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Using numerical modelling to evaluate the capillary fringe groundwater ridging hypothesis of streamflow generation

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Abstract

The controls on pre-event water contributions to streamflow are still poorly understood, despite a number of proposed processes. One of the most common is the capillary fringe induced groundwater ridging mechanism, identified in many environments as a control on rapid mobilization of groundwater into the channel during events. Nevertheless, despite widespread acceptance, there is little evidence for such a phenomenon outside of particular environments and test cases for which it has been quantified. We use a flow and transport modelling tool to test a number of hypotheses concerning the capillary-fringe groundwater ridging mechanism. The original Abdul and Gilham (Abdul, A.S., Gillham, R.W., 1989. Field studies of the effects of the capillary fringe on streamflow generation. Journal of Hydrology 112, 1–18) laboratory experiment (that is still regarded by those working in the field as the main proof-of-concept) is replicated numerically within a 2D finite element code. An indication of the 'spaces' of applicability of the process in the context of the laboratory experiment is determined (soil type, antecedent moisture, riparian volume, slope, rainfall intensity). We show that in only a limited number of cases, high proportions of pre-event water are sustained from this process.

Keywords: Hydrological processes; Numerical model; Capillary fringe; Groundwater ridging; Storm-runoff; Runoff sources

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1. Introduction

One of the lingering important issues in catchment hydrology is the 'rapid mobilization of old water'. As Kirchner (2003, p. 871) notes, in many small catchments, streamflow responds promptly to rainfall inputs, but fluctuations in passive tracers (such as water isotopes and, in seasalt-dominated catchments, chloride) are often strongly damped. This indicates that storm flow in these catchments is mostly 'old' pre-event water (Neal and Rosier, 1990; Sklash, 1990; Buttle, 1994; McDonnell, 2003). The question that recent commentaries have examined (Kirchner, 2003) is how do these catchments store water for weeks or months, but then release it in minutes or hours in response to rainfall inputs?

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Over the years, a variety of conceptual models have been invoked, to explain this paradox. One of the most widely cited is the capillary-fringe groundwater ridging hypothesis (Gillham, 1984), originally put forward by Sklash and Farvolden (1979) based on earlier hydrometric work by Ragan (1968). This hypothesis states that near the stream, if the tension saturated zone extends to the ground surface, only a small amount of water is needed to convert the system from unsaturated to saturated. This then steepens local hydraulic gradients and causes increased discharge of gravity-driven pre-event water to the channel. As Kirchner (2003) notes, the proposal of a conceptual model for prompt discharge of pre-event water is the easy part; the hard work lies in making such a model mechanistically plausible and quantitatively realistic. To date, this has not been achieved for the capillary fringe groundwater ridging hypothesis and its applicability remains unresolved.

In many areas the water table adjacent to the channel is near the surface. This is especially true of areas with gently sloping topography such as near-stream riparian zones (Fig. 1). The capillary fringe extends above the water table a distance that is inversely related to pore size, and so is larger for finer-textured soils. Water held under capillary tension is widely accepted as a potentially important stormflow source (Bazemore et al., 1994), and the capillary fringe is thought to play a role in the rapid formation of near stream groundwater ridges. Event water delivered to the surface of a catchment (by rainfall or snowmelt) is thought to displace the pre-event water, forcing it to the stream. Even a small amount of infiltrated water can rapidly change the negative capillary pressure head in the capillary fringe to a positive pressure head, thereby changing the water table gradient and forcing the pre-event water out. This eventuality can produce a very rapid rise in the near-stream water table, leading to seep zone formation (Pionke et al., 1988), where subsurface water is discharged to the land surface, which then drains to streams. The quantity of rainfall input into the subsurface may be significantly less than the contribution to the streamflow. A large rise in the water table close to the stream is a necessary condition for a substantial increase in the vertical outflow of groundwater (Rodhe, 1989; Calles, 1985).

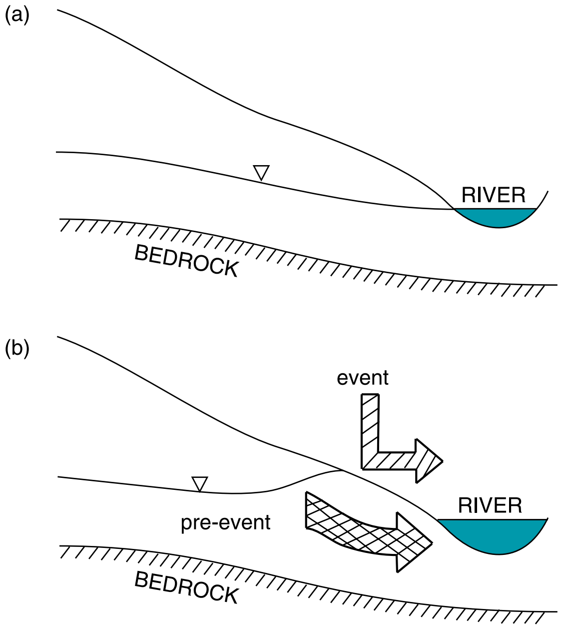


Fig. 1. The groundwater ridging mechanism of pre-event water discharge. Hypothesised water table profiles (a) prior to the event and (b) at peak runoff.

