Hydrol. Earth Syst. Sci., 18, 4185–4188, 2014
www.hydrol-earth-syst-sci.net/18/4185/2014/
doi:10.5194/hess-18-4185-2014

Hydrology and Earth System Sciences
Open Access

Preface

“Hillslope hydrological modelling for landslides prediction”

T. Bogaard[1] **and R. Greco**[2]

[1]Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands
[2]Dipartimento di Ingegneria Civile Design Edilizia e Ambiente, Seconda Università di Napoli, via Roma 29, 81031 Aversa (CE), Italy

Correspondence to: T. Bogaard (t.a.bogaard@tudelft.nl)

Looking at natural hazards and risks, such as landslides, debris flow and floods, we see a broad range of science fields involved: from earth science to engineering science, to management, policy and social science. Although research on natural hazards and risks contains mono-disciplinary aspects, it is best characterized by its multi-disciplinary nature. Moreover, the link to society has always been a very important driver in natural hazards research, pushed by the need for reliable prediction models to be implemented into early warning systems as well as by the required complete understanding of the physical mechanisms for the design of mitigation works. If we focus on landslide and debris flows as in this special issue of HESS, we will see impressive progress in the geotechnical and slope stability modelling needed for hazard analysis. Similarly, the risk management aspects, such as hazard mapping and risk assessment, have received much attention. Hydrology is an important aspect of landslide and debris flow assessment. Precipitation and snowmelt water infiltration, leading to local pore water pressure increase and/or matric suction decrease, is amongst the most common triggers of landslides. Fundamental knowledge about underlying processes affecting this infiltration process, such as macropore and fissure flow, water repellency, soil structure, soil–plant–atmosphere interactions as well as the effects of land use practices (e.g. deforestation, terracing, grazing), has strongly improved in the last decade or so, with a clear focus on more detailed knowledge of hydrological process dynamics. The hydrological process understanding progressed rapidly under pressure of societal needs such as prediction of discharge generation and contaminant transport, to name a few.

Although hydrology research is very strongly linked to natural hazards, such as landslides and debris flows, this improved hydrological knowledge has found its way into the landslide community rather modestly. In particular, the incorporation of hydrological processes into large-scale models is still incomplete and their application to landslide prediction limited. Landslide research tends to be more focused on novel methods to include spatial data and on the practical applicability of, e.g. landslide triggering modelling and statistical analyses for regional hazard and risk assessment. However, without stating that these fields have been fully exploited, we see that in our quantitative landslide and debris flow modelling the inclusion of increased process knowledge seems to lag behind. This in depth process understanding needs to be incorporated in our technical predictions in order to improve the reliability of early warning systems, mitigation works and landslide zonation.

This special issue aims to present innovative hydrological research applied to landslide studies to improve the understanding of the spatio-temporal patterns of slope movement mechanisms induced by precipitation. The initiative struck a sympathetic note, as many colleagues were facing these challenges. The topic of hydrology and landslides is finding more and more space in hydrological research, as witnessed by the number of relevant papers published, in special issues, e.g. on hydrology of unstable clay shales (Bogaard et al., 2012) and through the organization of workshops and special conference sessions, such as six EGU sessions on hydrology and landslides, three editions of the Italian Workshop on Landslides mainly dedicated to landslide hydrology (www.iwl.unina2.it), and special sessions at IAEG2014. Therefore, this Special Issue discusses the representation of hydrological processes in landslide modelling in order to increase our process understanding and, consequently, to improve the reliability of landslide hazard and risk assessment.

This Special Issue contains nine contributions covering all scales of hydrological landslide research and gives an excellent insight into how novel hydrological concepts can be included in landslide modelling. The contributions are organized along the increasing complexity of hydrological conceptualization, from including internal heterogeneity to novel implementation of boundary conditions and to conceptualize large fissures in landslide hydrological modelling. At the same time the contributions range from regional to hillslope scale.

