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Hydrologic Response Unit: The Missing Link In Hydrology

Freeman J Cook[a,b,c], Tony Weber[d], Vilim Filipovic[b]

[a]*Freeman Cook & Associates,* [b]*The University of Queensland,* [c]*Griffith Universty,* [d]*Alluvium Group*

Abstract: Hydrological processes were historically modelled using different approaches at varying spatial scales, yet a gap remained between plot-scale and catchment-scale models. This paper revisited the concept of the Hydrologic Response Unit (HRU) as a potential "missing link" in bridging this scale gap. The authors argued that traditional HRUs—spatial units assumed to be homogeneous in soil and land cover—oversimplified the heterogeneity present in real landscapes. A conceptual framework is presented that incorporated spatial variability in infiltration, runoff generation, and soil storage within HRUs (Fig.1).

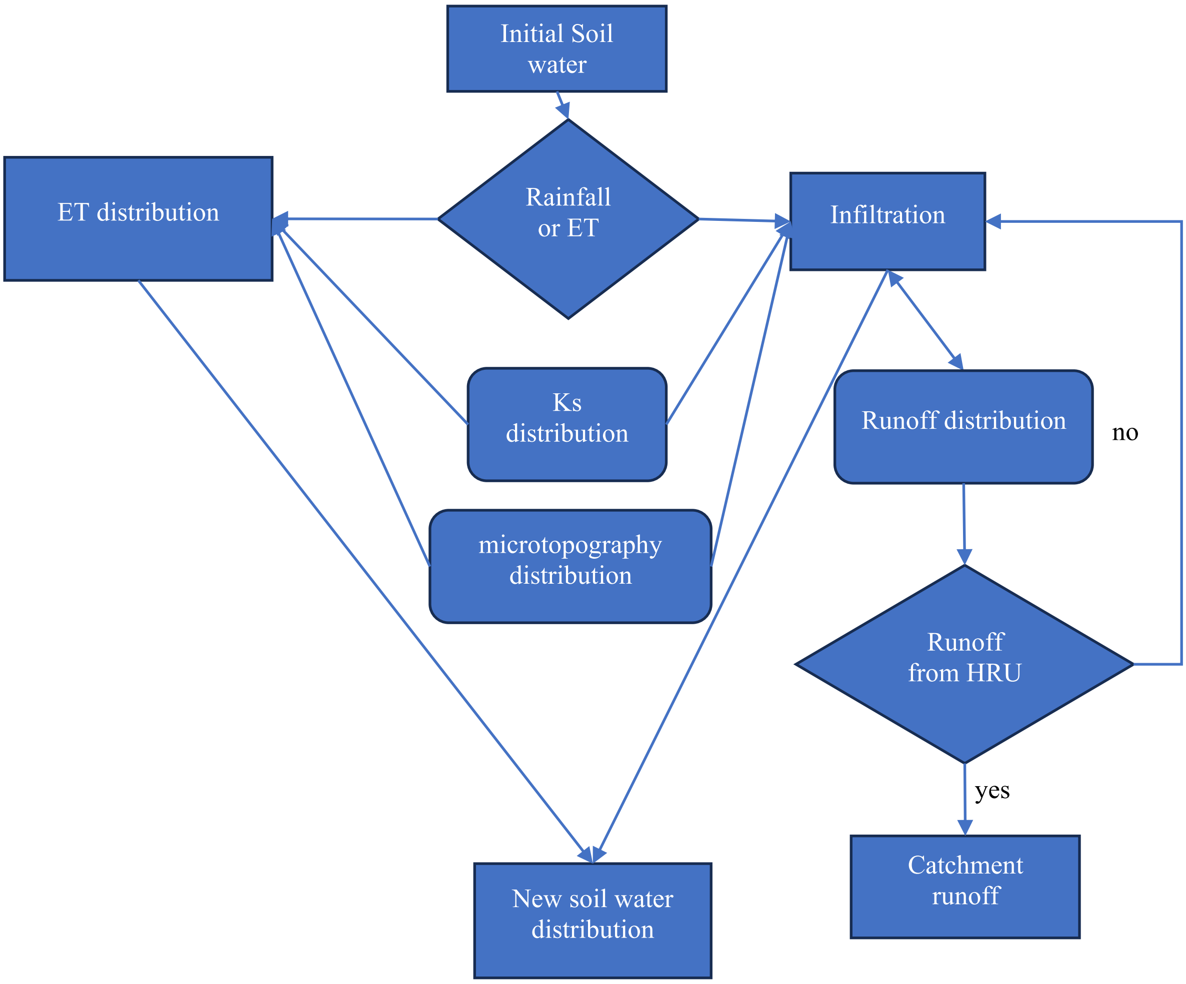

Figure 1. Conceptual model for how the soil properties and microtopography affect hydrologic response at HRU scale.

