A physical model demonstrating critical zone structure and flow processes in headwaters

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Running head: A physical model demonstrating critical zone structure in headwater

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Abstract

Equipped with complex terrain structure, physical models provide an alternative way in understanding and modeling how critical zone shapes hydrologic processes in headwaters for hydrology research and education. However, this type of physical models is limited by frustrating rain-erosion or gully-erosion. Herein, the technique of permeable bricks with cementation property that can help to solve the soil backfilling problem was adopted to construct a physical model with complex terrain. Through material tests for different aggregate-cement ratios, we found that saturated hydraulic conductivity (Ksat) of samples is well correlated with bulk density (BD), e.g., the correlation coefficient (R^2) is as high as 0.75 between Ksat and BD. Then, the test material selected was applied as a soil alternative in the physical model in which two artificial soil layers have been designed through altering BD. Additionally, the non-uniform scaling of terrain was applied for the convenience of teaching, and it was constructed by reducing a steep 0.31-ha zero-order basin to 1/130 in horizontal direction and 1/30 in vertical direction. Multiple observation items, e.g., shallow groundwater level, soil moisture content, subsurface and surface runoff, etc., could provide potential opportunity to explore the role of soil and terrain in modulating streamflow. We'd like to share this effective tool to facilitate the research works of critical zone science and enrich experimental teaching methods.

Description

Critical zone structures e.g., topography, soil and bedrock, are the first-order control in shaping runoff generation in headwater catchments (Zimmer et al., 2017; Harman & Kim, 2018; Anderson et al., 2019; Liu et al., 2019; Fan et al., 2020). But the critical zone beneath our feet, where subsurface flow moves, is invisible, and until recently, it is still an inaccessible and unknown world (Grant & Dietrich, 2017). The reason is mainly that the underlying surface of the watershed has huge heterogeneity at different scales. Meanwhile, it is hard to characterize subsurface flow path of transient runoff (Weiler et al., 2006). This explains why classroom teaching and short-term field trips are difficult to reproduce runoff formation in the critical zone at a glance view.

Contrary to field research, physical model is a practical means for theoretical verification and law discovery (Black, 1970; Etkina et al., 2002). Particularly, the fully controlled models with expected terrain and soil properties may have great potential to deepen our recognition of critical zone (Kleinhans et al., 2010). To our knowledge, soil trough with variable slopes has been widely accepted to investigate hydrological processes by many hydrologists. For example, the slope-variable soil trough in Hohai University comprises two contrast tanks to study the effects of vegetation cover on the runoff response (Song & Wang, 2019). In contrast to above soil troughs without considering plane shape, LEO is more favored by scholars for its convergent topography (Hopp et al., 2009; Gevaert et al., 2014). Even LEO is only a simple morphology, how to model the functions and structures of real-world catchments have been still a key difficulty for physical model developments. Since, as reported by Gevaert et al. (2014), the structures as well as functions can be ruined by an unintended gully erosion through a single heavy rainfall. And numerous studies have also shown that erosion of backfilling soil, caused by rainfall and overland flow, is a very common phenomenon in laboratory experiments (Bryan & Luk, 1981; Jomaa et al., 2010; Ran et al., 2012). This grand challenge is inhibiting physical models from developing variable and desired morphologies that reflect complex characteristics of critical zone.

To further facilitate education and research about the role of critical zone, a physical model with complex terrain has been built. The key of the model is to abandon the traditional backfilling soil and then seek for permeable material. Currently, permeable bricks made of fine aggregate (sand), coarse aggregate (gravel) and cement have been widely used for pavements to allow rainwater to quickly seep into the underground in the field of Low Impact Development (LID) (Dietz, 2007; Ahiablame et al., 2012; Eckart et al., 2017). The aim of the permeable materials is not only to strengthen the capability of infiltration, but also to enhance compressive strength and bending strength at the same time (Nishigaki, 2000; Poon & Chan, 2005; Debnath & Sarkar, 2019). Their maximum water holding capacity is about 13% (Wang et al., 2018), far smaller than that of the natural soils. Generally, the saturated hydraulic conductivity (Ksat) of materials is about one to three orders of magnitude higher than that of the natural soil (Wu et al., 2016; Zhou, 2018; Tang et al., 2019) for the reason that its principal particle components are far coarser than those of the natural soils. According to the suggested ratios, aggregate accounting for about 70% of total volume of concrete (Cai et al., 2018) and water cement ratio ranging from 0.3-0.4 (Debnath & Sarkar, 2019; Rahmani et al., 2020) were used in this study. But the fine aggregate ratio is increased to about 0.8 for weakening the permeability. Three cases with different aggregate cement ratios were tested by altering the bulk density of the mixed material (Tab. 1). Ksat was selected to be the only hydraulic indicator because it plays the key role in the seepage process (Chapuis, 2012). According to the test results (Fig. 1), the permeability of the materials matches that of the natural soil closely, while the field moisture capacity (FMC) is close to loam according to Field Estimation of Soil Water Content (2008). In addition, it is found that Ksat and FMC are both well correlated with bulk density (BD) in these three cases. In other words, the values of Ksat and FMC can be controlled through changing BD values of the mixed materials. Finally, the fitting curves in Case 2, i.e., the stronger nonlinear correlation (R^2=0.75) between Ksat and BD (Sriravindrarajah et al., 2012; Kevern et al., 2014; Debnath & Sarkar, 2019), were adopted.