1 Influence of soil heterogeneity on landslide hydrology

The heterogeneity of soil properties within a hillslope is an important issue that sometimes conceals the actual triggering mechanism of landslides. The influence of soil layering on flow paths and consequently pore water pressure build-up is discussed by Capparelli and Versace (2014). They developed a 2-D physically based infiltration model coupled with the infinite slope stability model and apply it to the slope of Sarno (southern Italy) consisting of a few metres of layered pyroclastic deposits covering a limestone fractured bedrock. Their results highlight the effects of coarse pumiceous layers situated below layers of fine volcanic ashes on the infiltration dynamics. In particular, they show how the rainfall of the previous weeks, which could not leak through the unsaturated pumices, created the predisposing condition for the initiation of shallow landslides. The wet state of the upper ashy layers favoured the establishment of a steep infiltration front during the intense triggering event, which did not reach the soil–bedrock interface. Therefore, as a result of the soil heterogeneity, the slope failure involved only the upper part of the soil cover, above the pumices.

2 Connection between landslide initiation and catchment hydrology

The issues coming from the variability of soil properties are felt also when landslide susceptibility is assessed at larger scales, in a catchment or even at regional level. Field experimental evidence suggests that subsurface, relatively fast, lateral flows, which are related to the runoff formation process in catchments, play a big role in landslide triggering and should be accounted for in the models to achieve reliable predictions. Consequently, while regional landslide hazard assessment is mainly done with heuristic map-overlay techniques and statistical rainfall intensity–duration thresholds, slope failure prediction can be improved if coupled physically based hydrological and slope stability modelling is performed at catchment scale. In this respect, the paper by Lepore et al. (2013) is a good example. Shallow landslide triggering in a tropical catchment in Puerto Rico is predicted with a distributed eco-hydrological model to evaluate the spatial and temporal distribution of the local factor of safety. The focus of the research is on the introduction of anisotropy of hydraulic conductivity to better reproduce the fast lateral redistribution of water observed in macroporous forest soil. The results show that, especially in layers with small hydraulic conductivity, a higher horizontal conductivity leads to a more realistic prediction of the unstable areas.

Along the same line, although in a completely different climate, Tao and Barros (2014) apply a 3-D distributed hydrological model to headwater catchments in the Appalachians. Also in this case, modelling results highlight the importance of lateral subsurface flow on the triggering of debris flows by rainfall events of different characteristics: a very intense convective summer storm and two longer-lasting moderately intense orographic winter storms. Indeed, debris flows are triggered when and where the horizontal subsurface flow peaks. The observed strong connection between runoff formation and landslide triggering even leads to coupled predictions of flash flood response and debris flow initiation at catchment scale.

Both above-mentioned papers stress the point that landslide susceptibility at catchment scale is very sensitive to soil geotechnical parameters, mainly to friction angle as well as to the adopted topographical resolution. Both these aspects become even more difficult to account for if anthropic activities modify slope morphology and soil properties. Such an issue is addressed by Penna et al. (2014). Shallow landslide triggering in a small catchment in Giampilieri (Sicily) is predicted with a hydrological model coupled with the infinite slope stability equation, assuming instantaneous infiltration towards a perched aquifer forming at the soil–bedrock interface where lateral subsurface flow occurs. The effects of different DEM resolutions on the prediction of slope stability are evaluated, distinguishing between landslides near forest roads and along natural slopes. The results show that the predicted unstable area tends to increase with increasing DEM resolution, and highlights that the highest resolution does not necessarily provide the best predictive results. For natural slopes, this seems related to overestimation of actual slope inclination, and, for road-related slides, this is due to the fact that it is not easy to properly introduce in the model the improvement of slope stability related to road construction works.

Regional landslide susceptibility assessment and precipitation thresholds for landslide triggering are currently done by two different approaches: physically based regional modelling and statistical rainfall intensity–duration thresholds. The former, the physically based models for regional risk assessment, are often bounded by limited data availability. The latter, the predictive power of rainfall intensity–duration thresholds, is limited because they do not directly take into account the factors related to specific characteristics of hillslopes. The way water is stored in a hillslope and exchanged with the other compartments of the catchment is only indirectly treated as a statistical link between (antecedent) rainfall and landslide occurrence, derived from precipitation records and historical landslide inventories. A more hybrid approach for deriving hydrology-related rainfall intensity–duration thresholds is proposed by Papa et al. (2013). Predictions of shallow debris flow triggering are carried out with a model in which a perched groundwater aquifer is related to the long-term antecedent precipitation, while infiltration through the unsaturated soil is related to the triggering rainfall event. The rainfall intensity–duration threshold corresponding to a given total percentage of unstable volume within a catchment is derived by a Monte Carlo analysis with a large number of rainfall intensity–duration and antecedent rainfall combinations. The application to a small catchment in the Amalfi Coast (southern Italy) indicates small effects of antecedent rainfall but a great sensitivity to uncertainty in soil physical properties.