Drawing on infiltration theory and microtopography, we demonstrated how non-uniform hydrologic responses emerged at the HRU scale and influenced runoff, drainage, and evapotranspiration processes. The implications for simulation-based hydrologic and water quality models were found to be significant: integrating spatial dynamics within HRUs improved the accuracy of flow and solute transport modeling. It was highlighted by emerging approaches, including convolution-based and ensemble methods, as promising strategies to capture sub-HRU variability within simulations. The findings supported the need for a new generation of HRU representations that preserved spatial heterogeneity.

Keywords: *Hydrologic response unit, infiltration, hydrology, microtopography, spatial variability*

1. INTRODUCTION

Hydrological processes operate across **multiple characteristic scales,** each governed by different modeling approaches. At the pore scale, fluid motion can be described by Hagen–Poiseuille equations, transitioning to Darcy's law at scales from centimeters to meters. At the catchment scale we can use the forcing parameters from climate and some topological parameters to fit the river outflow. There is a problem with the models that fit in between the catchment scale and the appropriate scale for capacity models.

Various attempts have been made to fill this gap which can rely on scaling up Darcy's law or capacity to the scale of tens of metres to kilometres. Models such as SWAT (Arnold et al., 1998) and SOURCE (Argent et al., 2009) split the landscape up into units which are consider preform hydrologically the same. These units termed either Hydrologic Response Units (HRUs) (Arnold et al., 1998) or Functional Units (Argent et al., 2009) are used to decrease the computational load in calculating the response to climate forcing, land management and vegetation. These HRU's assume uniformity in the properties of the units and often use a simplified form of Darcy's law in the form of a tipping bucket water balance model to define the hydrologic response. However, it is questionable if the assumptions of uniformity and the use of Darcy's Law and/or capacity models are appropriate at this scale.

We along with others (Poblete et al., 2020; Green et al., 2025; Yang et al. 2025) contend that idea of HRUs should be challenged and that there is a need for concerted research to be better able to model hydrologic processes at this missing link scale. This problem has been recognised for some time as Western et al. (2001, 2002, 2004) suggested that a lack of quantification of spatial dynamics in soil water processes was holding back understanding of hydrological processes. However, there does not seem to have been much progress made in incorporating these spatial dynamics into hydrologic models with HRUs.

In this paper, a conceptual framework to represent spatial non-uniformity within Hydrologic Response Units (HRUs) was proposed and examined how this influenced key hydrological processes. We focused on infiltration and runoff generation under variable rainfall, the resulting soil moisture distribution, and the implications for evapotranspiration and drainage. The paper also explored the implications for simulation-based hydrologic and water quality models and suggested potential pathways forward, including the integration of high-resolution data (e.g., remote sensing and cosmic-ray soil moisture observations) and the adoption of novel modeling techniques, even AI methods to more effectively capture sub-HRU variability.

2. CONCEPTUAL MODEL

The HRU concept assumes uniformity in response to hydrologic forcing but given the area of most HRUs is 100s of m^2 to km^2 this is unlikely apart from for specific conditions. Consider an HRU with the kind of area suggest there is likely to be at least some variability in both the microtopography and soil hydraulic properties. This means that there will be an interaction between the soil hydraulic properties and microtopography (Caviedes-Voullieme et al., 2021) the proposed conceptual model is shown in fig. 1.

2.1. Infiltration

For the Green-Ampt (GA) infiltration model Barry et al. 2005) provided an explicit solution with the infiltration (I_{GA} (m)) given by:

$$I_{GA}(t) = \frac{S^2}{2K_s}\left\{-1-\left[\frac{t^* + \ln\left(1+t^*+A\right)}{\left(1+t^*+A\right)^{-1}-1}\right]\right\}, \qquad A = \frac{6\sqrt{2t^*}}{6+\sqrt{2t^*}}, \qquad t^* = \frac{2K_s^2 t}{S^2} \quad [1]$$

where t^* is dimensionless time, t is time (s), K_s is saturated hydraulic conductivity (m s^{-1}), A is a dimensionless time parameter and S is the sorptivity (m $s^{-1/2}$), for a GA (delta function) soil is given by (Parlange 1975, Neuman, 1976) as $S^2 = 2\Delta\theta K_s\left(H+\psi_f\right)$, H is the ponded head of water on the soil surface (m), ψ_f is the wetting front matric water potential (m). The time when water starts to the soil surface (time to ponding, t_p (s)) can be found by (White et al., 1989):

$$t_p = \frac{0.55}{\bar{R}_p}\left[\frac{S^2(\theta_{dry})}{K_s}\right]\ln\left[\frac{R(t_p)}{R(t_p)-K_s}\right] \quad [2]$$

where $\bar{R}_p = t_p^{-1}\int_0^{t_p} R(t)\,dt$ is the variable water application rate (=surface flux) with time (m s^{-1}), M is a soil specific property = 0.55, $R(t_p)$ is the surface flux into the soil at t_p (m s^{-1})

