Dear Prof. Glade, dear Thomas,

Thanks you for your letter and for the very helpful reviewers' comments concerning our manuscript. The comments were valuable and helpful for revising and improving our paper. We have studied the comments carefully and have thoroughly revised the manuscript. We have added a number of paragraphs in the Introduction and the Discussion and significantly modified the Methods and the Results Sections. We have spent a considerable effort in calculating the Nash-Sutcliffe model efficiency for all described model runs of the original simple and modified tank models in Section 5 and, by this, we could demonstrate that our modified tank model has a much higher explanatory power than the standard tank model.

We have carefully edited the revised paper including figures and made it more concise in two complete revisions. As this applied to the complete paper we have not marked all language changes and grammar changes. However, the main changes made in response to the reviewers' comments, as listed here, are marked in red in the revised paper.

Thanks for all efforts

Wen and Michael

Review1:

General commons: the main drawback in this manuscript is lack of information about frozen soils and reasons why authors not include it to the research, as well critical evaluation of using methods in the paragraph of discussion.

(1) I would advise the authors of this paper to describe climate condition in the region of investigation and rainfall patterns for the observed period that influence on the landslide initiation.

> *>The climate condition and rainfall description are now added in section 3.1:* ***>Implemented (Line 3-16, Page 10):*** *"The Aggenalm is exposed to a sub-continental climate with a pronounced summer precipitation maximum and an annually changing share of 15–40 % of the mean annual precipitation that fall as snow. Abundant snow cover restricts freezing of the top to few tens of cms allowing water penetration in cracks etc. Due to the all-year humid climate (see Figure 4, nearby meteo-stations such at the Brünnsteinhaus, the Sudelfeld (Polizeiheim) and the Tatzelwurm indicate mean annual precipitation of 1594, 1523 and 1660 mm/a at similar elevations), the rapid drainage of water in the permeable underground (pore water pressure reduces 2-3 kPa within 15 days) and the deep-seated nature of the slope movement (depth is 30-40 m), we did not explicitly consider evapotranspiration. However, the daily reduction of pore pressure (~0.3 kPa/day) includes an empirical component of evapotranspiration.*

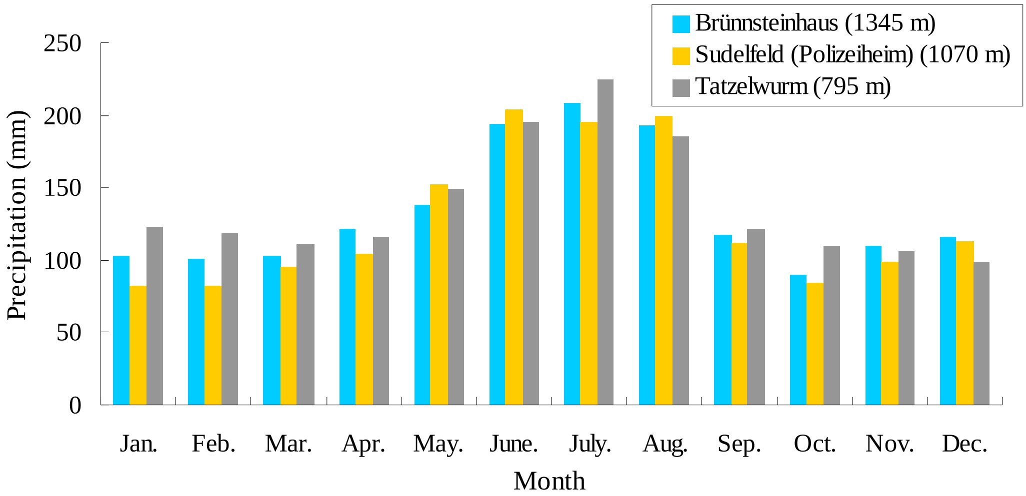

Figure 4 Mean monthly precipitation (1931–1960 and 1961–1990) for the Brünnsteinhaus, the Sudelfeld (Polizeiheim), and Tatzelwurm meteorological stations (data from Germany's National Meteorological Service DWD)."

(2) In the Figure 1b the font of text is not clear enough. I suggest using different font.

> *> **Implemented (Line 1-2, Page 8):** We adjusted the size of Figure 1 as the relative size of the font is restricted.*

(3) According to the monitored data from winter season the presence of frozen soil greatly affects the amount of runoff produced from snowmelt. From the site description one is unable to find information about frozen soils. If there is significant relationship between frozen soils, infiltration and PWP then you include effect of frozen soils to the tank models.

> *> We added this explanation at the end of Section 3.4: **>Implemented (Line 4-14, Page 12 and Line 1-9, Page 16):** "We ignore surface runoff flow resulting from snowmelt and heavy rainfall as (1) the slope angle is less than 15°, (2) the cumulative snowpack is no more than 70 cm during monitoring days and (3) the infiltration rate of slope in Quaternary deposits and on carbonates is relatively high. We ignore freezing effects on infiltration as (1) ground sealing by freezing is presumably not an issue since the bottom temperature of snow (BTS) is next to 0°C underlain by a warmer subsoil in addition to high permeable subsoil. (2) Snow accumulation during winters and winter rainfall precipitation prevent effective cooling of ground. Due to the all-year humid climate, the rapid drainage of water in the permeable underground and the deep-seated nature of the slope movement, we did not explicitly consider evapotranspiration."*

(4) Line 9: you did not explain why your data of PWP, temperature and humidity averaged over a 24-hour period, why you use this time frame? **-** Line 15: how you performed validation of tank model?

>We explain the choice of 24-hour periods in Section 3.2: ***>Implemented (Line 2-4, Page 11):*** *"Since the whole monitoring period lasts for almost 3 years and time lags are in the range of days, days were considered to be the most robust, appropriate standard reference time unit, also to keep results comparable to previous studies"*

>We explain the validation of tank model in Section 3.2: ***>Implemented (Line 8-11, Page 11):*** *"To validate the parametrized model, 55 days of rainfall (July 2009 to August 2009) and 44 days of snowmelt (March 2009 to April 2009) are used to compare model-calculated pore water pressure with real pore water pressure readings."*

(5) Authors have produced an interesting dataset but more needs to be done in the "Highlights of the modified model" before publication where major drawbacks and critical overview of the using methods must be included.

>The major drawbacks and critical overview of using methods have been added in section 5.4: ***>Implemented (Line 28-29, Page 23; Line 1-4, Page 24):*** *"The naturally inevitable drawback for any "probabilistic model" is that it is physically not explicit. The presented model would need e.g. further adjustments for permafrost regions, with heavily frozen soils, for very steep slopes, with significant surface runoff and for very heterogeneous slopes, with complex fractured rock masses. However, it seems well suited for large mountain landslides on moderately inclined slopes in alpine conditions with significant snow accumulations."*

(6) Linguistic alterations: some paragraphs have to be rewritten (Discussions and Conclusions)

> We then have spent considerable effort in repeatedly editing the revised paper and in making it even more concise. As this applied to the complete paper we have not marked all language changes and grammar changes; however, the main changes made in response to the reviewers' comments, as listed here, are marked in red in the revised paper.

Dear Prof. Glade,

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Thanks for all efforts

Wen and Michael

Review2:

(1)

1.1 The approach is not novel. Tank models have been used widely in landslide research as cited by the authors. Often, their use is justified by the absence of more detailed knowledge about the hydro-mechanical processes and driven by direct practical concerns. Other model approaches have been used and often include better a conceptualization of the hydrological processes and the mechanical response. The hydrological approaches are lumped here under a non-descript mention in lines 12-16 of page 3.

> *>We have taken this concern very serious and we have implemented a complete new section to refer our model to the previous state of the art and to demonstrate what is novel about our equivalent infiltration method including snowmelt and infiltration time lags.* ***>Implemented (from Line 1, Page 5 to Line 4 Page 7):***"

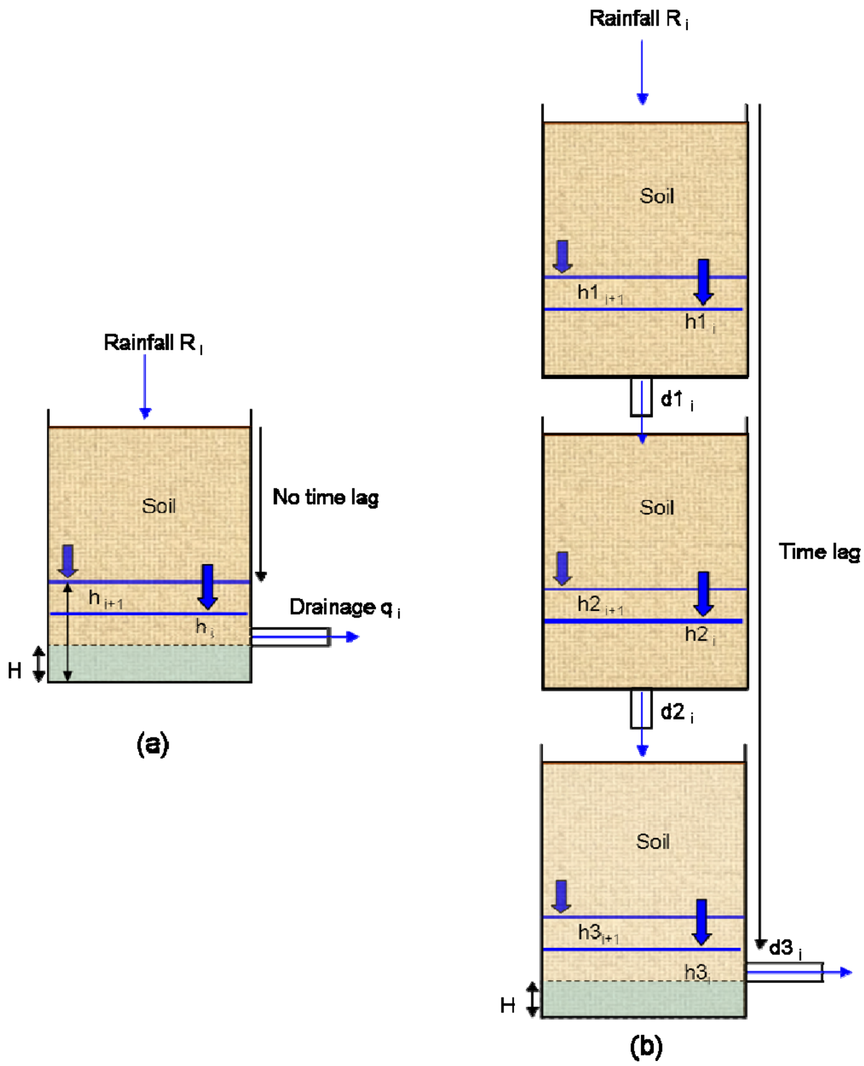

Figure 1 Details of simple tank model and multi-tank model applied in deep-seated landslides (a) Schematic diagram of simple tank model (b) Schematic diagram of multi-tank model

The Fig. 1(a) shows the work mode of a simple tank model.

