafin, L.M. and Ayres, J.F. (eds) 'Proceedings of the

23rd Annual Conference of the Grassland Society of NSW (Grassland Society of NSW Inc: Orange)', 137-140, 2008.

Matsuo, T., and Sasyo, Y.: Non-Melting Phenomena of Snowflakes Observed in Sub saturated Air below Freezing Level, Journal of the Meteorological Society of Japan. 59, 26-32, 1981.

Mayer, K., Müller-Koch, K., and von Poschinger, A.: Dealing with landslide hazards in the Bavarian Alps[C]//Proceedings of the 1st European conference on landslides, Prague. Balkema, Rotterdam. 417-421, 2002.

Matsuura, S., Asano, S., and Okamoto, T.: Relationship between rain and/or meltwater, pore-water pressure and displacement of a reactivated landslide. Engineering Geology, 101 (1), 49-59, 2008.

Mandl, G. W.: The Alpine sector of the Tethyan shelf—examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 61-77, 2000.

Madritsch, H. and Millen, B. M. J.: Hydrogeologic evidence for a continuous basal shear zone within a deep-seated gravitational slope deformation (Eastern Alps, Tyrol, Austria). Landslides, 4 (2), 149-162, 2007.

Michiue, M.: A method for predicting slope failures on cliff and mountain due to heavy rain. Natural disaster science 7 (1),1-12, 1985.

Nickmann, M., Spaun, G., and Thuro, K.: Engineering geological classification of weak rocks. International Association for Engineering Geology and the Environment, 492, 9, 2006.

Nishii, R. and Matsuoka, N.: Monitoring rapid head scarp movement in an alpine rockslide, Engineering Geology, 115 (1), 49-57, 2010.

Ohtsu, H., Janrungautai, S. and Takahashi, K.: A study on the slope risk evaluation due to rainfall using the simplified storage tank model. In: Proceeding of the 2nd Southeast Asia Workshop on Rock Engineering, Bangkok, Thailand, 67-72, 2003.

Rango, A. and Martinec, J.: Revisiting the degree-day method for snowmelt computations. JAWRA – J. Am. Water Resour. Assoc. 31, 657–670, 1995.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2015-341, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 18 January 2016

Rahardjo, H., Leong, E. C. and Rezaur, R, B.: Effect of antecedent rainfall on pore-water pressure distribution characteristics in residual soil slopes under tropical rainfall. Hydrological Processes, 22 (4), 506-523, 2008.

Rahardjo, H., Nio, A. S., Leong, E. C. and Song, N. Y.: Effects of groundwater table position and soil properties on stability of slope during rainfall. Journal of geotechnical and geoenvironmental engineering, 136 (11), 1555-1564, 2010.

Schaap, M. G. and Van Genuchten, M. T.: A modified Mualem–van Genuchten formulation for improved description of the hydraulic conductivity near saturation. Vadose Zone Journal, 5 (1), 27-34, 2006.

Sidle, R. C.: Field observations and process understanding in hydrology: essential components in scaling. Hydrological Processes, 20 (6), 1439-1445, 2006.

Singer, J., Schuhbäck, S., Wasmeier, P., Thuro, K., Heunecke, O., Wunderlich, T. and Festl, J.: Monitoring the Aggenalm landslide using economic deformation measurement techniques. Austrian J Earth Sci, 102 (2), 20-34, 2009

Schulz, W. H., McKenna, J. P., Kibler, J. D. and Biavati, G.: Relations between hydrology and velocity of a continuously moving landslide—evidence of pore-pressure feedback regulating landslide motion? Landslides, 6 (3),181-190. 2009.

Simoni, A., Berti, M., Generali, M., Elmi, C. and Ghirotti, M.: Preliminary results from pore pressure monitoring on an unstable clay slope. Engineering Geology 73, 117–128, 2004.

Suzuki, M. and Kobashi, S.: The critical rainfall for the disasters caused by slope failures. Journal of Japan Society of Erosion Control Engineering (Shin-Sabo), 34 (2), 16-26, 1981.

Takahashi, K., Ohnish, Y., Xiong, J. and Koyama, T.: Tank model and its application to groundwater table prediction of slope. Chinese Journal of Rock Mechanics and Engineering 27 (12), 2501–2508, 2008.