Sklash and Farvolden (1979) used isotopic and hydrometric studies to suggest the operation of groundwater ridging in catchments. In addition, they used simple model simulations to suggest the development of a groundwater ridge and pre-event water discharge. The groundwater ridging hypothesis has been cited for a number of projects to explain the hydrological, isotopic and hydrochemical responses of catchments (e.g. DeWalle et al., 1988; Pionke et al., 1988; Potter et al., 1988; Swistock et al., 1989; Bathurst and Cooley, 1996). The groundwater ridging mechanism has been observed and documented by Gillham (1984), Abdul and Gillham (1984, 1989), Novakowski and Gillham (1988), Blowes and Gillham (1988), Waddington et al. (1993), Jayatilaka and Gillham (1996), and Jayatilaka et al. (1996). They have demonstrated that this mechanism as a possibility in both laboratory and field studies (Gillham, 1984; Abdul and Gillham, 1984, 1989), and have used these results for 'hard-coding' the mechanism in a hydrological model (Jayatilaka and Gillham, 1996). Other studies have advocated the groundwater ridging mechanism (Pearce et al., 1986; Sklash et al., 1986), although McDonnell (1990) has proved these instances to be invalid upon closer inspection, as there was no evidence for a capillary fringe in the soil moisture release curve.

A particularly influential piece of research has been the laboratory experiments of Abdul and Gillham (1984). They used a plexiglass box packed with sloping sand in conjunction with tensiometers and a rainfall simulator, shown in Fig. 2. With the input of precipitation, hydraulic head and 'streamflow' were monitored, and it was concluded that groundwater ridging could occur under certain watertable positions. In their experiments Abdul and Gillham used sand obtained from the Perch Lake Basin of Atomic Energy Canada Ltd at Chalk River, Ontario. This was relatively uniform sand from an anthropogenically disturbed site and exhibited a 300 mm capillary fringe. This research and the subsequent field experiments by Gillham and colleagues, on sand similar to that found at Perch Lake (Abdul and Gillham, 1989; Novakowski and Gillham, 1988; Blowes and Gillham, 1988), have formed a backbone to the argument for the capillary fringe mechanism as a major generator of pre-event water. However, it should be noted that although no attempt was made by Gillham and colleagues to determine the limits of applicability of the capillary fringe mechanism, they did clearly state various cautions concerning generalization outside of the specific laboratory and field conditions that they tested.

The widespread applicability of the groundwater ridging mechanism remains uncertain (McDonnell, 1990; McDonnell and Buttle, 1998). Rapid pre-event contributions to stormflow can originate from a range of hydrological processes such as transmissivity feedback or macropore flow (McDonnell and Buttle, 1998). One conceptual paradox is that the capillary fringe height of a soil is usually inversely related to its hydraulic conductivity. Therefore, the greater the propensity for capillary fringe rise, the less likely that rapid Darcian flux of groundwater can occur even with steepened hydraulic gradients

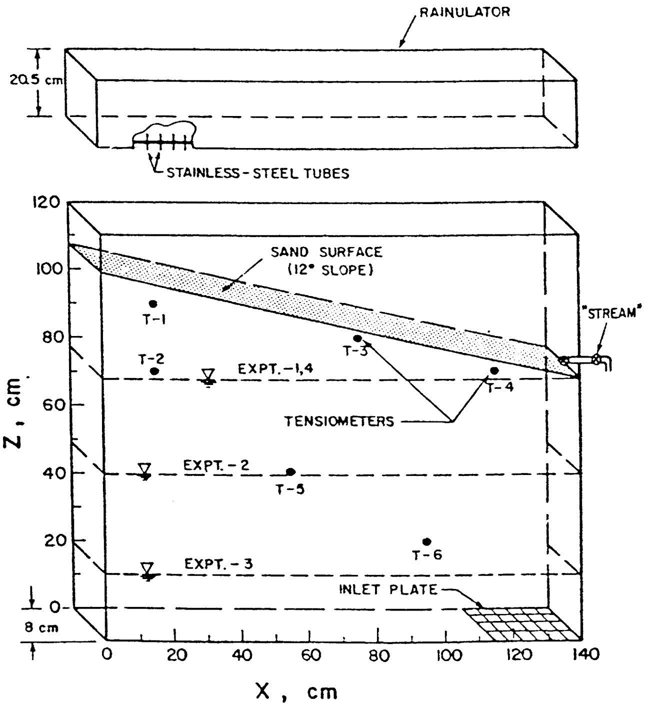


Fig. 2. Abdul and Gillham's Plexiglass Box (Abdul and Gillham, 1984).

in the near stream zone (Zaltsberg, 1986; McDonnell and Buttle, 1998).

In fact, Abdul and Gillham (1984) did note that a capillary fringe could affect runoff processes in two ways: (i) the rapidly rising water table that occurs when the capillary fringe extends to the ground surface causes increased hydraulic gradients in the groundwater zone, causing a rapid increase in the discharge of groundwater to the stream; (ii) the rapidly rising water table may result in free surface conditions at the ground surface, resulting in overland flow. The first results in high pre-event water contributions to streamflow; the second, high event contributions. Abdul and Gillham suggested that the relative importance of these processes would depend upon the rainfall intensity, the surface slope and the hydraulic conductivity of the soil. Thus the groundwater ridging mechanism would not be responsible for pre-event water discharge in all environments. Even when groundwater ridges do develop, there may be no associated discharge of pre-event water (Buttle and Sami, 1992). VanderKwaak and Sudicky (2000) carried out model simulations that suggested that while the low storage capacity of the capillary fringe is responsible for the rapid hydrological response and increased subsurface head gradients, they do not cause significant groundwater seepage. McDonnell and Buttle (1998) suggest that in most humid catchments the capillary fringe is not responsible for rapid streamflow. Further research is unquestionably required to determine the generality of the mechanism (Abdul and Gillham, 1984; Bonell, 1998).