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

$$q_i = ah_i \, , \qquad (2)$$

where R_i is the rainfall and q_i is the drainage of the i^{th} day. h_i is groundwater table height of the i^{th} day. a is the parameter for the relation between h_i and q_i. Obviously, for the deep-seated landslides, due to the long infiltration the rainfall (R_i) cannot totally contribute to the change of groundwater table (h_{i+1} - h_i) within one day. Thus, simple tank models do not consider infiltration time lags induced by a long infiltration path, previous moisture and snowmelt. This inhibits their applicability to deep-seated landslide. By contrast, the Fig. 1(b) describes the work principle of multi-tank models in deep-seated landslides mainly considering the vertical infiltrations.

$$\begin{cases} h1_{i+1} - h1_i = R_i - d1_i \\ d1_i = a1h1_i \end{cases} \qquad (3)$$

where $h1_{i+1}$, $h1_i$ are water table levels of the i+1th and ith day in higher soil layer; $d1_i$ is the infiltration of the ith day in middle soil layer; a1 is parameter of relation between $h1_i$ and $d1_i$; R_i is the rainfall of the ith day.

$$\begin{cases} h2_{i+1} - h2_i = d1_i - d2_i \\ d2_i = a2h2_i \end{cases} \qquad (4)$$

where $h2_{i+1}$, $h2_i$ are water table levels of the i+1th and ith day in middle soil layer; $d2_i$ is the infiltration of the ith day in lower soil layer; a2 is parameter of relation between $h2_i$ and $d2_i$.

$$\begin{cases} h3_{i+1} - h3_i = d2_i - d3_i \\ d3_i = a3h3_i \end{cases} \qquad (5)$$

where $h3_{i+1}$, $h3_i$ are water table levels of the i+1th and ith day in lower soil layer; $d3_i$ is the drainage of ith day; a3 is parameter of relation between $h3_i$ and $d3_i$.

From the Equations (3) to (5), there are 7 unknown ($h1_{i+1}$, $h1_i$, a1, $h2_{i+1}$, $h2_i$, a2, a3) and 3 known parameters ($h3_{i+1}$, $h3_i$, R_i). In order to get the 7 unknown values, even usage of some advanced algorithms does not effectively estimate the parameters. Multi-tank models can deal with infiltration time lags to some extent by adding tanks but even then they (i) require data from several monitoring boreholes to track groundwater flow supplies in complicated geological structures and (ii) they are presently not designed to replicate time lags of increased infiltration, e.g., following snowmelt (Iverson, 2000; Sidle, 2006; Nishii and Matsuoka, 2010). Applying multi-tank models to compensate for time lags is questionable as especially deep-seated landslides would need several tanks to replicate time lags and every added new tank in vertical direction introduces 3 new parameters at least. This would reduce robustness and reliability of system especially if we just use the monitored groundwater table for the parameter training of whole system.

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. The innovation of our approach is to calculate equivalent infiltration before it enters the tank. The equivalent infiltration deals with the infiltration time lag including snow accumulation and snowmelt in deep-seated landslides based on a simple tank model structure. We hypothesize and provide quantitative evidence that, compared to a simple tank model, our modified model has a higher accuracy and physical meaning by controlling equivalent infiltration including snow accumulation and snowmelt; compared to multi-tank model our modified model is more robust and reliable."

1.2 A fairer evaluation of the consensus and state-of-the-art on the modeling of the hydrological response of rainfall-driven landslide is needed. The qualification that "many of these parameters cannot be measured easily" is too little to discard this evidence completely and the underlying problems are not given sufficient thought in the formulation of the research objective of the manuscript. The tank model may be used to describe the hydrology of the Aggenalm landslide but with what purpose and what the required accuracy are is not specified; therefore, the choice to use this type of model is insufficiently justified.

>In addition, we implemented a new section in the Introduction to thoroughly describe the state-of-the-art on the modeling of the hydrological response. ***>Implemented (Line 3-17, Page 4):*** *"Traditional deterministic models have advantages due to their explicit physical and mechanical approaches, but they require accurate knowledge, testing and monitoring of soil physical parameters which are often not available with sufficient accuracy. For example, the widely used Richards Equation with Van Genuchten method needs soil suction tests under variable moisture content, saturated water content, residual water content, and the pore-size distribution of materials which are difficult to achieve for complex landslides with multiple reworked materials. (2) Empirical-statistical models employ optimization or fitting parameters in their model structure. Tank and other models need historical monitoring data to train parameters (Faris and Fathani, 2013; Abebe et al. 2010). Such empirical models, because of their simple conceptualized structure, do rely to a smaller degree on explicit physical and mechanical approaches. However, they can avoid the problems induced by the uncertainty of material parameterisation and its spatial arrangement in the landslide mass. They can, therefore, be applied to a wide range of different landslide settings and we estimate that for more than 90% of all landslides no explicit parameters on soil suction etc. are available."*

(2)
2.1 The fact that a simple model is used is contradictory with the wish to study deep seated, complicated landslides. In principle, adding a time lag is not different from adding a multi-tank model (Eq. 4) like a Nash cascade.

>Thanks for this comment - we add section 3.4 to explain model assumptions to simplify slope hydrology (see the answer 3.2 below). We also added a section to explain the drawback of using multi-tank for adding a time lag. See also the introduction above of multi-tank models for dealing with infiltration time lags (answer 1.1). ***>Implemented (Line 13-24, Page 6):*** *"Multi-tank models can deal with infiltration time lags to some extent by adding tanks but even then they (i) require data from several monitoring boreholes to track groundwater flow supplies in complicated geological structures and (ii) they are presently not designed to replicate time lags of increased infiltration, e.g., following snowmelt (Iverson, 2000; Sidle, 2006; Nishii and Matsuoka, 2010). Applying multi-tank models to compensate for time lags is questionable as especially deep-seated landslides would need several tanks to replicate time lags and every added new tank in vertical direction introduces 3 new parameters at least. This would reduce robustness and reliability of system especially if we just use the monitored groundwater table for the parameter training of whole system."*

2.2 This limitation is severe as the addition of these model components is done without an a priori conceptualization of the pertinent hydrological processes or subject to a rigorous assessment of the added parameterization costs and uncertainty.

>A rigorous assessment of the added parameterization costs and uncertainty is a good suggestion. However, there is no effective application of multi-tank model in deep-seated landslides. In addition, no standard procedure can valuate the parameterization costs and

uncertainty. Thus, comparison of parameterization costs and uncertainty can at present not be operated realistically without generating a multi-tank model which is beyond the scope of this paper.

2.3 No attempt is made to quantify the parameters of Eq. 7 in terms of processes (e.g., evapotranspiration, interception and groundwater recharge).

> We explain this effect of evapotranspiration on groundwater table: ***>Implemented (Line 4-6, Page 13):*** *"Due to the all-year humid climate, the rapid drainage of water in the permeable underground and the deep-seated nature of the slope movement, we did not explicitly consider evapotranspiration."* ***>Implemented (Line 6-12, Page 10):*** *"Due to the all-year humid climate (see Figure 4, nearby meteo-stations such at the Brünnsteinhaus, the Sudelfeld (Polizeiheim) and the Tatzelwurm indicate mean annual precipitation of 1594, 1523 and 1660 mm/a at similar elevations), the rapid drainage of water in the permeable underground (pore water pressure reduces 2-3 kPa within 15 days) and the deep-seated nature of the slope movement (depth is 30-40 m), we did not explicitly consider evapotranspiration. However, the daily reduction of pore pressure (~0.3 kPa/day) includes an empirical component of evapotranspiration."*

2.4 This sits ill-at-ease with the fact that for example snow melt itself is made land cover dependent by use of the forest fraction (Eq. 12). By doing so, again, the manuscript fails to innovate as similar work has explored the added benefit of process based approaches earlier (e.g., Bogaard & Van Asch, doi:10.1002/esp.419).

*>For the snow accumulation/snow melt, we introduce well-operating empirical equations into the tank model and we do not aim at improving the estimation ability of snow model itself. This is a rough estimation since the precise calculation is very complex, but on the other hand we aggregate changes in pore pressure over years and daily uncertainties in snowmelt will be smoothed out after a few days. >****Implemented in the Introduction (Line 8-15, Page 7)****: "While, for the snowmelt calculation we used empirical equations to make the process earlier, because sophisticated models which can calculate the snowmelt precisely are quite complex and require several physical parameters, including topography, precipitation, air temperature, wind speed and direction, humidity, downwelling shortwave and longwave radiation, cloud cover, and surface pressure (Garen and Marks, 2005; Herrero et al., 2009; Lakhankar et al., 2013). In addition, compared to the original tank model without considering the snowmelt, we emphasized the tank model coupling the function of snowmelt (we just choose the simple snowmelt module)."*

(3)

3.1 The fact that hydrological input is directly transferred into pore pressure is an assumption not proven to any conceivable standard in the paper and one that is highly tenuous in case of deep-seated, complicated landslides (e.g., the effect of undrained loading).

>Since the groundwater table cannot be measured directly, the prediction model of

*groundwater usually extracts the transformed pore water pressure data then makes a water table prediction. After that, predicted water table is transformed into pore water pressure for validation. What we did is coupling the pore water pressure directly into the model. >**Implemented (Line 7-12, Page 13):** The major part of pore water pressure is static pressure induced by water table height. Minor components are seepage force and the difference of pressures in the available pore space over drier and wetter periods. Since the tank model is a "grey box model", we do not know the exact proportions of static pressure, seepage pressure, and pressure dynamics in pore space, which are all three included in our equivalent pore water pressure.*

*>We add the explanation about the "pore water pressure" is positive pressure in section 3.3. Thus, we can set up the link between groundwater table and pore water pressure. **>Implemented (from Line 16, Page 14 to Line 2, Page 15):** "Hereby, "pore water pressure" is positive pressure induced by groundwater table height. It does not refer to perched water or negative pore water pressures."*

3.2 This is particular the case as any natural variability in what supposedly is a highly heterogeneous sub-surface (Figure 2) is left out of consideration completely by analyzing only one well that is located relatively deep into the incompetent marl layers. Accumulation of groundwater in the more pervious and fractured materials higher on the slope (dolomite and debris) and any subsequent loading is left completely out of the equation.

*>We add section 3.4 to explain model assumptions to simplify slope hydrology: **>Implemented (Line 5-11, Page 15):** "We assume that Quaternary deposits control the hydraulic properties of the tank model (tank interior with soil/rock in Fig. 5). The fractured limestone and dolomite control the water flow from higher to lower elevations (groundwater inflow and drainage in Fig. 5). The marly Kössen Beds are treated as impermeable layers (thin, low porosity and high normal stress above). As this is a regional groundwater table estimation, we use the modified tank model to simulate the groundwater table changes induced by precipitation."*

3.3 In this light, a formulation of an objective in terms of movement (hazard; see also point 1) and a separate validation of the pore pressure levels in terms of acceleration of the entire landslide body are definitely missing.