The dependence of landslide initiation on antecedent precipitation is related to processes linking hillslope hydrology with catchment storage. This aspect is often neglected in landslide hydrology, whereas modelling the lower boundary condition in a hillslope in 2-D or 3-D, through which water exchanges occur between the surface soil layers and deeper groundwater system, is one of the most difficult problems. How fast does water flow from the critical top soil layer to the deeper groundwater system (or vice versa)? Or, similarly, how to quantitatively model the dynamics of perched aquifers building up at interfaces of different permeabilities? The interaction between the perched groundwater and the shallow unsaturated cover is studied by Greco et al. (2013). The water potential at the bottom of a shallow unsaturated pyroclastic deposit is linked to the water level of a perched aquifer stored in the underlying fractured limestone bedrock, conceptually modelled as a linear reservoir. The model is applied to the slope of Cervinara (southern Italy). The results show that shallow landslide triggering is favoured by a high water level in the perched aquifer, as a strong reduction of suction in the unsaturated cover is required to establish a vertical hydraulic gradient to get rainwater to infiltrate through the soil–bedrock interface.

3 The role of preferential flow in landslide hydrology

As pointed out in many contributions to this Special Issue, macropores greatly influence subsurface flow in hillslopes, which can strongly connect to landslide initiation. Three contributions discuss, at hillslope scale, the influence of macropores and fissures on the hydrological and landslide dynamics. At the pre-alpine hillslope of Rufiberg (Switzerland), tracer experiments carried out by Schneider et al. (2014) showed that interconnected macropores were mainly present in the upper organic soil layer and caused a very shallow subsurface storm flow in the first 50 cm depth. Such a drainage process, better visualized by dye tracer experiments rather than by solute tracer experiments, effectively transfers significant volumes of water downslope and prevents saturated overland flow at rainfall intensity up to $20\,\mathrm{mm\,h^{-1}}$. Nonetheless, the presence of vertical macropores also allowed recharge to a perched confined aquifer whose water level increase could be responsible for landslide triggering.

The work of van der Spek et al. (2013) shows how macropores sometimes have a stabilizing effect on a landslide. They developed a mixed physically based and conceptual hydrological model of the complex landslide in varved clays in the Trièves area (French Alps). The varved clays are constituted by alternating layers of silt (conductive) and clays (much less conductive), covered by a colluvium layer. A perched unconfined aquifer develops in the colluvium, and a second deeper system of confined aquifers in the silt layers encompasses the slip surface, and directly affects the movement of the landslide. The recharge of the lower aquifer occurs through a network of interconnected mechanically induced fissures, conceptually modelled as a linear reservoir. The fissures facilitate both infiltration to and drainage from the silt layers of the varved clays, depending on the hydraulic gradient between fissures and the surrounding. This influences the activation of landslide movement by water infiltration from fissure to varved clay body as well as the stabilizing due to drainage from the landslide body to the draining fissures. The obtained results show that, on the long run, such a model is capable of reliably predicting the periods of landslide activation. However, the study also highlights the importance of more in depth research on the water exchange between those two domains. Furthermore, research is needed to achieve a better parameterization of such a model, especially in terms of how fissure width and distance are affected by landslide movements.

The dynamic feedback of soil displacements and deformations on landslide hydrology features is discussed by Krzeminska et al. (2013), who make use of a dual permeability model to account for preferential flow through mechanical fissures in a slowly moving clay landslide in the southern French Alps (Super Sauze). They introduce feedback (hydrological and geomechanical) between fissures, hydraulic properties and slope stability in a simplified way, as more fissures develop where the local factor of safety is lower, as there the landslide is supposed to undergo larger displacements. Also in this case, the results show how dynamic fissures, usually thought of as favouring a quick build-up of positive pore pressure, and thus destabilizing the slide, can in some cases facilitate drainage of landslide body, helping to release the pressure, and thus leading to more stable conditions.