There are three important components of the groundwater ridging mechanism: (i) rapid near-stream water table rise; (ii) rapid pre-event water mobilization to the stream; (iii) eventual dominance of overland flow over an increasing surface saturated contributing area. The appropriate rainfall characteristics, soil materials, slope morphology and angle will determine the magnitude and importance of this mechanism (Bonell, 1998). Table 1 gives a summary of evidence relating to the importance of groundwater ridging under different situations. The expense, time and difficulty of experimenting with different grain size types and conditions in the field and laboratory has precluded the testing of this mechanism. Hitherto, most research into groundwater ridging has been site specific and therefore has produced limited spatial and temporal understanding.

Hydrological models are useful hypothesis testing tools that enable us study combinations of conditions which have not yet been encountered in field studies or cannot be replicated on field scale (Gold and Kellogg, 1997; Johansson, 1985). They allow controlled experimentation and have powerful visualisation allowing us to 'see inside' hillslopes. However, one has to be cautious when using numerical models, because they suffer from a number of philosophical and practical problems. For example, they can only ever represent our current understanding of hydrological processes, and more usually only represent a subset of this understanding. Key debates regarding physically based models continue to revolve around model configuration (Cloke et al., 2003); acquisition of necessary input data (Seibert and McDonnell, 2002), effective parameterisation (Beven, 2000; Beven and Freer, 2001), model evaluation and calibration (Anderson and Bates, 2001), scale dependency (Blöschl and Sivapalan, 1995), equifinality (Beven, in press) and uncertainty estimation (Beven and Freer, 2001). We acknowledge that modelling studies can only ever act as a guide to reality and cannot make definite predictions. We therefore advocate further testing of the results presented in this paper, in the field, laboratory and with other modelling systems.

This paper applies a hydrological model to explicitly test the hypothesis of groundwater ridging in a range of riparian environments. The laboratory experiment of Abdul and Gillham (1984) is used as a platform for testing, with the positive presence of the groundwater ridging mechanism being determined by: (a) a high proportion of pre-event water in the stream channel and (b) pressure ridge development near the stream. Three specific questions are addressed:

(i) What is the relationship between capillary fringe height, water table response, and hydraulic conductivity in a hillslope–riparian context?
(ii) How important is riparian groundwater ridging to the displacement of pre-event water to the stream channel?
(iii) What are the areas, times and instances where groundwater ridging is an important process?

Table 1
Riparian characteristics and evidence for the groundwater ridging mechanism

Characteristic	Reference	Evidence	Spatial applicability
Soil texture	Abdul and Gillham (1989); Jayatilaka et al. (1996), Sklash and Farvolden (1979)	Observed groundwater ridging at field-sites with shallow sandy aquifers	*No consistency in terms of the requirement of sand-textured materials, but suggested is likely*
	Youngs et al. (1996)	Demonstrated the capillary-fringe effect for the specialized case of ponded infiltration from a circular pond into a silt loam overlying an artesian, very permeable substratum of sandy material	*Not in macroporous soils*
	Buttle and Sami (1992)	Found no evidence of old water displacement with groundwater ridging in a Canadian Shield forested catchment underlain by a sandy aquifer	
	Germann (1990)	Not in macroporous soils	
Slope	Abdul and Gillham (1989)	Demonstrated for a low relief area (4°–9°)	*Expected to dominate only on shallow slopes where capillary fringe reaches land surface*
	Bonell (1993), Bonell et al. (1998)	The ridging mechanism might be less significant on steeper slopes where the permanent water table is located at much greater depths from the stream edge	
Precipitation	Bonell et al. (1998), Elsenbeer et al. (1995), Elsenbeer and Lack (1996)	Environments with very high rain intensities, event water dominates and no groundwater ridging mechanism operates	Rainfall may be important but only for certain slopes and soils, i.e. is a secondary control
	Abdul and Gillham (1984)	Groundwater ridging occurs under a number of different rainfalls	
Vegetation	Abdul and Gillham (1989) and Sklash and Farvolden (1979)	Ridging mechanism occurs on grass covered hillslope	Vegetation may strongly influence the development of the groundwater ridging mechanism
	Buttle and Sami (1992)	No groundwater ridging occurs on forested slopes	

2. Model platform

The conceptual model used in this study uses the Richards equation for matrix flow. A discrete capillary fringe in a soil is then modelled with the use of the Brooks-Corey soil moisture algorithm. These two attributes of the conceptual model implicitly disregard any non-Darcian processes that are responsible for pre-event water discharge and/or pressure ridge development.

ESTEL-2D solves the Richards equation in saturated and unsaturated porous media with the finite element technique and simulates solute transport with the random walk particle method. It is capable of solving problems involving complex hillslope–riparian interactions (Claxton et al., 2003). The flow component of the model is described fully by Cloke (2003) and Renaud et al. (2003). Accordingly only an outline description is given here.