*>Our aim is only to estimate the local ground water table in deep-seated landslides. The relation between landslide movement and the groundwater table is not the focus of this manuscript. Firstly, the groundwater table is a regional estimation. Secondly, the landslide movement is complex and time-depended and material strength is also very important besides groundwater table. **>Implemented (Line 19-28, Page 7):** "It should be pointed out our aim is only to estimate the local pore water pressure in deep-seated landslides. The relation between landslide movement and the groundwater table is not the focus of this study. The landslide movement is complex and time-depended and material strength is also very*

important besides groundwater table. It has been hypothesised that deep-seated landslide velocity, although linked to pore pressure-induced changes in effective stress, is also governed by rate-induced changes in shear strength of the materials, caused by changing mechanical properties during shear deformation (Lupini et al., 1981; Skempton, 1985; Angeli et al., 1996; Picarelli, 2007); and/or consolidation and strength regain during periods of rest (Nieuwenhuis, 1991; Angeli et al., 2004)."

3.4 Similarly, an evaluation of the tank model in relation to other observed pore pressures / groundwater levels (e.g., the second well indicated in Figure 2, B2) would certainly add rigour to the assessment and may help to prove its actual worth.

>An evaluation of the tank model in relation to other observed pore pressures/ groundwater levels would certainly add rigor to the assessment. Unfortunately, we have only one persistently functioning pore water pressure sensor in another well broke down.

3.5 In terms of the mathematical formulation, the method is already fraught as changes in groundwater height are equated to the input in terms of water slice, thus neglecting the effect of the available pore space in which the water table is formed. Hence groundwater fluctuations and related pore pressure variations under the assumption of a freely draining aquifer are underestimated. Re (3), it also means that dynamics in the available pore space over drier and wetter periods are also ignored. Furthermore, the authors neglect seepage forces (p. 8, line 11) but using hydrostatic forces is questionable as it is not proven how water flows through the landslide complex and if the simulated groundwater level can be simply extrapolated to an effective pore pressure at the potential slip plane.

>We add more details about explanation and calculation of pore water pressure by our tank model in Eq.(10) (11) and Eq.(12). ***>Implemented (from Line 14, Page13 to Line 14, Page14):*** *"* $\Delta h_i = h_{i+1} - h_i = \frac{\alpha}{n}(ER_i + ES_i) - (q_i - g_i)$ *(10)*

where α *is a proportional coefficient (only for ideal tank model,* α *is one)and n is the average porosity of slope mass. Hereby, "pore water pressure" is mainly positive pressure induced by groundwater table height. It does not refer to perched water or negative pore water pressures.*
Thus, PWP can be linearly correlated to groundwater levels as Eq. (11).

$$\Delta PWP_i = \frac{\alpha g'}{n}(ER_i + ES_i) - \Delta PWP_{(g+q)i} \cdot \qquad (11)$$

where, g' is acceleration of gravity, $\Delta PWP_{(g+q)i}$ *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 major part of pore water pressure is static pressure induced by water table height. Minor components are seepage force and the difference of pressures in the available pore space over drier and wetter periods. Since the tank model is a "grey box model", we do not know the exact proportions of static pressure, seepage pressure, and pressure dynamics in pore space, which are all three included in our* *equivalent pore water pressure.*

$$\Delta PWP_i = \alpha '(ER_i + ES_i) - \Delta PWP_{(g+q)i} \qquad (12)$$

In Eq. (12), $\alpha '$ *replaces* $\frac{\alpha g}{n}$ *to simplify the model."*

(4)

4.1 In a similar vein to the above, the authors, whilst drawing from hydrology and using a water balance approach in their tank model, do not observe its physical foundation of conservation of mass.

> *The answer 1.2 has showed the character of empirical model that the physical mechanism and parameters are never known perfectly. However, compared to deterministic model, this tank model can improve the accuracy of prediction and overcome the effect from uncertain materials due to calibration of observation data. As we said in Section1, this is an "empirical model" based on a modified water balance equation. Its physical foundation of conservation of mass is: input is subsurface water flow and infiltration while the output is the drainage, although the mass of water can not be measured directly.*

4.2 Equations 8 through 9 are fitted empirically and independently and closure of the water balance is not attested. From a hydrological perspective, it is strange to put the pore water pressure in the exponent of Equation 9 as it assumes that the recession of groundwater storage always starts at 13.4kPa, which violates directly the above principle. A linear reservoir of the form Q= aS**b would be more valid and more flexible to apply.

>Implemented (Line 9-Line 12, Page17): *"Almost every landslide has a basic water table or minimum water table (here starts at ~29 kPa). It means the "drainage position" is higher than the "bedrock" (other cases see: Matsuura et al., 2008; Schulz et al., 2009;Yin et al., 2010)."*

*>According to the reviewer's opinion, we used a linear reservoir of the form Q= aS*b to describe the drainage and groundwater table as Eq.(14) and Eq.(15):* **>Implemented (Line 14-17, Page 17):**

" $$PWP_{i+1} = a' PWP_i + b \,. \qquad (14)$$

where a' *and* b *are fitted coefficients.*

Thus, ΔPWP_i *calculation could be rewritten as:*

$$\Delta PWP_i = \alpha^{'}(ER_i + ES_i) - ((a'-1)PWP_i + b)\,. \qquad (15)"$$

4.3 In terms of hydrological functioning, the fact that only one point is considered and the physiographic context of the landslide is completely ignored is inexcusable. It cannot be accepted without evidence that the groundwater variations at point B4 halfway the slope are only governed by the local precipitation input and that the resulting groundwater levels are representative for the landslide as a whole. Furthermore, a regional water balance should be conducted to exclude any effects of lateral inflow from the higher elevations of the Kössen formation (Figure 2) or any spatial distribution in precipitation due to orography and exposure. At present, the model is merely a black box and any semblance to the observed signal at the point too much circumstantial.

>We focus on the regional groundwater table and we do not claim it is representative for the landslide as a whole same as the precipitation distribution. Thus, for the research object-regional groundwater, it is affected by vertical infiltration, lateral inflow, and lateral drainage. ***>Implemented (Line 19-20, Page 7):*** *"It should be pointed out our aim is only to estimate the local pore water pressure in deep-seated landslides."*

4.4 In terms of the analysis, performance is explored but only partly explained. In addition to the RMSE, model performance should be explored using Nash-Sutcliffe model efficiency or Kling-Gupta as is standard in hydrology.

>We have taken a considerable effort in calculating the Nash-Sutcliffe model efficiency for all described model runs of the original simple and modified tank models in Section 5.
>Implemented (Line 2-7, Page 22): *"In order to evaluate the performance of the modified tank model with respect to heavy rainfall and snowmelt, we introduce the standard Nash–Sutcliffe (1970) efficiency (NSE) which is the most widely used criterion for calibration and evaluation of hydrological models with observed data. NSE is dimensionless and is scaled onto the interval [inf. to 1.0]. NSE is taken to be the 'mean of the observations' (Murphy, 1988) and if NSE is smaller than 0, the model is no better than using the observed mean as a predictor. "*
> Implemented (From Line 19, Page 22 to Line 3 Page 23): *"The NSEs of the original tank model and our modified tank model during the heave rainfall season are -0.09 and 0.63 respectively. It means the standard original tank model is no better than the 'mean of the observations' while our modified tank model has a significantly higher explanatory power."*
> Implemented (Line 12-14, Page 23): *"The NSEs of the original tank model and modified tank model during the snowmelt season are -5.95 and 0.75 respectively which emphasizes the performance of the modified tank model."*

4.5 Improvements should be evaluated in terms of the added information versus the added uncertainty and the importance there of clearly follow from the research objective. Rather than calibrating model components, a corrected model with a stronger physical base should be used and calibrated using a clear objective function and issues of equifinality and the resulting parameter space be clearly evaluated.

>We reduce the uncertainty by introducing equivalent infiltration and snow accumulation/melt equations based on simple tank model. This does not increase the numbers of parameters compared to multi-tank model which has a higher uncertainty/degree of freedom because of added parameters (see the answer 1.1). This solved the research objective-using relatively simple way to deal with infiltration time lag in large landslide. We now calculate RMSE and Nash-Sutcliffe model efficiency of our modified and the simple tank model. Since there is no effective multi-tank model application in deep-seated landslides, we

cannot evaluate the model efficiency between our modified and a default multi-tank model.

4.6 In terms of the snow model, I fail to see why the partitioning of precipitation into snow and rainfall cannot be based more reliably on the temperature (Eq. 10, which now can give snow in summer as it depends on the relationship between temperature and relative humidity only).

>Temperature and humidity are the main factors for estimation of precipitation. Accuracy temperature of snowline is the key to judge the type of precipitation, however, it is difficult to obtain even armed with the advanced device considering the variation of air temperature effect. Our snowfall/melt model is a state of the art statistical model not a physical model but we are only judging change in pore water pressure and in case of minor accuracies of daily snowmelt rates this smooths out over time. ***>Implemented (Line 4-7, Page 7):*** *"The prediction of precipitation type is very difficult, because the vertical height of snow flakes is not easily calculated without advanced technology (Czys et al., 1996; Ahrens, 2007). Thus, in our study the judgment of precipitation type is still using the widely used statistic model."*

4.7 And why forest fraction influences (and how) on the melt index of the snow melt model. I assume it is a constant value but this is not clear and overall methods are not fully transparent.

>Forest fraction influencing on the melt index is still an empirical formula. In field, precise information is not easy to obtain (see answer 2.4). ***>Implemented (Line 26-28, Page 18):*** *"In this case, we think that the best strategy is the usage of the empirical formula, since >80% of the landslides are not forest covered and the forest cover only applies to the upper highly fractured limestone portion that is at a significant distance from the pore pressure measurement."*

4.8 In terms of text, the manuscript is readable with minor mistakes (e.g., page 3, line 28: mode= model) but the sentences are sometimes convoluted. However, the nomenclature is put in poor English throughout. References are mostly relevant (but see (1)) and correct although the order in the reference list is not purely alphabetical.

>We have edited the language of the whole paper carefully and in two complete revisions made the paper significantly more concise after all revisions have been achieved.

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 significant impacts on infrastructure. Pore water pressure plays an important role in determining the stability of hydrologically triggered deep-seated landslides. Based on a simple tank model structure, we improve groundwater level prediction by introducing time lags associated with groundwater supply caused by snow accumulation, snowmelt, and infiltration in deep-seated landslides. In this study, we demonstrate an equivalent infiltration calculation to improve the estimation of time lags using a modified tank model to calculate regional groundwater levels. Applied to the deep-seated Aggenalm Landslide in the German Alps at 1000-1200 m asl, our results predict daily changes in pore water pressure ranging from -1 to 1.6 kPa depending on daily rainfall and snowmelt which are compared to piezometric measurements in boreholes. 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. The modified tank model compares well to borehole-derived water pressures. Changes of pore water pressure can be modelled 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 which includes snow accumulation, snow melt and infiltration effects and can effectively predict changes in pore water pressure in alpine environments.