I_p is the cumulative infiltration up to t_p (m). Cook (2021) combine this with the time compression concept (TCC) (Salvicci and Entekhabi, 1994) to give the infiltration with time as:

$$I(t) = \int_0^t R(t)\,dt, \qquad t < t_p$$

$$I(t_p) = \int_0^{t_p} R(t)\,dt = \bar{R}.t_p, \qquad t = t_p$$

$$I(t) = I_{GA}\left(t-(t_p-t_c)\right) = \frac{S^2}{2K_s}\left\{-1-\left[\frac{t^*+\ln\left(1+t^*+A\right)}{\left(1+t^*+A\right)^{-1}-1}\right]\right\}, \; t > t_p \qquad [3]$$

$$t^* = \frac{2K_s^2\left(t-(t_p-t_c)\right)}{S^2}$$

The value of t_c is the time at which the GA model gives an infiltration rate $i(t_c)$ equal to the surface flux ($R(t_p)$) at t_p. This can be achieved using recursive methods such as Newton-Raphson (Ralston, 1965). The cumulative infiltration $I(t_c)$ calculated with Eqn (1) will be equal to the actual cumulative infiltration $\bar{R}t_p$, so $t_p = I(t_c)/\bar{R}$. K_s is considered to be a highly varaiable with the coefficient of variation usually gtreater than 100% and log-normally distributed. Thus over an area of a HRU this variability would be expected. Thus, the time to ponding, infiltration and localised runoff will vary across the HRU. The cumulative probability (P) for such a distribution is given by:

$$P(x) = \frac{1}{2}\left[1+erf\left(\frac{\ln(x)-\mu_{\ln}}{\sigma_{\ln}\sqrt{2}}\right)\right] \qquad [4]$$

where $\mu_{\ln}$ is the mean and $\sigma_{\ln}$ is the standard deviation of the log transformed distribution and x is a value within the distribution. If we consider that $x = R(t)$ then eqn (4) can be used to determine how much of the area in a HRU would be contributing runoff with increasing x. A simple example is let the coefficient of variantion = 1 and $\mu_{\ln}$ = 1 the value of $\sigma_{\ln}$ to achieve this is then 0.527, then the mean in non-log transformed terms is $\mu = \exp\left(\mu_{\ln} + 1/2\sigma_{\ln}^2\right)$ = 3.12 mm/hr and the median and mode are 2.718 and 1.0 mm/hr respectively. What this would implie is that when the $R(t)$ = 2.718 mm/hr 50% of the area would be generating runoff and at 1 mm/hr 16% of the area would be generating runoff and when $R(t) = K_s$ = 4.48 mm/hr 69% of the area would be generating runoff (Fig.2).

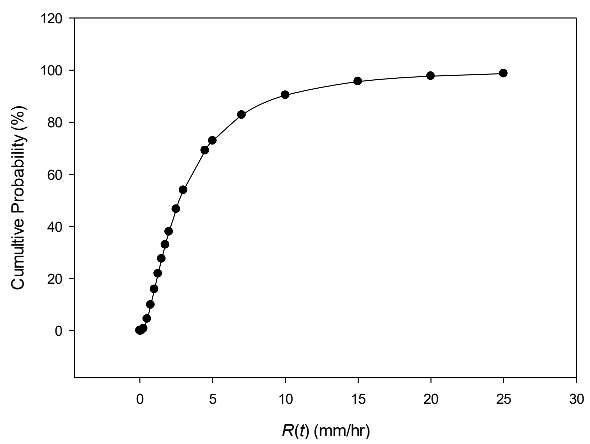

Figure 2. Cumulative probability (area of runoff) versus rainfall rate for soil with mean *Ks* 0f 4.48 mm/hr and $\mu_{\ln} = \sigma_{\ln}$ = 0.527. See text for definition of $\mu_{\ln}$ and $\sigma_{\ln}$.