The prototype of the physical model is a steep 0.31-ha zero-order basin (hereafter referred to as H1), which is located within the Hemuqiao Hydrological Experimental Stational Station (30°34' N, 119°47' E; 135 ha) in Taihu Basin in southeastern China (Han et al., 2020). For the convenience of teaching and construction, the horizontal scale ratio between the model and H1 is 1:130 and the vertical scale ratio is 1:30. The exact measurements of the employed physical model are 6.2 m (length) × 3.9 m (width) × 2 m (height) (Fig. 2a). The model is located in a meteorological observation field for hydro-meteorological education. The model mainly comprises impermeable layer paved by concrete and two artificial soil layers (Fig. 2b). These two artificial soil layers were made of a selected material according to the relationship of Ksat-FMC-BD (Fig. 1b). The two artificial soil layers are filled homogeneously, whose thickness ratio between the upper and lower layers are consistent with the prototype, and the thickness are 8 cm and 24 cm, respectively. The corresponding Ksat values are 1.4 mm/min and 0.2 mm/min, which are approximately the average values of the upper and lower soils in H1. However, the FMC values in the upper and lower layers are around 20% and 14%, of which the lower value is 18% less than real-world value. The reason is that the proportion of the components in the selected material stays the same but clay content in the lower soils in H1 is increased. Over the artificial soil layers, fake turf was paved for the case of raindrops splashing down and direct sunlight (Fig. 2b).

In the physical model, various processes in both natural and artificial rainfall-runoff events can be monitored (Fig. 2c&d). For the purpose of education and research, four projects have been established. First, 12 groundwater wells are set to observe how free water changes at different locations on the hillslope model, how the wells respond to rainfall process, and how topography and media affect the storage and discharge of free soil water (McMillan & Srinivasan, 2015; Han et al, 2020). Second, in order to understand changes of soil temperature and moisture content, TDR probes are vertically inserted into the upper artificial soil layer. Third, at the outlet (Fig. 2d), there is a weir (Han et al., 2016) that can simultaneously observe surface and subsurface runoff. Finally, two cameras are used to cover all possible positions that generate runoff during rainstorms.

We usually present the physical model at natural rainfall events. After a rainfall-runoff event, the maintainer could be asked to collect all data. Then the continuous time series would be stored for hydrological characteristic analysis of the model. In summary, it provides us with an efficient tool to identify the role of critical zone structures in shaping streamflow. The artificial soil has controllable hydraulic properties for permeable layers in the model, which is of potential to replace the real-world soils. More importantly, compared to the backfilling soil, it resists erosion and is not easy to deform so as to promote the development of the physical models with complex terrain.

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References

Ahiablame, L. M., Engel, B. A., & Chaubey I. (2012). Effectiveness of low impact development practices: Literature review and suggestions for future research. *Water Air Soil Pollut* , *223* , 4253–4273. https://doi.org/10.1007/s11270-012-1189-2

Anderson, R. S., Rajaram, H., & Anderson, S. P. (2019). Climate driven coevolution of weathering profiles and hillslope topography generates dramatic differences in critical zone architecture[J].*Hydrological Processes* . *33* (1), 4-19.*https://doi.org/10.1002/hyp.13307*

Black, P. (1970). Runoff from watershed models. *Water Resources Research* , *6* , 465-477.