Nomenclature

α	related coefficient between equivalent infiltration and increased ground water table, 1	$h1_{i+1}$	water table level of the $i+1^{th}$ day in higher soil layer, mm
α'	related coefficient between equivalent infiltration and increased pore water pressure, kPa/mm	$h2_i$	water table level of the i^{th} day in middle soil layer, mm
β	average value of pore water pressure changed by drainage and ground water supply, kPa.	$h2_{i+1}$	water table level of the $i+1^{th}$ day in middle soil layer, mm
a	parameter for the relation between h_i and q_i, 1	$h3_i$	water table level of the i^{th} day in lower soil layer, mm
a'	related coefficient between pore water pressure of i^{th} day and $i+1^{th}$ day without infiltration, kPa.	$h3_{i+1}$	water table level of the $i+1^{th}$ day in lower soil layer, mm
$a1$	parameter for the relation between $h1_i$ and $d1_i$, 1	H	base water table, mm
$a2$	parameter for the relation between $h2_i$ and $d2_i$, 1	M'	daily snowmelt, mm
$a3$	parameter for the relation between $h3_i$ and $d3_i$, 1	n	average porosity of slope mass, 1
b	related coefficient between pore water pressure of i^{th} day and $i+1^{th}$ day without infiltration, 1	q_i	drainage of i^{th} day, mm
$d1_i$	infiltration of the i^{th} day in middle soil layer, mm	PWP_i	pore water pressure of i^{th} day, kPa
$d2_i$	infiltration of the i^{th} day in lower soil layer, mm	$\Delta PWP_{(g+q)i}$	PWP changed by drainage combined groundwater supply, kPa
$d3_i$	drainage of i^{th} day in lower soil layer, mm	ΔPWP_i	change of pore water pressure of i^{th} day, kPa
ER_i	equivalent rainfall of i^{th} day, mm	$R_i^{(n)}$	part of rainfall of i^{th} day to changed pore water pressure of i^{th} day, mm
ES_i	equivalent snowmelt of i^{th} day, mm	RH	relative humidity, 1

f_m	degree-day factor for snowmelt rate, mm/°C	RH_t	threshold of relative humidity, 1
F	canopy covers percent, 1	M	time about effect of infiltration reducing to 50%, 1
g_i	ground water supply of i^{th} day, mm	R_i	rainfall of i^{th} day, mm
g'	acceleration of gravity, m/s^2	$S_i^{(n)}$	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_{i+1}	ground water table height the $i+1^{th}$ day, mm	T_d	daily average temperature, °C
$h1_i$	water table level of the i^{th} day in higher soil layer, mm		

1 Introduction

Deep-seated landslides in the European Alps and other Mountain Environments pose a significant 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 for hydrologically controlled 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 changes 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). Generally, two ways are employed to estimate the groundwater changes: (1) Depending on the precise information of permeability and infiltration of material, the Green and Ampt Model is generally used to describe groundwater infiltration and water table changes (producing PWP) in saturated material (Chen and Young, 2006). Richards Equation (Weill et al., 2009) with the Van

Genuchten Equation (Schaap and Van Genuchten, 2006) or the Fredlund and Xing (1994) method show better performance in the evaluation of infiltration and groundwater table in unsaturated material. Traditional deterministic models have advantages due to their explicit physical and mechanical approaches, but they require accurate knowledge, testing and monitoring of soil physical parameters which are often not available with sufficient accuracy. For example, the widely used Richards Equation with Van Genuchten method needs soil suction tests under variable moisture content, saturated water content, residual water content, and the pore-size distribution of materials which are difficult to achieve for complex landslides with multiple reworked materials. (2) Empirical-statistical models employ optimization or fitting parameters in their model structure. Tank and other models need historical monitoring data to train parameters (Faris and Fathani, 2013; Abebe et al. 2010). Such empirical models, because of their simple conceptualized structure, do rely to a smaller degree on explicit physical and mechanical approaches. However, they can avoid the problems induced by the uncertainty of material parameterisation and its spatial arrangement in the landslide mass. They can, therefore, be applied to a wide range of different landslide settings and we estimate that for more than 90% of all landslides no explicit parameters on soil suction etc. are available. As one of the most common empirical models, 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).

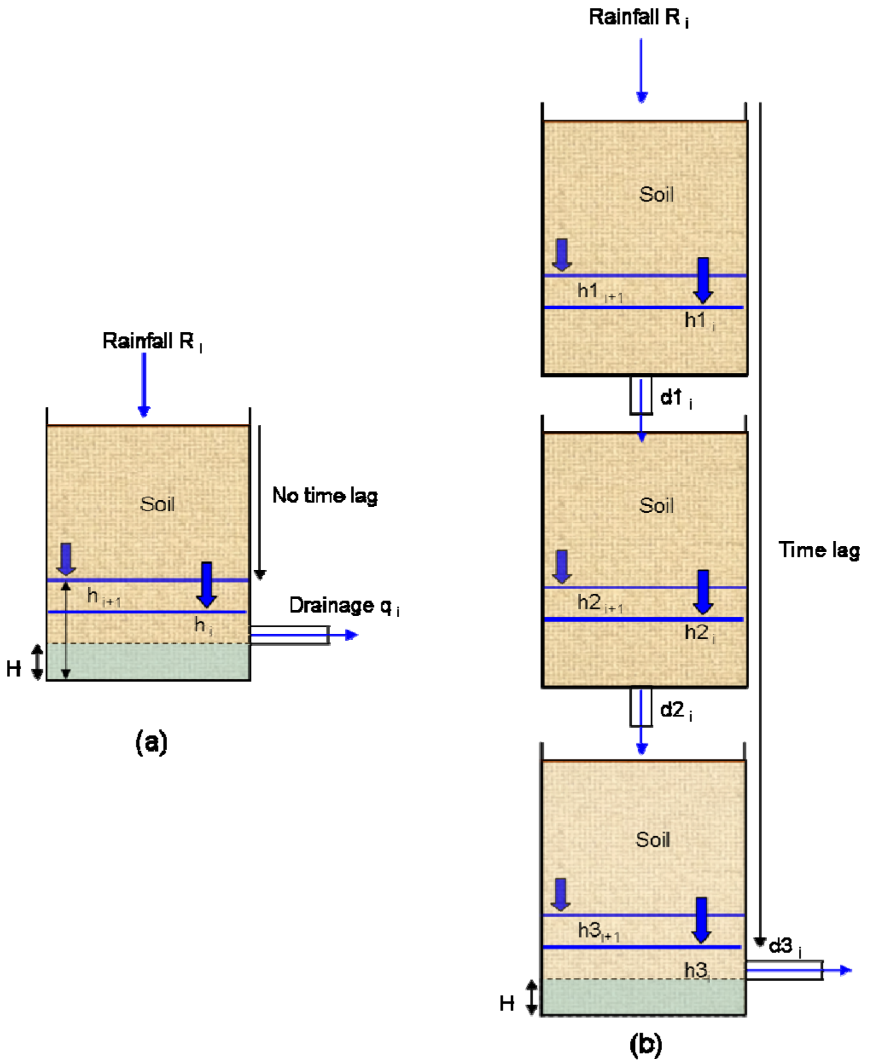

Figure 1 Details of simple tank model and multi-tank model applied in deep-seated landslides (a) Schematic diagram of simple tank model (b) Schematic diagram of multi-tank model

The Fig. 1(a) shows the work mode of a simple tank model.

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

$$q_i = ah_i \ , \qquad (2)$$

where R_i is the rainfall and q_i is the drainage of the i^{th} day. h_i is groundwater table height of the i^{th} day. a is the parameter for the relation between h_i and q_i. Obviously, for the deep-seated landslides, due to the long infiltration the rainfall (R_i) cannot totally contribute to the change of groundwater table (h_{i+1} - h_i) within one day. Thus, simple tank models do not consider infiltration time lags induced by a long infiltration path, previous moisture and snowmelt. This inhibits their applicability to deep-seated landslide. By contrast, the Fig. 1(b) describes the work principle of multi-tank models in deep-seated landslides mainly considering the vertical infiltrations.

$$\begin{cases} h1_{i+1} - h1_i = R_i - d1_i \\ d1_i = a1h1_i \end{cases} \quad (3)$$

where $h1_{i+1}$, $h1_i$ are water table levels of the $i+1^{th}$ and i^{th} day in higher soil layer; $d1_i$ is the infiltration of the i^{th} day in middle soil layer; $a1$ is parameter of relation between $h1_i$ and $d1_i$; R_i is the rainfall of the i^{th} day.

$$\begin{cases} h2_{i+1} - h2_i = d1_i - d2_i \\ d2_i = a2h2_i \end{cases} \quad (4)$$

where $h2_{i+1}$, $h2_i$ are water table levels of the $i+1^{th}$ and i^{th} day in middle soil layer; $d2_i$ is the infiltration of the i^{th} day in lower soil layer; $a2$ is parameter of relation between $h2_i$ and $d2_i$.

$$\begin{cases} h3_{i+1} - h3_i = d2_i - d3_i \\ d3_i = a3h3_i \end{cases} \quad (5)$$

where $h3_{i+1}$, $h3_i$ are water table levels of the $i+1^{th}$ and i^{th} day in lower soil layer; $d3_i$ is the drainage of i^{th} day; $a3$ is parameter of relation between $h3_i$ and $d3_i$.

From the Equations (3) to (5), there are 7 unknown ($h1_{i+1}$, $h1_i$, $a1$, $h2_{i+1}$, $h2_i$, $a2$, $a3$) and 3 known parameters ($h3_{i+1}$, $h3_i$, R_i). In order to get the 7 unknown values, even usage of some advanced algorithms does not effectively estimate the parameters. Multi-tank models can deal with infiltration time lags to some extent by adding tanks but even then they (i) require data from several monitoring boreholes to track groundwater flow supplies in complicated geological structures and (ii) they are presently not designed to replicate time lags of increased infiltration, e.g., following snowmelt (Iverson, 2000; Sidle, 2006; Nishii and Matsuoka, 2010). Applying multi-tank models to compensate for time lags is questionable as especially deep-seated landslides would need several tanks to replicate time lags and every added new tank in vertical direction introduces 3 new parameters at least. This would reduce robustness and reliability of system especially if we just use the monitored groundwater table for the parameter training of whole system.

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. The innovation of our approach is to calculate equivalent infiltration before it enters the tank. The equivalent infiltration deals with the infiltration time lag including snow accumulation and snowmelt in deep-seated landslides based on a simple tank model structure. We hypothesize and provide quantitative evidence that, compared to a simple tank model, our modified model has a higher accuracy and physical meaning by controlling equivalent infiltration including snow accumulation and snowmelt; compared to multi-tank model our modified model is more robust and reliable. The prediction of precipitation type is very difficult, because the vertical height of snow flakes is not easily calculated without advanced technology (Czys et al., 1996; Ahrens, 2007). Thus, in our study the judgment of precipitation type is still using the widely used statistic model. While, for the snowmelt calculation we used empirical equations to make the process earlier, because sophisticated models which can calculate the snowmelt precisely are quite complex and require several physical parameters, including topography, precipitation, air temperature, wind speed and direction, humidity, downwelling shortwave and longwave radiation, cloud cover, and surface pressure (Garen and Marks, 2005; Herrero et al., 2009; Lakhankar et al., 2013). In addition, compared to the original tank model without considering the snowmelt, we emphasized the tank model coupling the function of snowmelt (we just choose the simple snowmelt module). We apply our model to the Aggenalm landslide, where predicted PWP changes can be tested against piezometric borehole monitoring data. The monitoring network design and installation, as well as detailed monitoring data, and the introduction of monitoring devices have been described previously in detail (THURO et al., 2009; Thuro et al., 2011a; Thuro et al., 2011b; Festl et al., 2012; Thuro et al., 2013). It should be pointed out our aim is only to estimate the local pore water pressure in deep-seated landslides. The relation between landslide movement and the groundwater table is not the focus of this study. The landslide movement is complex and time-depended and material strength is also very important besides groundwater table. It has been hypothesised that deep-seated landslide velocity, although linked to pore pressure-induced changes in effective stress, is also governed by rate-induced changes in shear strength of the materials, caused by changing mechanical properties during shear deformation (Lupini et al., 1981; Skempton, 1985; Angeli et al., 1996; Picarelli, 2007); and/or consolidation and strength regain during periods of rest (Nieuwenhuis, 1991; Angeli et al., 2004).

