

HYDROLOGICAL RESPONSE CHARACTERIZATION OF THE SUBSURFACE FLOW IN HILLSLOPE: A REVIEW

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ABSTRACT

The article explores the concepts and techniques of hillslope hydrology, various pathways that water travels in a hillslope to the stream networks. Topographic characteristics such as elevation, gradient, orientation, hillslope length, longitudinal and transverse curvatures play an important role for enrouting water. These characters not only influence the volume and time of water runoff but influence its quality through control of flow patterns and water travel time distributions across the hillslope. Tracer studies estimate the velocity of the flow, which can present the information about the paths of the underground flow. However, it is observed that physical measurement of these flow paths is complicated and need more time besides difficult to collect data, since the soil parameters vary spatially, initial moisture varies and usually, the datasets available exclude extreme hydrological events. Computational modeling then appears quite worthwhile asset in this regard as it allows simulating and studying hydrological responses, which does not need a substantial amount of empirical data. Hydrological catchment modeling has changed over the past decades, at least when it comes to understanding watershed behaviour, which was formerly an engineer-bound solution and now a scientific process of hypothesis testing and understanding.

Keywords: Hydrology, topographical characteristics, quality stream water, celerity and simulation

INTRODUCTION

A clear comprehension of the factors regulating runoff in mountainous catchments is essential for sustainable water resource management in arid and semi-arid zones. Specifically, the behaviour of hillslope soil moisture during rainfall events plays a central role in controlling the rainfall–runoff relationship.

Slopes in hilly regions channel water from catchment areas to downstream zones. This process occurs either through preferential flow paths or, more commonly, via subsurface flow, as the shallow soils and underlying impermeable bedrock limit deep percolation and thus restrict groundwater recharge. The effectiveness of this mechanism depends on slope characteristics, soil properties, vegetation density, and land-use practices. Degraded or deforested areas often accelerate runoff and erosion, reducing the potential benefits of hillslope storage. Moreover, the capacity of hillslopes to mitigate large-scale flood losses is limited during extreme rainfall events, when natural storage is rapidly exceeded (Blume and van Meerveld, 2015). The capacity of a hillslope to temporarily store precipitation inputs and subsequently release water represents a critical determinant of its hydrological response. Nanda and Safeeq (2023) revealed a higher frequency of preferential flow events during drought periods compared to normal water years, which can be attributed to increased soil hydrophobicity under prolonged dry conditions. This behaviour indicates that soil water interaction substantially alters infiltration dynamics, enhancing the likelihood of bypass flow pathways. Moreover, greater variability in soil moisture changes was detected at deeper depths, suggesting heterogeneous subsurface responses to infiltration under stressed hydrological conditions. This mechanism regulates the partitioning of rainfall into infiltration, subsurface flow, and surface runoff, thereby controlling the timing, magnitude, and hydrograph characteristics of discharge delivered to adjacent channels. High storage capacity, typically associated with porous soils, moderate slopes, and dense vegetation, attenuates peak flows, enhances groundwater recharge, and sustains base flow contributions.

Although heterogeneity has been viewed as a chaotic difference in the properties of soils, the idea of organized heterogeneity suggests to correlation of properties and correlation of flow paths spatially (Jackish *et al.*, 2017). Xiong *et al.* (2026) finds strong spatial heterogeneity in rainfall response controlled by slope aspect, soil properties, lateral flow, and rainfall characteristics

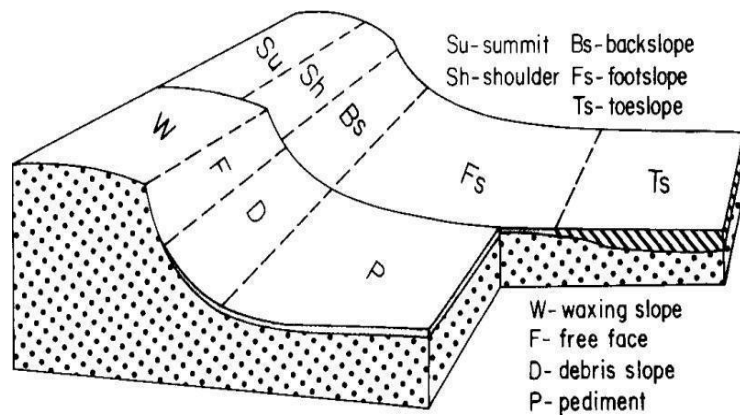
Hallema *et al.* (2016) highlighted that topography and soil infiltration capacity are fundamental controls on runoff generation, influencing both flow distribution and the travel time of water moving downslope. This insight underscores the interaction between structural (topographic slope, curvature, aspect) and functional (infiltration and permeability) factors in determining hydrological responses to rainfall events. Thus, integrating topographic analysis with soil-vegetation dynamics provides a more holistic understanding of runoff generation and travel time

variability in catchment hydrology. Ruhe (1960) divided hillslope elements according to topographic characteristics, characterised them as summit, shoulder, backslope, foot slope and toe slope (Table 1 and Figure 1).