Takahashi, K.: Research of underground water numerical analysis method that considering water cycle system. PhD thesis, Kyoto University, Kyoto, Japan, 2004.

Tsaparas, I., Rahardjo, H., Toll, D. G. and Leong, E. C.: Controlling parameters for rainfall-induced landslides. Computers and Geotechnics, 29 (1), 1-27. 2002.

Thuro, K., Wunderlich, Th. & Heunecke, O., Singer, J., Schuhbäck, St., Wasmeier, P., Glabsch, J. & Festl, J. (2009): Low cost 3D early warning system for alpine instable slopes - the Aggenalm Landslide monitoring system. Kostengünstiges 3D Frühwarnsystem für alpine instabile Hänge - Das Überwachungssystem der Aggenalm-Hangbewegung. – Geomechanics & Tunnelling - Geomechanik & Tunnelbau 3: 221-237.

Thuro, K., Singer, J., Festl, J., Wunderlich, Th., Wasmeier, P., Reith, Ch., Heunecke, O., Glabsch, J. and Schuhbäck, St.: New landslide monitoring techniques–developments and experiences of the alpEWAS project.-Journal of Applied Geodesy 4, 69-90, 2010.

Thuro, K., Singer, J. & Festl, J. (2011a): A geosensor network based monitoring and early warning system for landslides.– In: Catani, F., Margottini, A., Trigila, A. & Iadanza, C. (Eds.): The Second World Landslide Forum. Abstract Book. – The Second World Landslide Forum, 3.-9. Oktober, Rom, Italien, Abstract WLF2-2011-0214, S. 267; Paper, 6 P., Rom (Italian National Institute for Environmental Protection and Research).

Thuro, K., Singer, J. & Festl, J. (2011b): Low cost 3D early warning system for alpine instable slopes – the Aggenalm Landslide monitoring system. - In: Slope stability 2011. International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Vancouver, Canada 18.- 21.09.2011. 12 p. (digital).

Thuro, K., Singer, J. & Festl, J. (2013): A Geosensor Network Based Monitoring and Early Warning System for Landslides. – In: Margottini, C., Canuti, P. & Sassa, K. (2013): Landslide Science and Practice, Volume 2: Early Warning, Instrumentation and Monitoring. – 685 p., Heidelberg, New York, etc. (Springer), 79-86.

Uchimura, T., Tanaka, R., Suzuki, D. and Yamada, S.: Evaluation of hydraulic properties of slope ground based on monitoring data of moisture contents. In: Proceedings of the 4th Japan-Taiwan Joint Workshop on Geotechnical Hazards from Large Earthquakes and Heavy Rainfalls, Sendai, Japan, 85-90, 2010

Wang, G. and Sassa, K.: Pore-pressure generation and movement of rainfall-induced landslides: effects of grain size and fine-particle content. Engineering geology, 69 (1), 109-125, 2003.

Wagner, J. A.: Mean temperature from 1000 mb to 500 mb as a predictor of precipitation type. Bull. Amer. Meteor. Soc., 38, 584–590, 1957.

Weill, S., Mouche, E. and Patin, J.: A generalized Richards equation for surface/subsurface flow modelling. Journal of Hydrology, 366 (1), 9-20, 2009.

Wilkinson, P. L. and Brooks, S. M.: Anderson MG.: Investigating the effect of moisture extraction by vegetation upon slope stability:further developments of a combinedhydrology and stability model (CHASM). British Hydrological Society International Symposium on Hydrology in a Changing Environment. Theme 4: Hydrology of environmental hazards, Exeter, 165–178, 1998.

Wilkinson, P. L., Anderson, M. G. and Lloyd, D. M.: An integrated hydrological model for rain-induced landslide prediction. Earth Surface Processes and Landforms, 27 (12), 1285-1297, 2002.

Xiong, J., Ohnish, Y., Takahashi, K. and Koyama, T.: Parameter determination of multi-tank model with dynamically dimensioned search. Proc Symp Rock mech Jpn 38, 19–24, 2009.

Yin, Y., Wang, H., Gao, Y. and Li, X.: Real-time monitoring and early warning of landslides at relocated Wushan Town, the Three Gorges Reservoir, China. Landslides 7 (3), 339-349, 2010.