2 Site descriptions

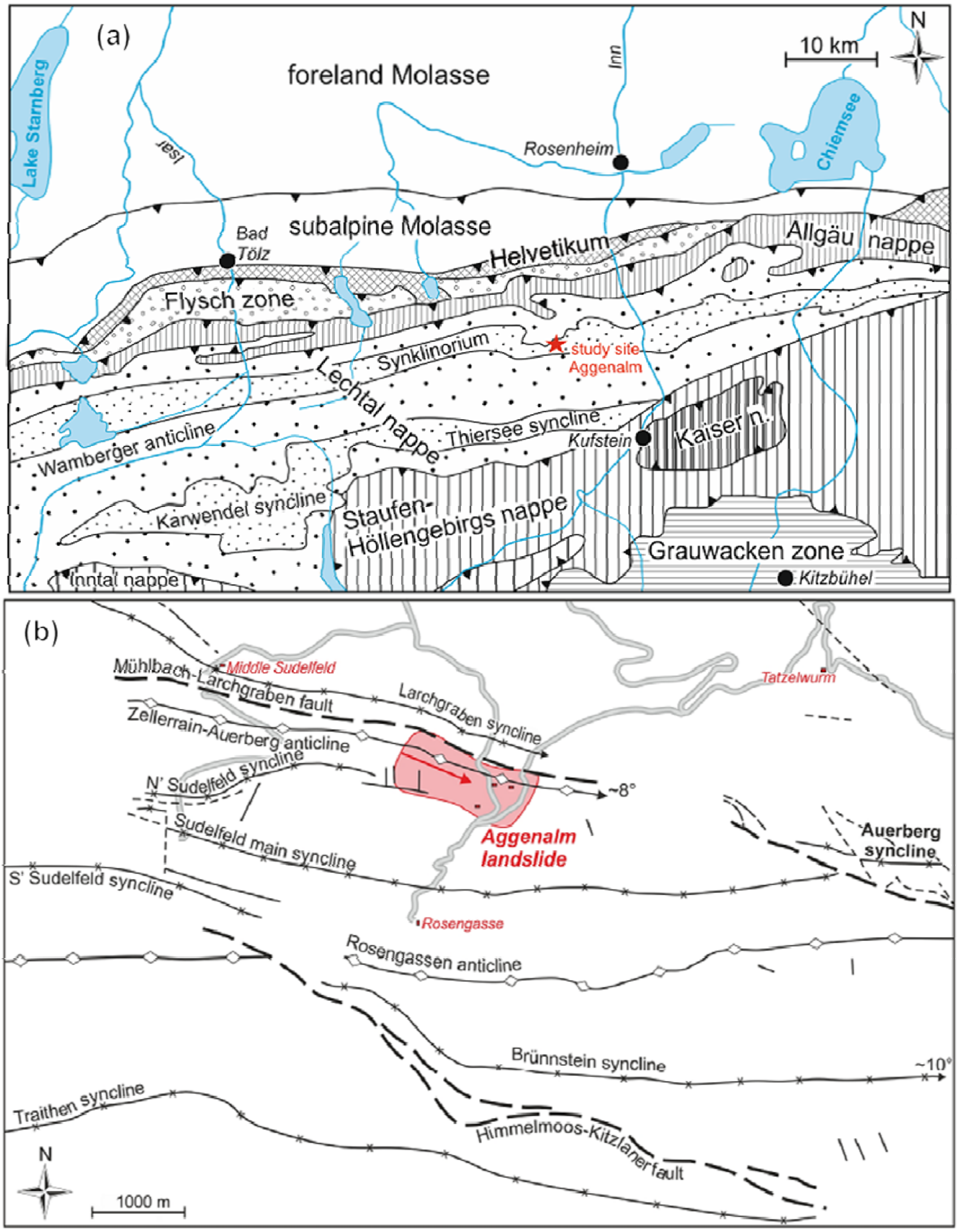

Figure 2 (a) Tectonic map of the Northern Calcareous Alps between Lake Starnberg and Lake Chiemsee. The Aggenalm Landslide is situated in the Lechtal Nappe within the Synklinorium, a major syncline–anticline–syncline fold belt, which can be traced through the whole region. (Schmidt-thome, 1964; Gwinner, 1971) (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 Aggenalm Landslide (Festl, 2014).

The Aggenalm Landslide is situated in the Bavarian Alps in the Sudelfeld region near Bayrischzell (Fig. 2). 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. 3). 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. 3). 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.

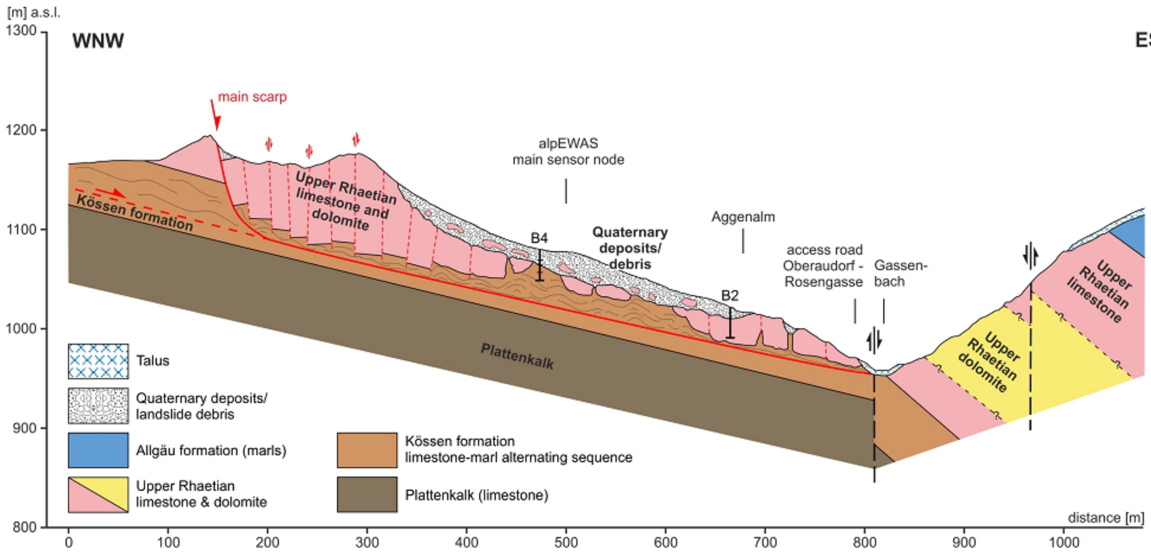

Figure 3 Geological profile of the Aggenalm Landslide (Festl, 2014)

3 Data and Methods

3.1 Climate conditions

The Aggenalm is exposed to a sub-continental climate with a pronounced summer precipitation maximum and an annually changing share of 15–40 % of the mean annual precipitation that fall as snow. Abundant snow cover restricts freezing of the top to few tens of cms allowing water penetration in cracks etc. Due to the all-year humid climate (see Figure 4, nearby meteo-stations such at the Brünnsteinhaus, the Sudelfeld (Polizeiheim) and the Tatzelwurm indicate mean annual precipitation of 1594, 1523 and 1660 mm/a at similar elevations), the rapid drainage of water in the permeable underground (pore water pressure reduces 2-3 kPa within 15 days) and the deep-seated nature of the slope movement (depth is 30-40 m), we did not explicitly consider evapotranspiration. However, the daily reduction of pore pressure (~0.3 kPa/day) includes an empirical component of evapotranspiration.

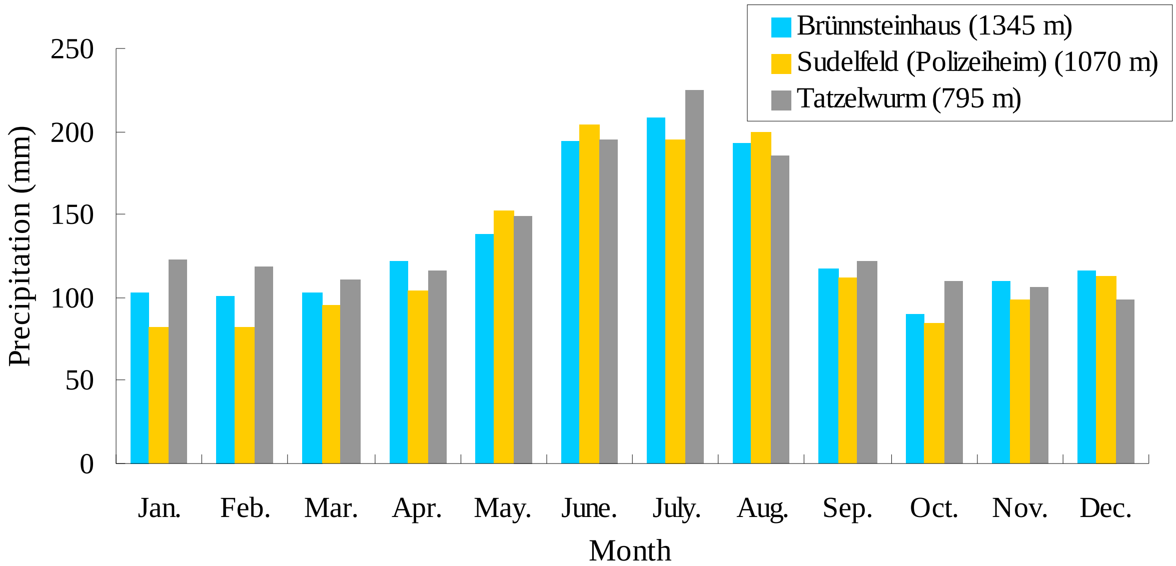

Figure 4 Mean monthly precipitation (1931–1960 and 1961–1990) for the Brünnsteinhaus, the Sudelfeld (Polizeiheim), and Tatzelwurm meteorological stations (data from Germany's National Meteorological Service DWD).