Bryan, R. B., & Luk, S. (1981). Laboratory experiments on the variation of soil erosion under simulated rainfall. Geoderma. 4(26), 245-265.*https://doi.org/10.1016/0016-7061(81)90023-9*

Cai, R., Mandula, Chai, J. (2017). Research on the performance of sand-based environmental-friendly water permeable bricks. *IOP Conference Series: Earth and Environmental Science* , *113* (1). https://doi.org/10.1088/1755-1315/113/1/012136

Chapuis, R. P. (2012). Predicting the saturated hydraulic conductivity of soils: a review. Bulletin of Engineering Geology and the Environment, 71, 401-434.*https://doi.org/10.1007/s10064-012-0418-7*

Debnath, B., & Sarkar, P. P. (2019). Permeability prediction and pore structure feature of pervious concrete using brick as aggregate.*Construction and Building Materials* , *213* , 643-651. https://doi.org/10.1016/j.conbuildmat.2019.04.099

Dietz, M. E. (2007). Low impact development practices: A review of current research and recommendations for future directions. *Water Air Soil Pollut* , *186* , 351–363. https://doi.org/10.1007/s11270-007-9484-z

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development–A review. *Science of the Total Environment* , *607* , 413-432. http://dx.doi.org/10.1016/j.scitotenv.2017.06.254

Etkina, E. (2002). Role of Experiments in Physics Instruction — A Process Approach[J].*The Physics Teacher* . *40* (6). https://doi.org/10.1119/1.1511592

Fan, Y., Grant, G., & Anderson, S. P. (2019). Water within, moving through, and shaping the Earth's surface: Introducing a special issue on water in the critical zone. *Hydrological Processes* . *Preface 25* (33). https://doi.org/10.1002/hyp.13638

Gevaert, A. I., Teuling, A. J., Uijlenhoet, R., DeLong, S. B., Huxman, T. E., Pangle, L. A., Breshears, D. D., Chorover, J., Pelletier, J. D., Saleska, S. R., Zeng, X., Troch, P. A. (2014). Hillslope-scale experiment demonstrates the role of convergence during two-step saturation[J]. *Hydrology and Earth System Sciences* ,*18* (9). https://doi.org/10.5194/hess-18-3681-2014

Grant, G. E., &Dietrich, W. E. (2017). The frontier beneath our feet.*Water Resources Research* . *53* . https://doi.org/10.1002/2017WR020835

Han, X., J Liu, J., Srivastava, P., Mitra, S., & He, R. (2020). Effects of critical zone structure on patterns of flow connectivity induced by rainstorms in a steep forested catchment. *Journal of Hydrology* . https://doi.org/10.1016/j.jhydrol.2020.125032

Han, X., J Liu, J., Jiang, C., He, D., & Liang, Y. (2016). A weir for simultaneously observing surface flow and interflow on hillside, Copyright no. CN205102879U, China.

Han, X. (2018). Study on surface structures and hydrological connectivity in an experiment catchment in humid region of Southern China. Ph.D. Thesis, Hohai University, China.

Harman, C. J., & Kim, M. (2018). A low-dimensional model of bedrock weathering and lateral flow coevolution in hillslopes: 1. Hydraulic theory of reactive transport. *Hydrological Processes* , *33* , 466–475. https://doi.org/10.1002/hyp.13360

Hopp, L., Harman, C., Desilets, S. L. E., Graham, C. B., McDonnell, J. J., and Troch, P. A. (2009). Hillslope hydrology under glass: confronting fundamental questions of soil-water-biota coevolution at Biosphere 2. *Hydrology and Earth System Sciences* . *13* , 2105–2118. https://doi.org/10.5194/hess-13-2105-2009

Jomaa, S., Barry, D. A., Heng, B. C. P., Brovelli, A., Sander, G. C., Parlange, J. Y. (2012). Influence of rock fragment coverage on soil erosion and hydrological response: Laboratory flume experiments and modeling. *Water Resources Research* . *5* (48).*https://doi.org/10.1029/2011WR011255*

Kevern, J.T., Wang, K., & Schaefer, V.R. (2010). Effect of coarse aggregate on the freeze–thaw durability of pervious concrete.*Journal of Materials in Civil Engineering* , *5* (22), 469–475. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000049

Kleinhans, M. G., Bierkens, M. F. P., & van der Perk, M. (2010). On the use of laboratory experimentation: "Hydrologists, bring out shovels and garden hoses and hit the dirt". *Hydrology and Earth System Sciences* , *14* , 369–382. https://doi.org/10.5194/hess-14-369-2010