ESTEL-2D is developed on ‘current best practice’ as defined in recent literature on the numerical analysis of the Richards Equation. The ‘mixed’ form of the Richards equation is solved

$$\frac{\partial \theta}{\partial t} = \underline{\nabla}(\underline{\underline{K}}\,\underline{\nabla}(h+z)) + S \tag{1}$$

where t is the time (T); θ is the volumetric moisture content (L^3L^{-3}); h is the pressure head (L); K is the hydraulic conductivity tensor (LT^{-1}); z is the elevation (L) and S is a source term (T^{-1}) which can represent additional processes such as evapotranspiration. The model can also solve the *h*-based form of the Richards equation, however the mixed form has been used in the following cases because of its excellent mass conservation properties (Celia et al., 1990).

Initial conditions consist of a specification of the pressure head at each computational node. The boundary conditions for the system must be supplied at each boundary node as one of three types (Zauderer, 1983, pp. 167): imposed head (Dirichlet), imposed head gradient (Neumann) or both (Cauchy). Renaud et al. (2003) gives a full description of how these are implemented mathematically in ESTEL-2D, including the incorporation of a dynamic seepage face capability.

The above equation system is solved in time and space. The time discretization for the Richards equation is defined using the modified Picard iterative scheme based on a time discretization of the mixed form of the Richards equation (Celia et al., 1990). The finite element spatial discretization uses the Galerkin variational formulation on an unstructured mesh of triangular elements.

The Richards equation is solved to give the pressure head, from which values of hydraulic head, Darcian velocity and moisture content can subsequently be derived using additional relationships.

Overland flow is calculated using a one-dimensional finite difference approach, which was selected due to its simplicity to implement and its total mass conservation. The 1D overland flow module runs along the surface boundary of the finite element model and account for infiltration and seepage. Water is routed downslope using the Manning equation.

Solute transport is solved using the random walk particle method (RWPM) of Uffink (1988). The RWPM consists of representing a plume of solute by a cloud of particles which are displaced according to the following stochastic equation

$$X_i(t+\Delta t) = X_i(t) + \left(\upsilon_i + \frac{\partial D_{i,j}}{\partial x_j}\right)\Delta t + Z_i\sqrt{6D_i\,\Delta t} \tag{2}$$

where $X=(X_i)$ is the particle position, $\upsilon=(\upsilon_i)$ the water velocity, t the time, Δt the time step, $D=(Dij)$ the dispersion tensor and $Z=(Zj)$ a vector of two random numbers taken from a uniform distribution between 0 and 1. The indices i and j vary between 1 and 2 and refer respectively to the x and y components of the vectors and tensor.

The density of a cloud of particles displaced by the random walk equation obeys a modified form of the Itô–Fokker–Plank equation, equivalent to the governing advection–dispersion equation for solute transport in porous media. In ESTEL-2D, the unstructured mesh of triangles of the finite element analysis is also used to track the particles in the domain. Overshoot is completely avoided with the Conjugated Course algorithm of Cordes et al. (1991). The intersection of the particle's trajectory with the edges of the triangles is done in a local coordinate system to minimise rounding errors.

The particles can be used to calculate the proportion of pre-event water reaching the channel. Several hundred thousand particles are introduced into the model domain in order to represent either 'event' water (depending on the rainfall) or 'pre-event' water (depending on the moisture content). The particles are counted as they reach the stream channel and the proportion of pre-event water through time is calculated. The percentage of the runoff from a slope that is pre-event water falls into one of six 'Pre-Event Zones' (PEZs), depicted in Fig. 3. The maximum PEZ of the runoff from a slope during the initial part of a storm gives an indication of the dominant streamflow generation processes operating in the riparian area (high PEZ indicates subsurface discharge is the main contributor to storm runoff).

3. Configuration of the test case

Simulations of the Abdul and Gillham laboratory sand box experiment are used as a platform for testing the groundwater ridging mechanism. The Abdul and Gillham domain consists of an impermeable 'box' with a uniformly sloping infiltration/seepage boundary at 12° (see Fig. 2). This sloping surface, combined with the rising water table from the application of rainwater into the box, causes the rapid generation of hydraulic gradients directed towards the toe of the slope (i.e. the stream as defined by an outlet tap on the righthand side of the box). In this study, we replicate the Abdul and Gillham conditions numerically, using a mesh representing the plexiglass box with 7593 elements and 3915 nodes. A simulated rainfall flux is incident on the top of the domain. Six virtual 'tensiometers', labelled

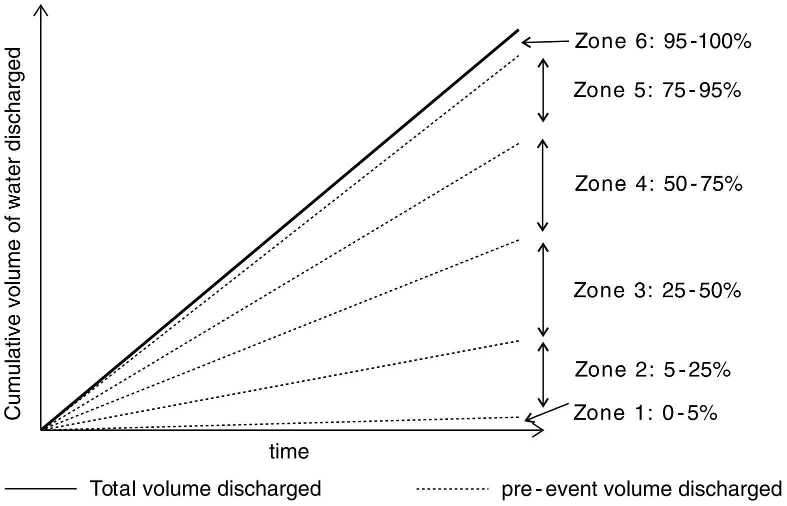


Fig. 3. Zones of pre-event water proportions (PEZs) in a cumulative volumetric discharge hydrograph (rising limb only).