3.2 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. 3) (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) Since the whole monitoring period lasts for almost 3 years and time lags are in the range of days, days were considered to be the most robust, appropriate standard reference time unit, also to keep results comparable to previous studies. The monitoring period lasts from February 2009 to December 2011. Considering data loss in some months, we have approximately 24 months of valid data. To parametrise the modified tank model, we use data from 13 months (May 2009 to June 2009; September 2009 to December 2009; February 2010 to August 2010). To validate the parametrized model, 55 days of rainfall (July 2009 to August 2009) and 44 days of snowmelt (March 2009 to April 2009) are used to compare model-calculated pore water pressure with real pore water pressure readings. In addition, a long-term consistency simulation of two years' PWP levels is compared to the two years of monitoring data of PWP levels bridging the data gaps.

3.3 The modified tank model including snowmelt and infiltration

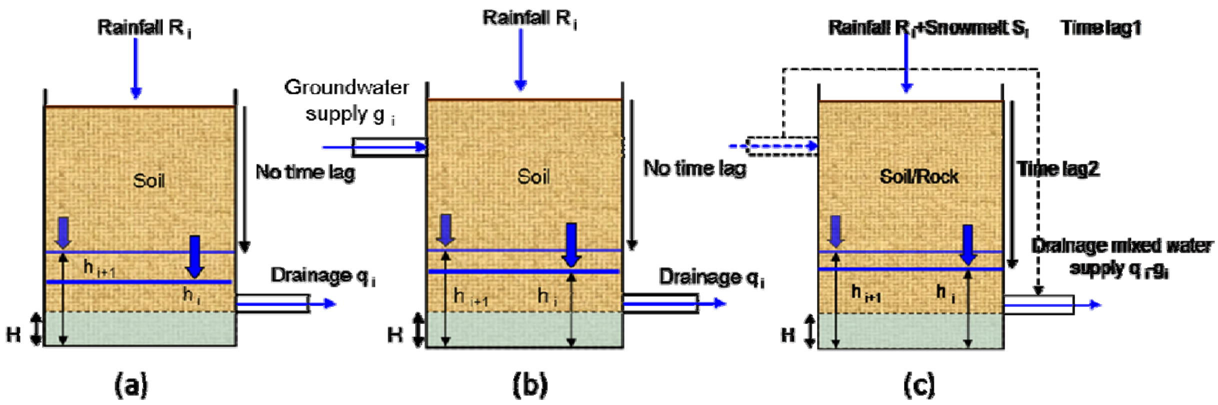

Figure 5 Design of the modified tank model. (a) Original tank model considering the vertical infiltration and drainage affecting the water table. (b) Improved model considering both vertical infiltration and horizontal water flow. (c) Modified tank model including water supply and two time lags (snowmelt and infiltration).

Figure 5 demonstrates the successive 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. 5a shows the basic concept of the original tank model, the daily change in the groundwater table height h_{i+1} - h_i is

$$h_{i+1} - h_i = R_i - q_i \ . \qquad (6)$$

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.

If groundwater supply illustrated in Fig. 3b is incorporated in the tank model, the daily change in groundwater table height h_{i+1} - h_i is

$$h_{i+1} - h_i = R_i - (q_i - g_i), \quad (7)$$

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

Incorporating snowmelt, Equation 3 should be written as

$$h_{i+1} - h_i = R_i + S_i - (q_i - g_i), \quad (8)$$

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

Snow accumulation and snowmelt produces our *time lag 1* controlled by ambient temperature. Long infiltration paths which can take one or more days to reach the water table in deep-seated landslide masses cause *time lag 2* (Fig. 5c). The infiltration in i^{th} day does not only affect the groundwater table of the i^{th} day but also the groundwater table over the following n days if *time lag2* is more than one day. 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}). For a time lag of two days, the total daily variations (h_{i+2}-h_{i+1}) in response to rainfall and snowmelt can be described by $R_{i-1}^{(3)} + S_{i-1}^{(3)}, R_i^{(2)} + S_i^{(2)}$, $R_{i+1}^{(1)} + S_{i+1}^{(1)}$, considering that the groundwater table in $i+1^{th}$ day is not only affected by the infiltration today but also by the infiltration of the previous two days (Fig. 6).

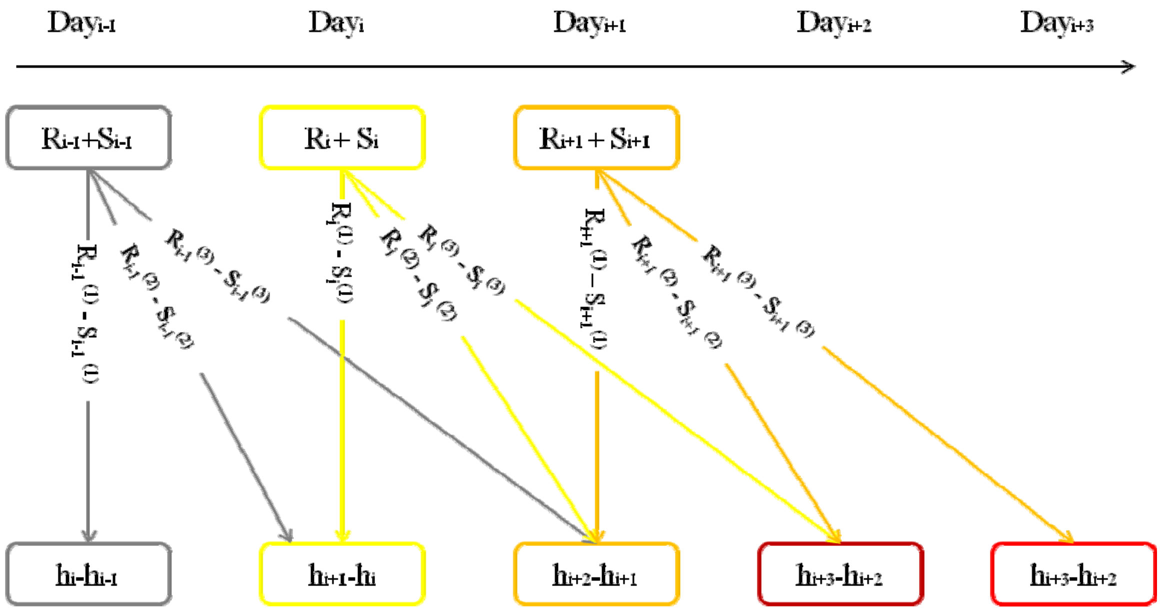

Figure 6 Schematic diagram of water infiltration from the surface to the groundwater table for a *time lag 2* of 2 days.

The 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 some authors (Suzuki and Kobashi, 1981; Matsuura et al., 2003; Sumio Matsuura et al., 2008) who define equivalent infiltration as

$$ER_i + ES_i = (0.5)^{1/M} R_i + (0.5)^{1/M} ER_{i-1} + (0.5)^{1/M} S_i + (0.5)^{1/M} ES_{i-1} \cdot \qquad (9)$$

where ER_{i-1} and ES_{i-1} represent the equivalent rainfall and snowmelt of $i\text{-}1^{th}$ 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 by field observations. 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:

$$\Delta h_i = h_{i+1} - h_i = \frac{\alpha}{n}(ER_i + ES_i) - (q_i - g_i) \cdot \qquad (10)$$

where α is a proportional coefficient (only for ideal tank model, α is one) and n is the average porosity of slope mass. Hereby, “pore water pressure” is mainly positive pressure induced by groundwater table height. It does not refer to perched water or negative pore water pressures.

Thus, *PWP* can be linearly correlated to groundwater levels as Eq. (11).

$$\Delta PWP_i = \frac{\alpha g'}{n}(ER_i + ES_i) - \Delta PWP_{(g+q)i} \quad (11)$$

where, *g'* is acceleration of gravity, $\Delta PWP_{(g+q)i}$ is the *PWP* change 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 major part of pore water pressure is static pressure induced by water table height. Minor components are seepage force and the difference of pressures in the available pore space over drier and wetter periods. Since the tank model is a "grey box model", we do not know the exact proportions of static pressure, seepage pressure, and pressure dynamics in pore space, which are all three included in our equivalent pore water pressure.

$$\Delta PWP_i = \alpha'(ER_i + ES_i) - \Delta PWP_{(g+q)i} \quad (12)$$

In Eq. (12), α' replaces $\frac{\alpha g}{n}$ to simplify the model. The workflow chart of our modified tank model for change of PWP_i is indicated in Fig. 7.

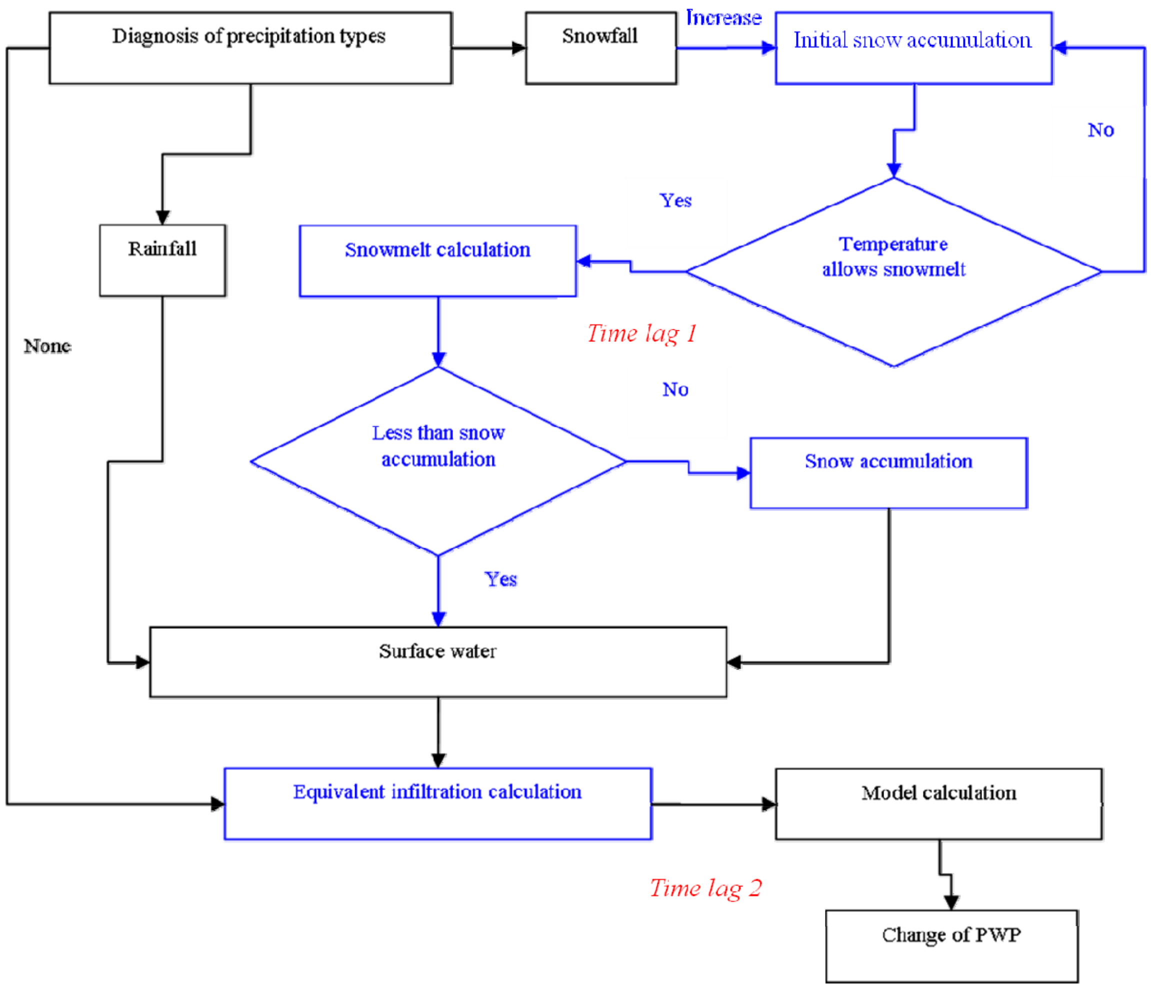

Figure 7 The workflow chart of the modified tank model with respect to the original model. Time lags from snow accumulation, snowmelt and infiltration are highlighted in blue.