Table 1: Hillslope elements based on profile curvature

Hillslope element	Description
Summit	The summit is also referred to as plateau because this relatively flat zone is higher than the rest of the hillslope. Mass wasting processes are almost absent, leaching and rain splash dominate.
Shoulder	When looking down from the summit, the shoulder below the summit has a slightly convex slope. This is where soil creep can occur.
Backslope	Part of hillslope with a concave slope between shoulder and foot slope called debris slope in the classification of King (1953).
Foot slope	Also called glacis, the foot slope is less concave than the backslope above it.
Toe-slope	The toe-slope or valley bottom is rather flat (1-2 per cent slope) and characterized by alluvial deposition with greater clay and silt content than upstream parts.

Figure 1: Cross section of hillslope showing different elements



According to Scaini *et al.*, (2018), besides soil properties, the nature of underlying bedrock structure had remarkable impact on the subsurface runoff. The topographical control and the hydrological processes interaction play a significant role in the definition of hydrologic connectivity. Digital elevation models or digital terrain models lead to extraction of topographic attributes which are essential to the characterization of patterns in the hydrological processes and drainage network mapping in watershed. Estimates of velocities and celerity may be made using tracer data that may assist the interpretation of the flow paths in the subsurface.

HILLSLOPE RESPONSE: VELOCITY AND CELERITY ESTIMATION

The velocity with which a perturbation to the flow of water travels through a particular flow domain is also known as celerity according to McDonnell and Beven (2014). The celerity response depends on the type of disturbance and moisture that pre-exists. Tracer studies in hydrological studies were used to determine the rate at which the water reacts with the tracers added and thereafter comes to reach stream systems. The input-output data of tracer experiments shows a distribution of transit times of the flow within a catchment. In addition to this, tracer data can be used to determine celerity, thus helping in the interpretation of subsurface flow pathways. New modelling frames have included the uses of celerity distributions, which appear in the form of the resultant hydrograph.

To facilitate analysis, there should be definition of celerity using available data in the form of operational definition. The basic principle under which this method is based is that there are hydrological responses which may be used as a good predictor of the first wetting celerity in the unsaturated zone like the initial response to a rain event. The celerity may also be identified with regard to the time of peak in water table and peak in hydrograph. But as to discharge, it is believed to symbolize the quick circulation routes via fractured bedrock of the hillslopes as implied by the recent studies (Wrede *et al.*, 2015).

PROCEDURES TO INTRUDE INSIDE UNDERGROUND CONNECTIVITY

Knowing of the subsurface hillslope-stream connectivity is key to both understanding and predicting runoff responses such as floods, and monitoring of stream water quality. Hence, there is a strong need to understand the hillslope-stream hydrological connections in regard to how and when they form and what controls them. A challenge of researching on preferential flow lies in the fact that it is exhibited on different scales, its strong rate of spatial variation, and its intensive temporal characteristics. It will therefore be quite necessary to determine the processes and timing of the hillslope-stream hydrological coupling and its controlling factors. However, what makes establishing hillslope-stream connectivity a tricky endeavour is the fact that it is a relatively underground phenomenon which is not visible. A majority of studies have resorted to a multi-method technique (e.g. using a combination of flow measurements in trenches with the

measurement of groundwater levels and streamflow) to increase the understanding of each individual measurement.

VIRTUAL EXPERIMENTS AND HILLSLOPE MODELS

In hillslopes, it is difficult to determine the interaction between the major drivers of subsurface flow and hillslope-stream linkages. These problems aggravated, as directly visualising flow pathways inside the soil is difficult, pronounced spatial variability of soil properties, temporal variations in antecedent moisture conditions, and available data that fails to capture extreme hydrological events. A benefit of numerical simulations is that they allow the analysis of the hydrological response by not requiring a huge number of empirical observations. The purpose of these virtual experiments is not to represent and model completely a particular system or field site. Rather, they enable examination of the role of hillslope characteristics, initial conditions, input variables, and feedbacks amongst them in terms of hillslope hydrological behaviour. Significant numbers of studies have been conducted over the past two decades on various aspects of hillslope hydrology, including: overland flow, streamflow, vertical and lateral preferential flow, non-equilibrium flow dual-porosity flow.

Sarkar and Dutta, (2015) found about the creation of a perceptual or a predictive model of the involved processes that regulated the response at the catchment scale. It is imperative that the model chosen ought to be in a position to depict the likely hydrological processes. This has promoted development of various physically-based hydrological in several countries in the world to cater the behaviour of water in hillslope. Some of the models such as TOPMODEL, A physically - based numerical hillslope model (QSOIL), HYDROTEL. Among these, TOPMODEL can be adjusted to consider kinematic wave routing of a subsurface flow. Nonetheless, the model is not the direct characterization of the vertical and the lateral preferential flow of soil. Another physically- based, spatially- distributed hydrological model is HYDROTEL, that is capable of managing geospatial data can be used in real time streamflow forecasting, hydrological impacts assessment on the physical changes and modelling the spatial distribution of soil moisture, evapotranspiration, subsurface runoff and vertical water budget. The physical process of soil macropore flow is absent in the model and the time step (1 h) in the model is too big to capture the rapid processes of preferential flow.