T-1 to T-6 in Fig. 2, allow us to monitor (in a virtual sense), changes in the hydraulic head as rainfall is applied. Initial conditions are at equilibrium with a zero pressure head at a specified elevation.

4. Results

4.1. Preliminary model simulations

Small element sizes are often required for non-linear problems of infiltration (Vogel et al., 2001). An optimal mesh density, balancing computer run time and accuracy of the solution was found to be 0.02 m. Two initial water table heights (0.20 and 0.75 m) were simulated to verify that the code could converge to a solution with varying initial conditions. Table 2 gives the numerical setup parameters used for simulations in this investigation. An adaptive timestepping routine is used in the ESTEL-2D model code which automatically adjusts the time step to optimise both the computational time required and the precision of the solution. The maximum timestep used in this case was 1 s and the minimum was 2×10^{-3} s.

Preliminary simulations produced realistic steady-state results, with a seepage face developing over half of the top boundary, identical to the pattern found by Abdul and Gillham in the laboratory (Fig. 4a and b). In order to effectively model the Abdul and Gillham case, the representation of the soil moisture was carried out with the Brooks Corey (BC) algorithm (1964). Alternative algorithms such as the Millington and Quirk (1961) and van Genuchten (1980) did not yield numerical convergence for the Sand soil parameters suggested by the curves presented by Abdul and Gillham in their 1984 paper. The BC algorithm includes an explicit representation of the air entry (bubbling) pressure, but this has implications for the simulated near saturation behaviour of the soil, i.e. we

Table 2
Numerical setup parameters used for simulations

Numerical parameter	Description of setup
Timestepping strategy	Adaptive (multiplication/division step = 1.5)
Accuracy of the iterative scheme for the pressure head	1.0×10^{-8}
Accuracy of the iterative scheme for the moisture content	1.0×10^{-6}
Convergence criterion	Variable depending on saturation
	For the unsaturated zone (Huang et al., 1996)
	For the saturated zone (standard relative criterion)
Implicitation	0.55