3.4 Model assumptions to simplify slope hydrology

We assume that Quaternary deposits control the hydraulic properties of the tank model (tank interior with soil/rock in Fig. 5). The fractured limestone and dolomite control the water flow from higher to lower elevations (groundwater inflow and drainage in Fig. 5). The marly Kössen Beds are treated as impermeable layers (thin, low porosity and high normal stress above). As this is a regional groundwater table estimation, we can use the modified tank model to simulate the groundwater table changes induced by precipitation. We ignore surface runoff flow resulting from snowmelt and heavy rainfall as (1) the slope angle is less than 15°, (2) the cumulative snowpack is no more than 70 cm during monitoring days and (3) the infiltration rate of slope in Quaternary deposits and on carbonates is relatively high. We ignore freezing effects on infiltration as (1) ground sealing by freezing is presumably not an issue since the bottom temperature of snow (BTS) is next to 0°C underlain by a warmer subsoil in addition to high permeable subsoil. (2) Snow accumulation during winters and winter rainfall precipitation prevent effective cooling of ground. Due to the all-year humid climate, the rapid drainage of water in the permeable underground and the deep-seated nature of the slope movement, we did not explicitly consider evapotranspiration.

3.5 Determining change in pore water pressure in the modified tank model

In order to determine an appropriate value of α' for Aggenalm Landslide, we use 13 months training data to fit equivalent rainfall and ΔPWP (Fig. 8).

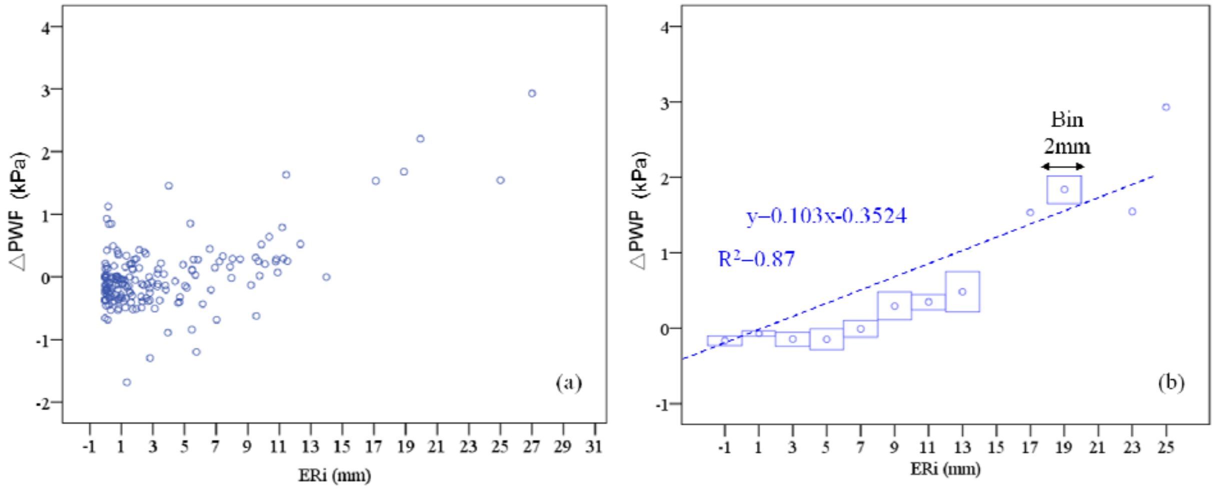

Figure 8 (a) Daily equivalent rainfall ER_i versus daily change of pore water pressure $\triangle PWP_i$ in absolute values for 13 months (Sep. 2009 - Feb. 2010 and May 2010 – Nov 2010). (b) $\triangle PWP_i$ has been aggregated in bins of mean values for discrete steps of daily equivalent rainfall (mean +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. 8a. We then aggregate bins of mean values of daily change of pore water pressure for daily equivalent rainfall (Fig. 8b) to replace data of the same width (Fig. 8a) (Freedman et al., 1998). The result shows change of PWP_i as

$$\Delta PWP_i = \alpha' ER_i - \beta \,. \qquad (13)$$

where, α' [kPa/mm] is 0.103 and relates rainfall to pore pressure increase and β (-0.3524) [kPa] is the average daily decrease of pore water pressure by drainage. This means 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 original tank theory 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. 9a, the observation of *PWP* is within 48 days without rainfall input where drainage is still combined with groundwater supply. Almost every landslide has a basic water table or minimum water table (here starts at ~29 kPa). It means the "drainage position" is higher than the "bedrock" (other cases see: Matsuura et al., 2008; Schulz et al., 2009;Yin et al., 2010). The relation between PWP_{i+1} and PWP_i without rainfall infiltration is shown in Fig. 9b and equation (14).

$$PWP_{i+1} = a'PWP_i + b\,. \tag{14}$$

where a' and b are fitted coefficients.

Thus, ΔPWP_i calculation could be rewritten as:

$$\Delta PWP_i = \alpha'(ER_i + ES_i) - ((a'-1)PWP_i + b)\,. \tag{15}$$

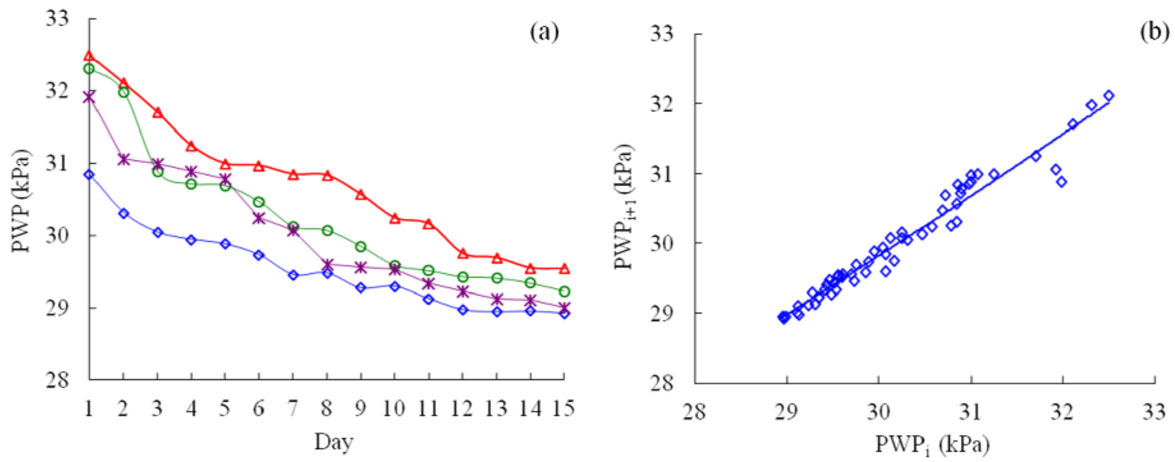

Figure 9 (a) Observation of *PWP* vs. time for four fifteen-day-long periods without rainfall or snowmelt. (Number of samples: n=48) (b) PWP_i vs. PWP_{i+1} (i^{th} day of *PWP* correlates to $i+1^{th}$ day of *PWP* for four fifteen-day-long periods without rainfall or snowmelt (Number of samples: n=48).

3.6 Snowmelt calculations in modified tank model

3.6.1 Diagnosis of precipitation types

A threshold temperature under which the precipitation falls as snow 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 accurately determined (Wagner, 1957; Koolwine, 1975; Bocchieri, 1980; Czys et al., 1996; Ahrens, 2007). The most common approach is to derive statistical relationships between some predictors and different precipitation types (Bourgouin, 2000). We select a statistical model (empirical formula) 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:

$$RH_t = 124.9e^{-0.0698T_d} \quad (16)$$

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

3.6.2 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:

$$M' = f_m(T_d - T_0) \quad (17)$$

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. We apply a widely used empirical f_m (e.g., Gottlieb, 1980; Lang, 1986; Braun et al., 1994; Hock, 2003), which reflects canopy cover in percent, beginning time of snowmelt, etc.. In this case, we think that the best strategy is the usage of the empirical formula, since >80% of the landslides are not forest covered and the forest cover only applies to the upper highly fractured limestone portion that is at a significant distance from the pore pressure measurement. Here, the degree-day factor is calculated by the empirical formula as follows:

$$f_m = 2.92 - 0.0164F \,. \qquad (18)$$

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

4 Results

4.1 Performance of modified tank model in heavy rainfall season

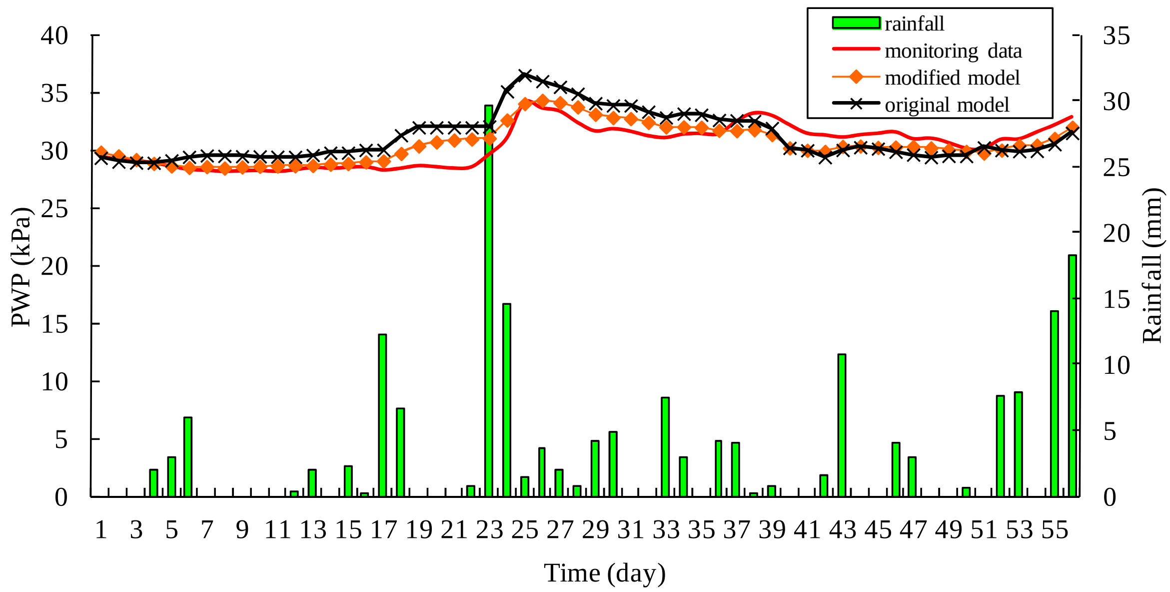

Figure 10 Estimation of the *PWP* using the original tank model and our modified tank model (snowmelt + time lag 1+2) during summer (07.07.2009 - 31.08.2009).