Liu, J., Han, X., Liu, L., Liang, Z., & He, R. (2019). Understanding of critical zone structures and hydrological connectivity: a review.*Advances in Water Science* . *30* (1),112-122. https://doi.org/10.14042/j.cnki.32.1309.2019.01.012

Mcmillan, H., Srinivasan, M. (2014). Controls and characteristics of variability in soil moisture and groundwater in a headwater catchment.*Hydrology and Earth System Sciences Discussions* , *11* (8), 9475-9517.*https://doi.org/10.5194/hessd-11-9475-2014*

Nishigaki, M. (2000). Producing permeable blocks and pavement bricks from molten slag. Waste Management, 20, 185-192.*https://doi.org/10.1016/S0166-1116(97)80186-0*

Poon, C. S., & Chan, D. (2006). Paving blocks made with recycled concrete aggregate and crushed clay brick. *Construction and Building Materials* , *20* , 569-577.*https://doi.org/10.1016/j.conbuildmat.2005.01.044*

Rahman, E., Sharbatdar M. K., & Beygi, M. H.A. (2020). The effect of water-to-cement ratio on the fracture behaviors and ductility of Roller Compacted Concrete Pavement (RCCP). Theoretical and Applied Fracture Mechanics, 109, 102753. https://doi.org/10.1016/j.tafmec.2020.102753

Ran, Q., Su, D., Li, P., & He, Z. (2012). Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion. *Journal of Hydrology* , (424-425), 99-111. https://doi.org/10.1016/j.jhydrol.2011.12.035

Song, S., & Wang, W. (2019). Impacts of Antecedent Soil Moisture on the Rainfall-Runoff Transformation Process Based on High-Resolution Observations in Soil Tank Experiments. *Water* , *11* (2), 296.*https://doi.org/10.3390/w11020296*

Sriravindrarajah, R., Wang, N.D.H., & Ervin, L.J.W. (2012). Mix design for pervious recycled aggregate concrete. *International Journal of Concrete Structures and Materials* , *4* (6), 239-246.*https://doi.org/10.1007/s40069-012-0024-x*

Tang, B., Gao, S., Wang, Y., Liu, X., & Zhang, N. (2019). Pore structure analysis of electrolytic manganese residue based permeable brick by using industrial CT. *Construction and Building Materials* , (208), 697-709.*https://doi.org/10.1016/j.conbuildmat.2019.03.066*

Wang, J., Meng, Q., Tan, K., Zhang, L., & Zhang, Y. (2018). Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment. *Building and Environment* , (140), 184-193. https://doi.org/10.1016/j.buildenv.2018.05.033

Weiler, M., Mcdonnell, J. J., Meerveld, I. T., & Uchida. (2006). T. Subsurface stormflow, in book: Encyclopedia of Hydrological Sciences.*https://doi.org/10.1002/0470848944.hsa119*

Wu. X., Ma, H., Wu, N., Shi, C., Zheng, Z., & Wang, Y. (2016). Nepheline-based water-permeable bricks from coal gangue and aluminum hydroxide. *Environmental Progress & Sustainable Energy* ,*3* (35), 779-785.*https://doi.org/10.1002/ep*

Zhou, C. (2018). Production of eco-friendly permeable brick from debris.*Construction and Building Materials* , (188), 850-859. https://doi.org/10.1016/j.conbuildmat.2018.08.049

Zimmer, M. A., & Gannon, J. P. (2017). Run-off processes from mountains to foothills: The role of soil stratigraphy and structure in influencing run-off characteristics across high to low relief landscapes.*Hydrological Processes* . *32* (11). https://doi.org/10.1002/hyp.11488

Case	Mass proportion %				Water Cement Ratio	Aggregate Cement Ratio	Fine Aggregate Ratio
	Coarse Aggregate	Fine Aggregate	Cement	Water			
1	10.5	47.4	31.6	10.5	0.33	1.83	0.82
2	10.5	44.7	34.3	10.5	0.31	1.61	0.81
3	10.5	42.1	36.9	10.5	0.29	1.43	0.80

*The raw materials used are fine aggregate with a particle size of 0.5 to 1.5 mm, composite portland cement with strength class 32.5, and crushed stones or coarse aggregate with a particle size of 0.5 to 1.5 cm. Fine aggregate ratio = mass of fine aggregate/(mass of fine and coarse aggregate).