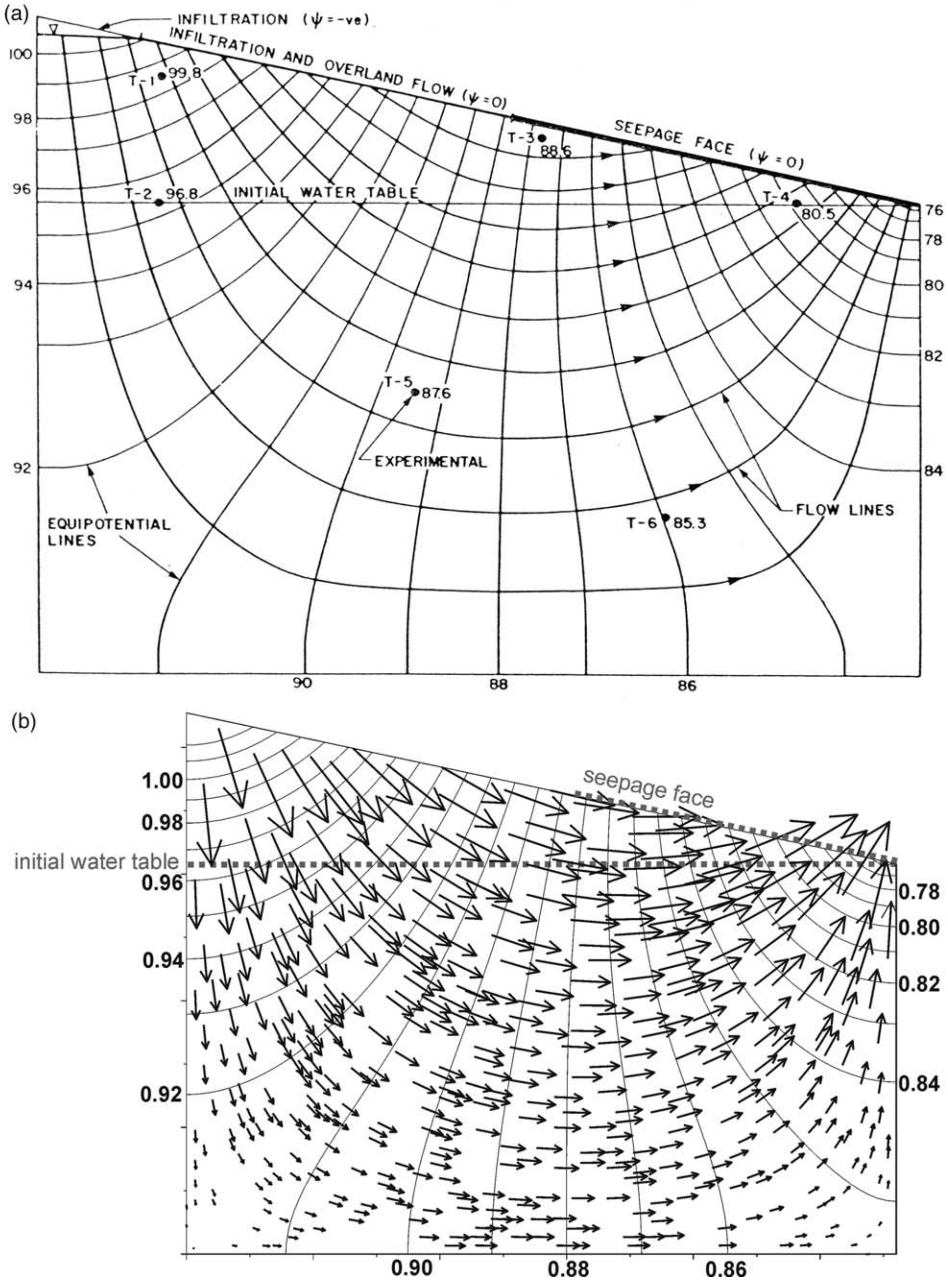


Fig. 4. Simulated steady state hydraulic flow net. (a) Abdul and Gillham (1984), hydraulic head isolines in centimetres; (b) ESTEL, hydraulic head isolines in meter.

are imposing an explicit capillary fringe and there is an instantaneous 'jump' in the water table at the air entry suction. For the preliminary simulations the BC algorithm has an air entry parameter value of 0.34 m, and there is no storage above the water table because the capillary fringe intersects the entire surface. Therefore, all simulated tensiometers respond instantaneously.

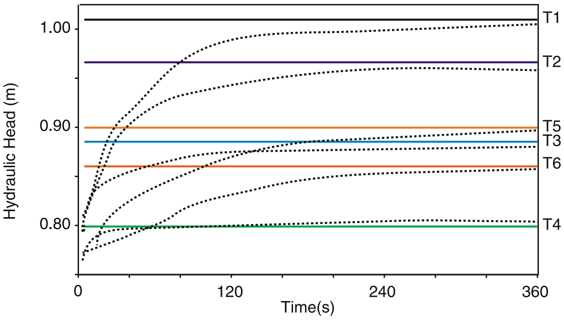


Fig. 5. Comparison of hydraulic head response of the six tensiometers: measured by Abdul and Gillham (dashed lines) and simulated by ESTEL (solid lines).

Fig. 5 shows a comparison of the modelled tensiometer response and the measured response from Abdul and Gillham's laboratory experiment. The Abdul and Gillham measurements are at a low temporal resolution for the rapid response period at the beginning of the experiment, and so little detailed comparison between measured and simulated response is possible. However, the overall pattern of response timings and magnitude indicates that the ESTEL-2D simulation is capturing the dynamics of the system being modelled. Abdul and Gillham suggest that the system approaches a new equilibrium after approximately 3 min. The simulated ESTEL-2D results suggest a near-instantaneous move to equilibrium because of the hard-coded air entry value in the soil moisture release curve used for simulations (BC algorithm). Abdul and Gillham attributed the delayed response to entrapped air bubbles in the soil matrix. Our modelling approach does not take account of the effects of air bubbles, and our model is thus only applicable when there is an existing unsaturated zone at the beginning of the simulation.

Following these preliminary simulations, Section 4.2 examines the process of groundwater ridging based on the Abdul and Gillham experiment.

4.2. Groundwater ridging

A set of numerical experiments were undertaken to (i) demonstrate that our model can replicate the groundwater ridging mechanism identified by Abdul and Gillham (1984) in their laboratory experiment, and (ii) use the numerical model within the constraints of the setup of the Abdul and Gillham Box (that is still regarded by those working in the field as the main proof-of-concept) to see how pre-event water is discharged *because* of the presence of the groundwater ridge. A water table height corresponding to 'expt 2' in Fig. 2 is used for these experiments. This is 27 cm below the top right-hand corner of the domain and corresponds to $y=0.5$ m from the base of the domain. This water table is lower than that used for the preliminary simulation to ensure that a portion of the domain is initially 'unsaturated', that is, without tension saturation. Our modelling approach is unable to simulate a higher water table, as it does not take account of the presence of air bubbles (see previous section). With a continuous incident rainfall the domain takes approximately 16 min (960 s) to fully saturate, T-4 being the first to respond and T-1 being the last. This is in good agreement with the findings of Abdul and Gillham (1984). The consequential development of a ridge in the pressure head and the Darcian velocity vectors can be clearly seen in Fig. 6. This figure shows the period of saturation, from 0 to 20 min, and the development of a groundwater pressure ridge (water table ridge). The Darcian velocity vectors can be seen to move away from the channel to fill the area of storage on the left of the domain. From the patterns of these velocity vectors, it is clear that there can be no discharge of pre-event water at the start of the simulation, as the hydraulic gradient (and therefore velocity) is directing the pre-event water away from the surface so that it fills the storage on the left of the domain. Although a ridge in the pressure forms, no discharge of pre-event water is associated with it. Pre-event water discharge begins at approximately 12 min (720 s) when the surface pressure head equals zero in the top right hand corner of the domain and the velocity is redirected to the outflow at this point. At a time of 12 min the ridge is fully formed and at a time of 20 min all storage is filled and the ridge has disappeared.