As shown in Fig. 10, 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 reasonable estimate 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*.

4.2 Performance of modified tank model in snowmelt season

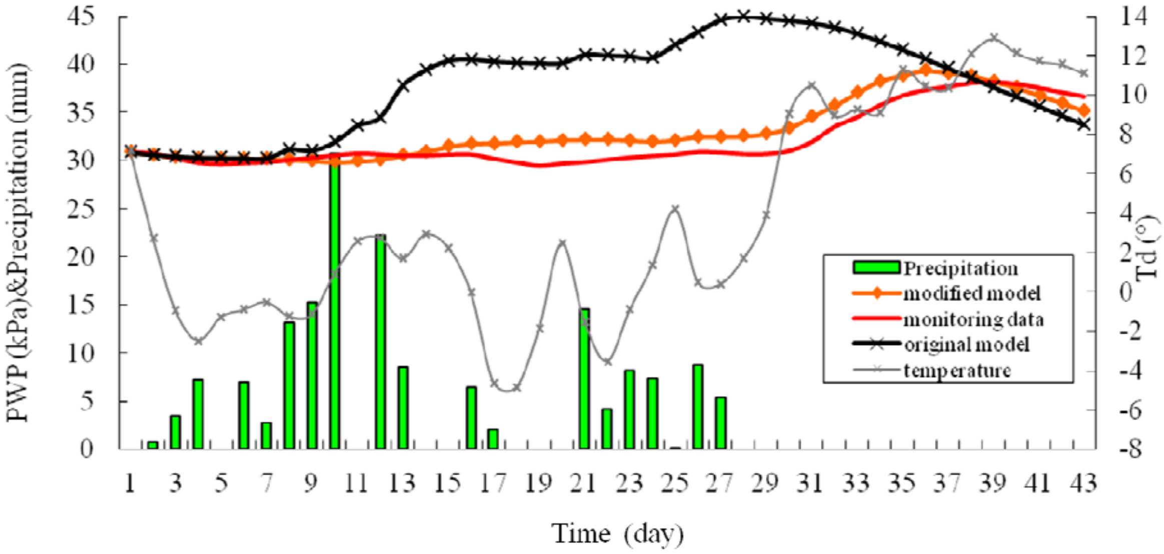

Figure 11 Estimation of the change of PWP using the original tank model and our modified tank model (snowmelt + time lag 1+2) in the snowmelt season (04.03.2009-15.04.2009).

The original model without snow accumulation and snowmelt failed to accurately estimate PWP during spring, as the change of *PWP* without *time lag 1* caused by the original model to overestimate *PWP* from the day 12-33. The modified tank model 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.12 indicates evaluation index of original and modified tank model including correlation, root mean square error (RMSE), and relative error. As shown in Fig. 13, modified tank model simulated the *PWP* levels in whole monitoring period.

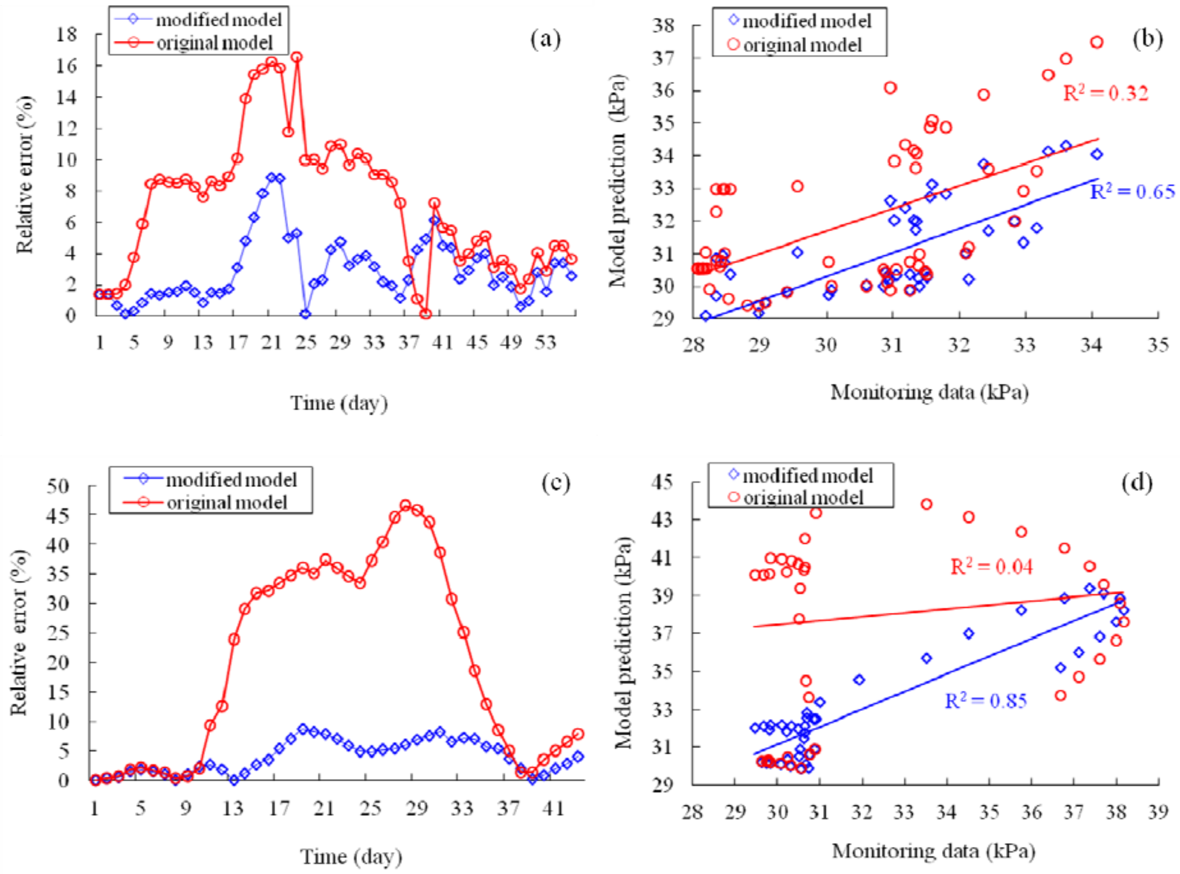

Figure 12 Evaluation of original and modified tank model (a) Correlation between measurements and original/modified tank model during a 54-day rainfall period (n=54). Root mean square errors (RMSE) for the original and modified models are 1.9 and 0.97 respectively. (b) Correlation between measurements and original/modified tank model in snowmelt period (n=47). Root mean square error (RMSE) approaches 5.4 and 1.3 for the original model and the modified model. (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).

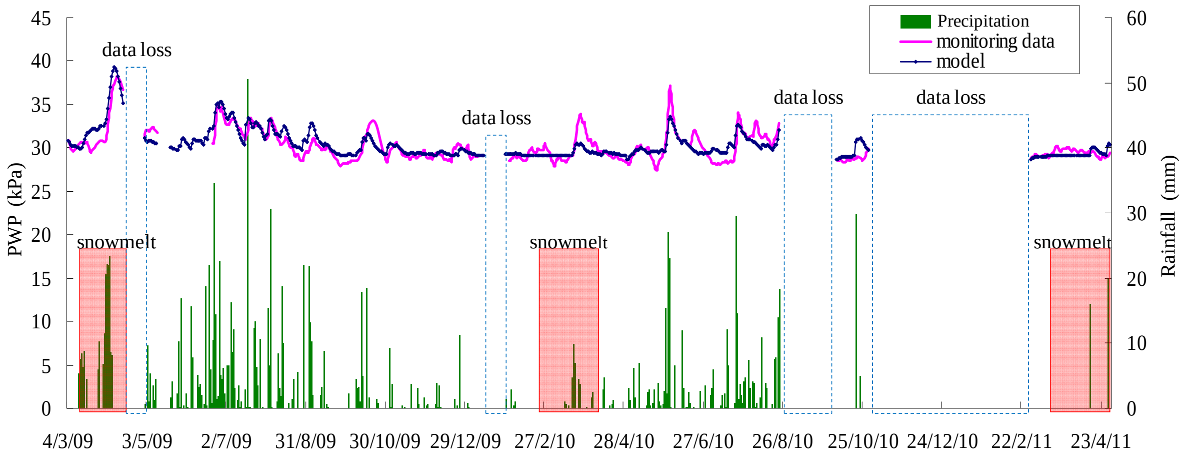

Figure 13 Long-term consistency simulation of *PWP* using the modified tank model throughout the entire monitoring period (04.03.2009-23.04.2011).

5 Discussion

In order to evaluate the performance of the modified tank model with respect to heavy rainfall and snowmelt, we introduce the standard Nash–Sutcliffe (1970) efficiency (NSE) which is the most widely used criterion for calibration and evaluation of hydrological models with observed data. NSE is dimensionless and is scaled onto the interval [inf. to 1.0]. NSE is taken to be the 'mean of the observations' (Murphy, 1988) and if NSE is smaller than 0, the model is no better than using the observed mean as a predictor.

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. 10). The relative errors in Fig.12a 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. 12a. 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). The NSEs of the original tank model and our modified tank model during the heave rainfall season are -0.09

and 0.63 respectively. This means the standard original tank model is no better than the 'mean of the observations' while our modified tank model has a significantly higher explanatory power.

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. The NSEs of the original tank model and modified tank model during the snowmelt season are -5.95 and 0.75 respectively, which emphasizes the performance of the modified tank model.

5.3 Highlights of our modified model

Compared to the simple tank model, our modified tank model improves the prediction ability by introducing the equivalent infiltration method to reduce the infiltration time lags. 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 not 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).

5.4 Drawbacks and limitations

The naturally inevitable drawback for any "empirical model" is that it is physically not explicit. The presented model would need e.g. further adjustments for permafrost regions, with heavily frozen soils, for very steep slopes, with significant surface runoff and for very heterogeneous slopes, with complex fractured rock masses. However, it seems well suited for large mountain landslides on moderately inclined slopes in alpine conditions with significant snow accumulations.

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 propose a modified tank model for the estimation of increased pore water pressure induced by rainfall or snowmelt events in deep-seated landslides. Compared to the original tank model, we simulate the fluctuation of *PWP* more accurately by reducing the time lag effects induced by snow accumulation, snow melt and infiltration into deep-seated landslides. In this modified model, a statistical method based on temperature and humidity controls precipitation type and a snowmelt model based on the temperature index method governs melting. Here we demonstrate a modified tank model for deep-seated landslides which includes snow accumulation, snow melt and infiltration effects and can effectively predict changes in pore water pressure in alpine environments.

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