Depending on the microtopography in the region where the runoff is generated this will result in either a build up of water to the localised retention capacity ($H(s)$), where s is the location in the HRU or runoff to a microtopographic location where the K_s is greater, and the water can be infiltrated. As R increases the proportion of the area where runoff is being generated will increase and the likelihood of overtopping of the microtopographic features will increase. Not only is the rainfall rate important but so is the duration in determining the degree of heterogeneity of the infiltration. When considering the combination of the hydrologic and microtopographic variability together we suggest that non-uniformity of the infiltration will look something like the arbitrary hypothetical function shown in Fig. 3.

An illustration of how this interaction between runoff and microtopography can cause nonuniformity in infiltration is provided by Cook (1983) and Filipovic et al., (2019). The average rate of irrigation was 20 mm/hr but due to the small 'footprint' size of the application the instantaneous irrigation rate, which lasted for 20 seconds, was 630 mm/hr which was greater than the saturated hydraulic conductivity of the soil. This resulted in runoff. The microtopography of the site had differences in heights of about 100 mm and spacing between the high points and low points of about 500 mm. The runoff resulted in puddles forming in the low areas. This resulted in the infiltration varying greatly with Christiansen uniformity coefficient varying from -23 to 39 which is a large decrease in the uniformity compared to the irrigation which had a Christiansen uniformity coefficient varying from 64 to 77. During rainfall which would be more continuous we do not expect such extreme nonuniformity, but it will still occur due to the redistribution of runoff from areas to low hydraulic conductivity to areas of high hydraulic conductivity. The formation of areas with free water on the soil surface will also further exacerbate the nonuniformity of infiltration due to macropores (Germann and Bevan 1985).

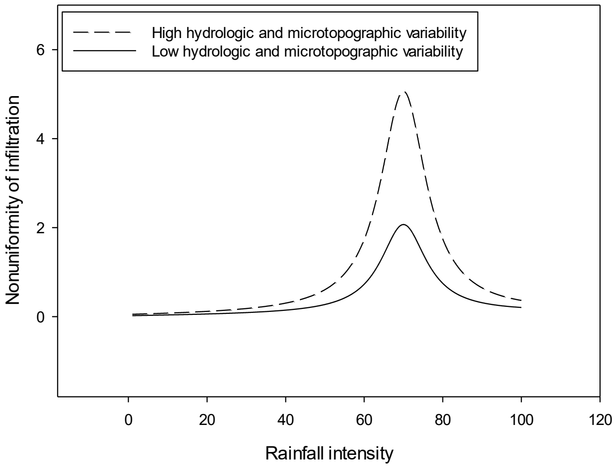

Figure 2. Hypothetical conceptual infiltration response in a HRU with rainfall intensity. The scales on both axes are arbitrary.

2.2. Drainage

Drainage from the HRU will also be affected by the nonuniformity of the response to rainfall. Since the depth of water infiltrated will be directly related to the integral with time of the infiltration rate the drainage will also vary in a similar manner to fig. 3. The drainage is usually described in models like SWAT and SOURCE from tipping bucket water balance models but these have been shown (Cook et al., 2023) to not be an accurate representation of the actual drainage process. A reconsideration of the HRU concept should result in how drainage is calculated.

2.3. Evapotranspiration

Evapotranspiration initially after wetting event results in a flux-controlled boundary condition reliant on the energy input into the soil/plant in contact with the atmosphere. For a bare soil the evaporation will continue at the potential rate until the transport of water to the soil surface is no longer able to keep up with this potential rate. The soil will then dry at the surface and the rate of evaporation will then depend on the rate of water transport to the soil surface. The evaporation rate (E_t (mm/hr)) can then be related to the desorptivity (D_e (mm/hr)) and the time period (t (hr)) of first stage evaporation by:

$$E_t = \frac{1}{2} D_e t^{1/2} \qquad [5]$$

This process also provides an opportunity to measure the nonuniformity in a HRU using remote sensing especially with drones, as the colour of the soil surface will change when the surface becomes dry. Haverkamp suggested this as a means of measuring soil variability in an address to the World Congress of Soils in 1998 in Montpellier, but this idea does not seem to have been taken up. This mapping of the soil drying could be used to determine where to target soil physical measurements to provide an understanding of the variability. The desorptivity can then be used to scale the soil physical properties as well and may provide a means to limit the amount of soil physical measurements required to provide adequate information (see Lockington et al., 1994).

When a crop is present the depending on the leaf area index and especially in forests the surface will not be visible with remote sensing. However, as Haverkamp suggested it would be possible to look at the variation in evapotranspiration rate from the response of the vegetation to the variation in the water status of the soil. Again, remote sensing with drones or satellites using NDVI or infrared (surfaces with reduced evaporation will be hotter) could be used to determine nonuniformity. The complication may be with disease within the crop but if the study occurred over a number of seasons, it may be possible to reduce any errors caused by disease.