Fig. 7 shows the response of the discharge of pre-event water to the stream. The percentage of pre-event water in the discharge from the base of the slope was calculated at points in time. From Fig. 7, it can be seen that the response is not an immediate one and that the peak in the pre-event water discharge to the stream occurs between 900 and 3000 s (15 and 50 min). The maximum percentage of pre-event water only reaches ~8% in this case (which only just extends into

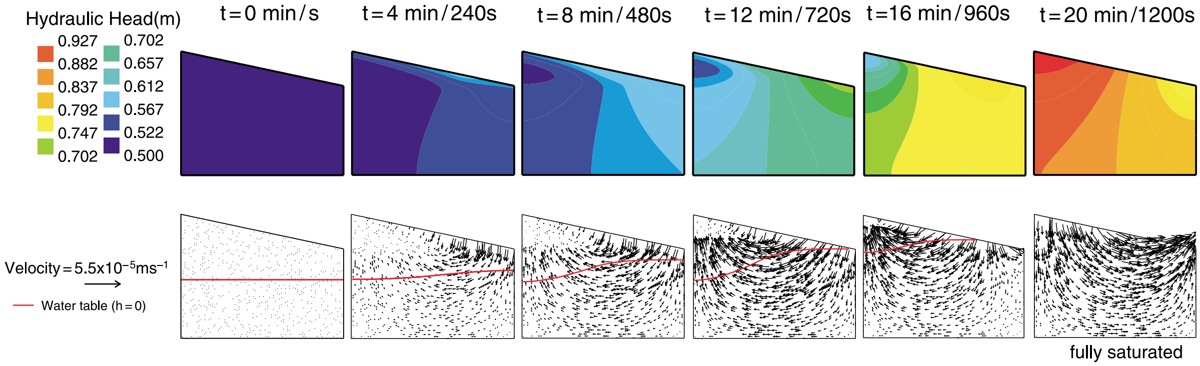


Fig. 6. The development of a groundwater ridge in the Abdul and Gillham domain.

PEZ 2) and the maximum value follows the complete saturation of the domain. The pre-event water forms a very small component of discharge before this time. After the peak, the percentage of pre-event water seems to retain an equilibrium value of approximately 2%.

From the results presented in the section above, it is apparent that the relationship between groundwater ridging and pre-event water displacement is not as obvious as the hypothesis has been taken to suggest. The consequent conditions for the groundwater ridging mechanism to operate are: the formation of a groundwater pressure ridge and a coincidental dominance of pre-event water in the discharge from the toe of the slope. In the above case, this was not how the groundwater ridge operated. Certainly, a rise in the water table is apparent in the Abdul and Gillham box as infiltrating water reaches the water table first on the right-hand side of the domain, causing a rapid change in pressure. There is also discharge of pre-event water from the riparian zone in this case. This manifests itself initially as a PEZ 2 or 3 discharge (depending on water table height). However, the percentage varies greatly with the timescale of observation (Fig. 7), and is not as large as has been found in field studies of groundwater ridging. For example, Sklash and Farvolden (1979) found values in the range of 60–80% or PEZ 4–5. The Abdul and Gillham case *does* explain rapid water table rise near to the stream. As a result of the particularly low storage capacity that exists when the zone of tension saturation extends to the soil surface, the application of water results in a rapidly rising water table as suggested by data in Ragan (1968) and theoretical arguments in Sklash and Farvolden (1979).

A groundwater ridge is usually considered as a rise in the water table (often to the surface) adjacent to the stream, however variations in this simplified behaviour are apparent. We suggest that the replicated Abdul and Gillham experiment shows particular phases in the development of the groundwater ridge, and a schematic of this process is shown in Fig. 8. The rapid rise in water table near the stream results in a strong reversed hydraulic gradient from the near-stream zone back into the hillslope. As the storage is filled and the groundwater ridge extends upslope, the ridge flattens (and with it the reversed hydraulic gradient) and a short-lived transitional phase is reached where a small hydraulic gradient from the hillslope to the stream occurs next to, and is able to compete with, the reversed gradient. Finally all storage is filled and the normal hillslope–stream gradient is found to occur. The transitional phase can be identified in the results presented in Fig. 6. At this point in time, some of the event water still infiltrates into the domain and thus

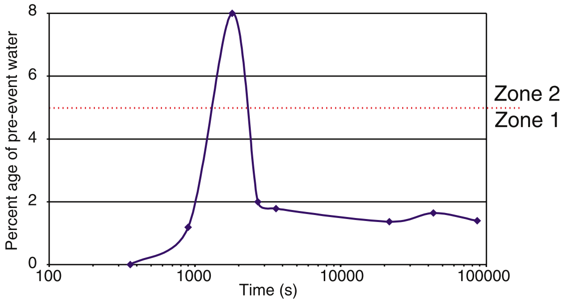


Fig. 7. Graph to show the change in the proportion of pre-event water (in the volume discharged at the stream) through time, for the Abdul and Gillham Sand and an initial water table height of 0.5 m.