Cui and Tian (2025) observed the linkage between rising groundwater level (GWL), enhanced transmissivity, and increased groundwater flux and described well established in variable source area (VSA) hydrology, where higher water tables reduce resistance to lateral subsurface flow. The recognition that threshold exceedance in GWL can trigger synchronized hillslope responses, thereby amplifying stormflow, is also consistent with threshold-dominated watershed behaviour.

The concept of a physically based numerical hillslope model (QSOIL) that can be used to simulate the topography and hydrology in infiltration and runoff processes was suggested using the concept of double porosity. It has overland flow modules, macropore flow modules, matrix flow modules and interaction and pipe flow modules. The model has some important physical parameters: surface roughness coefficient, soil macro porosity parameters, the velocity of flow through macropores and soil matrix parameters. The type of model simulates 2-D infiltration and runoff processes and 1-D infiltration process. A Multiple Interactive Pathways (MIPs) model represented the implications of soil heterogeneities as well as preferential flow pathways represented by Davies and Beven (2012).

GENERALIZATION OF INDIVIDUAL HILLSLOPES TO CATCHMENT SCALE

Although quantifying the connectivity between hillslopes and streams is a difficult operation, the latter can be said about expanding beyond individual hillslopes and measuring connectivity within broader areas. Few scaling approaches *viz.*, (1) field surveys and mapping (2) topographic metrics and landscape analysis use and (3) simulation models can be used. Although the first- and the second-based approach tend to create static maps of potential connectivity, the third approach gave advantage of dynamic and hence functional dimension of connectivity is possible.

MAPPING AND FIELD SURVEYS

In the study of hydrological connectivity, a sampling strategy should be chosen to ensure an adequate characterization of the heterogeneities that exert an immense impact on the response runoff in hillslope-scale (Smith *et al.*, 2010). Making downslope of main drainage divide, soil surfaces microtopography shows systematic changes as the area contributing up slopes enlarges and advective runoff completes soil surface (Horton, 1945).

TOPOGRAPHIC MEASURES AND LANDSCAPE MEASUREMENTS

The various definitions of hydrologic connectivity highlight the key variables—such as topography, surface and subsurface flow, and soil moisture patterns—that should be incorporated into a connectivity metric. Consequently, an effective measure should be highly sensitive to both wet and dry catchment microstates, as hydrologic connectivity is strongly influenced by rainfall and antecedent moisture conditions, which can trigger intense hillslope runoff (James, 2005). Preferential flow paths with high conductivity, along with interconnected saturated source areas, may also play a critical role in controlling catchment-scale hydrologic responses (Western *et al.*, 2001).

SIMULATION MODELS USAGE

The science behind hydrological catchment modelling has changed dramatically over the last couple of decades since the discipline was more of an engineering-based problem-solving tool more than a subject of scientific questioning and hypothesis making. Recent models aim to conceptualize the behaviour of catchments, as well as processes that are behind the creation of streamflow. The mentioned models could be considered as clear hypothesis of catchment dynamics (Andreassian *et al.*, 2009), which could be checked with the help of available data of catchments.

The types of models include simple soil moisture accounting-based models to complex process based where it attempts the physical description of the processes of water movement in a catchment which were documented (Beven, 1989). Process-based models allow drawing conclusions about those hydrological processes that are not actually visible on the corresponding level of time or space. Nonetheless, the process-based models are often with the problems like the parameterization excess and inefficiency. Preference will be given to emerging simpler models which may be used to predict future catchment states and can use more sophisticated algorithms of optimization and analysis of uncertainty. However, conceptual model parameters are often difficult to relate measurable characteristics of the catchment, which is an issue in the reliability of their extrapolation by use to conditions that differ to that on which the model was calibrated. Although field of applied hydrology was still seeing difficulty of incorporating the findings into a framework of models that could be used widely (Mc Donnell *et al.*, 2007). As a result, there is a part of hydrological modeling that has been growing towards implementations of flexible modelling frameworks for complicated analysis.

CONCLUSION

Modelling flexibility, a standard procedure within the flexible modelling paradigm, involves selecting the final model structure through calibration against observed streamflow data, which necessitates the exploration of numerous alternative model structures. Although adaptable modelling frameworks can function as curve-fitting tools, they also provide valuable insights into catchment behaviour through comparative analysis. While it is often possible to obtain a calibrated model that reproduces observed hydrographs across multiple catchments, the representation of internal states within such models remains relatively weak (Kirchner, 2006). This limitation highlights the importance of coupling modelling applications with experimental studies (Blöschl, 2006). Robust empirical data can offer new perspectives on traditional methodologies and theories that have long dominated hydrological modelling. Consequently, recent studies increasingly emphasize the integration of field observations and modelling information within a unified estimation framework, with methodological advances aimed at enhancing the effective use of complementary information in the modelling process.

DISCLAIMER (ARTIFICIAL INTELLIGENCE):

Author(s) hereby declares that generative AI technologies such as ChatGPT have not been used during writing the manuscript.

COMPETING INTERESTS

Authors have declared that no competing interest exists.

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