4 Conclusions

This special issue aims to discuss and advance the representation of hydrological processes in landslide modelling and consequently improve the reliability of landslide hazard and risk assessment. The nine innovative contributions range in complexity and scale, but at the same time present some clear challenges for hydrology and landslide research. We highlight three. First, the processes underlying "antecedent" moisture conditions need more physical underpinning especially in dual domain systems and need to be assessed independently, instead of making it an initial condition problem. This holds for slope specific modelling as well as regional hazard and risk assessment. Second, strongly connected to the first challenge, the influence of the lower boundary condition, the soil–bedrock interface or specific soil layering is well known to be very important in hillslopes. However, it is fair to say that in landslide research they are crucial, as this boundary condition does not only regulate flow condition but also the pore water pressure build-up and, as such, the development of slope instability. Lastly, an almost unexplored research field with regard to slope deformation and soil hydraulic properties will need to be addressed, which basically links to a more in-depth understanding of what the causes and triggers of landslides are and how natural and man-made slopes respond to precipitation and deformation.

References

Bogaard, T. A., Malet, J.-P., and Schmittbuhl, J.: Hydrological behaviour of unstable clay-shales slopes: the value of cross-disciplinary and multitechnological research at different scales, Hydrol. Process., 26, 2067–2070, doi:10.1002/hyp.9454, 2012.

Capparelli, G. and Versace, P.: Analysis of landslide triggering conditions in the Sarno area using a physically based model, Hydrol. Earth Syst. Sci., 18, 3225–3237, doi:10.5194/hess-18-3225-2014, 2014.

Greco, R., Comegna, L., Damiano, E., Guida, A., Olivares, L., and Picarelli, L.: Hydrological modelling of a slope covered with shallow pyroclastic deposits from field monitoring data, Hydrol. Earth Syst. Sci., 17, 4001-4013, doi:10.5194/hess-17-4001-2013, 2013.

Krzeminska, D. M., Bogaard, T. A., Malet, J.-P., and van Beek, L. P. H.: A model of hydrological and mechanical feedbacks of preferential fissure flow in a slow-moving landslide, Hydrol. Earth Syst. Sci., 17, 947–959, doi:10.5194/hess-17-947-2013, 2013.

Lepore, C., Arnone, E., Noto, L. V., Sivandran, G., and Bras, R. L.: Physically based modeling of rainfall-triggered landslides: a case study in the Luquillo forest, Puerto Rico, Hydrol. Earth Syst. Sci., 17, 3371–3387, doi:10.5194/hess-17-3371-2013, 2013.

Papa, M. N., Medina, V., Ciervo, F., and Bateman, A.: Derivation of critical rainfall thresholds for shallow landslides as a tool for debris flow early warning systems, Hydrol. Earth Syst. Sci., 17, 4095–4107, doi:10.5194/hess-17-4095-2013, 2013.

Penna, D., Borga, M., Aronica, G. T., Brigandì, G., and Tarolli, P.: The influence of grid resolution on the prediction of natural and road-related shallow landslides, Hydrol. Earth Syst. Sci., 18, 2127–2139, doi:10.5194/hess-18-2127-2014, 2014.

Schneider, P., Pool, S., Strouhal, L., and Seibert, J.: True colors – experimental identification of hydrological processes at a hillslope prone to slide, Hydrol. Earth Syst. Sci., 18, 875–892, doi:10.5194/hess-18-875-2014, 2014.

Tao, J. and Barros, A. P.: Coupled prediction of flood response and debris flow initiation during warm- and cold-season events in the Southern Appalachians, USA, Hydrol. Earth Syst. Sci., 18, 367–388, doi:10.5194/hess-18-367-2014, 2014.

van der Spek, J. E., Bogaard, T. A., and Bakker, M.: Characterization of groundwater dynamics in landslides in varved clays, Hydrol. Earth Syst. Sci., 17, 2171–2183, doi:10.5194/hess-17-2171-2013, 2013.