3. DISCUSSION

Runoff will fit the present HRU model well but for the wrong reasons. This is because as rainfall intensity increases the initially the localised runoff will be contained by the microtopography. As the intensity increases an increasing amount of the microtopography will be overwhelmed and an increase area will be generating runoff. Thus, we would expect a uniform runoff response from the HRU to rainfall intensity, which is generally found Jakeman and Hornberger (1993). However, if the runoff response is used to calibrate the hydrologic model this could result in the values assign to hydrologic parameters being incorrect and not good for modelling of other hydrologic processes in the HRU. Jakeman and Hornberger (1993) found a linear response between rainfall and runoff at scales down to a few hundred metre squared. However, this does not mean that the runoff process is uniform. For instance, the baseflow will be a convolution of the non-uniform drainage across the catchment area.

The result of nonuniformity in infiltration process combined with soil variability in soil water storage properties will result in nonuniformity in the water content. Huisman et al. (2002) found for a 60 x 60 m field that the variability in soil water content measured by TDR and ground penetrating radar was random beyond a lag of approximately 8 m and had a COV of 50% after irrigation. Sayde et al. (2014) used optic fibre cables to determine the variability of water content and water fluxes along 240 m lengths at three different depths. They concluded that Cosmic-Ray probes and remote sensing might provide average values but do not capture the finer scale detail which are important in irrigated agriculture and natural systems such as preferential flows and contaminant transport.

We are not advocating a case for full distributed models as these are hugely computationally intensive and not possible to parameterise. What we are advocating is a detailed examination of the interaction between microtopography and soil properties from which we should be able to define some emergent properties for the HRU. These emergent properties could then be incorporated into semi-distributed catchment models.

4. CONCLUSION: IMPLICATIONS FOR HYDROLOGIC AND WATER QUALITY MODELS

The concept proposed here for the non-uniformity of the response of HRUs to water fluxes has implications not only for hydrologic models but more so for water quality models (Lucas et al. 2025). Because of the interplay of the water fluxes with the microtopography the use of single lumped bucket or one-dimensional soil water models to represent the response hydrologic response is unlikely to be successful. These models will need to be coupled with a response function that considers the nonuniformity and flux strength such as proposed in Fig. 1.

For water quality the inability to use single lumped bucket or one-dimensional soil water models will only get worse as solutes are transported mainly by advection and there will be a wide range of soil water velocities across the HRU. This means that there is a need to reconsider how hydrologic processes are represented at the HRU scale. This is a large challenge but also an opportunity for scientists working in soil, topographic, hydrologic and remote sensing to develop new tools to represent hydrologic processes at this scale.

Combining measurements at the HRU scale with remote sensing with larger spatial discrimination footprints and methods like Cosmic-Ray neutron probe measurements should allow for a better understanding of how to scale up these dynamic spatial processes to the HRU scale.

The incorporation of spatial dynamics into HRUs will require modelling approaches to do this and some that should be considered are:

- **Convolution integrals:** treating the HRU response as the convolution of many small-scale responses. For instance, the runoff hydrograph of an HRU could be modeled as the integral of contributions from a distribution of travel times or infiltration capacities.
- **Summation methods:** explicitly summing sub-area responses. An HRU might be divided conceptually into percentile bands (e.g., 0–20% most permeable, etc.), and the model tracks each band's soil moisture and runoff, summing them for output.
- **Ensemble or Monte Carlo methods:** running a bundle of replicates for each HRU (each with different parameter realizations sampled from known distributions) and averaging the results. This can statistically approximate heterogeneity effects.
- **Artificial Intelligence (AI) or machine learning models:** using data-driven models to learn the relationship between forcing and HRU aggregate response from synthetic training data. Caution is needed to ensure they remain realistic and interpretable (hence "with limits"), but AI could efficiently encode complex interactions that are hard to capture with more traditional approaches.

These and other approaches represent promising avenues to eliminate the "missing link" in hydrology—i.e., to finally have robust, simulation-ready representations of intermediate-scale processes. Efforts are already underway in the community to improve model structures. In conclusion, embracing the inherent non-uniformity of HRUs and integrating it into simulation models will enhance our predictive capability for both hydrology and water quality. It will enable models to respond to changes in climate or land use with greater realism, since they will capture not just average behavior but the breadth of possible responses. Filling this niche in model hierarchy will connect detailed process understanding at the plot scale with the practical needs of catchment-scale simulation, ensuring that we no longer have a "missing link" in our hydrological toolbox.

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