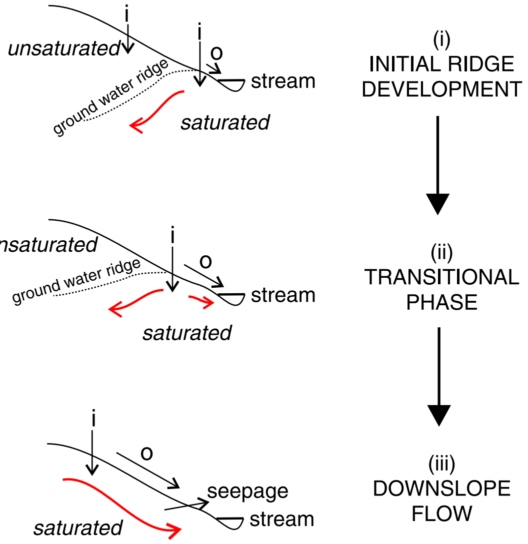


Fig. 8. Illustration of the three phases of the Abdul and Gillham (1984) ‘hillslope’ responding to infiltration. Phase (i): initial development of a pressure ridge; phase (ii): the transitional phase, when a groundwater ridge may lead to a high proportion of pre-event water in discharge to the stream; phase (iii): when a downslope flow hydraulic gradient exists. Unmarked arrows are the hydraulic gradients. i: infiltration; o: overland flow (here saturation overland flow).

does not contribute to overland flow. At the same time, pre-event water can be discharged to the stream channel, and this results in pre-event water forming a large proportion of the discharge. If the transitional phase coincides with the early part (seconds–minutes) of the simulation, then much of the overland flow that has been generated will not necessarily have reached the stream and this could make the proportion of pre-event water discharged to the stream even higher. This transitional phase could be much longer than observed in this experiment, if the riparian zone extends a long way from the stream.

In most cases, there is not an immediate response in the discharge to the application of rainfall as the groundwater ridging hypothesis suggests; there is a delay in the response (the delay is the time taken to reach the transitional stage from the initial ridge development stage). From the initial results presented here, it is suggested that this delay is connected to the height of the initial water table amongst other riparian characteristics. If the hydraulic gradient into the hillslope is strong and the groundwater ridge is in its initial development stage (very near the stream) then no near-stream normal gradient develops and hence no pre-event discharge occurs. From the cases presented above the timescale of the transitional phase is very short, and thus it can seem that pre-event water reaches the stream channel only once saturation of the domain has been completed and the reversed hydraulic gradient has disappeared.

It can thus be concluded from the initial simulated results presented here that groundwater ridging may occur in the same cases as pre-event water displacement, but it is not possible to cite it as the cause of this displacement (assuming that the hypothesis of groundwater ridging applies and thus the conceptual model used here is representative). The proportions of pre-event water measured here are not sufficiently high (i.e. less than 50%) to be significant; they do not exhibit levels high enough to explain field observations of pre-event water discharge.

It is important to note that the Abdul and Gillham case is a very particular one and these initial results and conclusions may not be extendable to other riparian dimensions and characteristics.

4.3. Pre-event water delivery in riparian zones with differing characteristics

The previous section has shown that a numerical model based on Richards equation can demonstrate the formation of a groundwater ridge in specific conditions. Within these specific conditions only a low proportion of pre-event water contributed to discharge to the stream. We now carry out a set of numerical simulations to look for evidence of the groundwater ridging mechanism in other conditions. It should be noted that these simulations are only an extension of the original Abdul and Gillham experiment, and thus can only be a first-step towards generalization. These experiments should therefore not be interpreted to represent the whole range of conditions found in nature. While still based on the original laboratory experiment, the riparian zone permutations are summarized in Table 3 and Fig. 9. Two values of initial water table depth were considered: deep (approximately 75% of slope depth from surface) and near-surface (approximately, 10% of slope depth from surface). Ideally simulations with the water table at the surface should also have been carried out, however as

Table 3
The variables and their associated values to be used in the multivariable analysis

Variable	Description of values tested in this analysis		
Initial water table depth (IWT)	L	Deep (approximately 75% of slope depth from surface)	
	H	Near-surface (approximately 10% of slope depth from surface)	
Rainfall intensity	L	1×10^{-8} ms^{-1} (0.036 mm h^{-1})	
	M	1×10^{-6} ms^{-1} (3.6 mm h^{-1})	
	H	1×10^{-4} ms^{-1} (360 mm h^{-1})	
Slope of riparian zone	L	4°	
	M	12°	
	H	36°	
Saturated hydraulic conductivity (K_s)	L	1×10^{-8} ms^{-1} (0.036 mm h^{-1})	
	M	1×10^{-6} ms^{-1} (3.6 mm h^{-1})	
	H	1×10^{-4} ms^{-1} (360 mm h^{-1})	
Capillary fringe height[a]	Low K_s	*Medium* K_s	*High* K_s
	L: 0.472 m	L: 0.051 m	L: 0.002 m
	M: 3.4 m	M: 0.389 m	M: 0.07 m
	H: 17.451 m	H: 2.039 m	H: 0.317 m
Volume of riparian zone[b]	L	Proportions of the Abdul and Gillham experiment	
	H	As for low volume but with × value multiplied by three	

L: 'low'; M: 'medium' and H: 'high'.

[a] Taken from information provided in Meyer et al. (1997).

[b] Volume in a two-dimensional case refers to area × 1 m.

noted previously, our modelling is unable to represent the dynamics of this case if the domain is completely saturated. This limits the scope of the applicability of this experiment, as in humid regions, for example, the initial water table may indeed be at the toe of the slope (at the stream surface). Soil parameters were taken from Meyer et al. (1997), and these and rainfall and slope parameters were varied to cover a range of typical hillslope values. Finally, as a first step to understand the influence of volume of the riparian zone on the mechanism, we varied the Abdul and Gillham domain volume by a factor of 3. It should be noted that it would be premature to extend the results of this study to natural hillslopes, where the volume may be much larger than those tested in this research.

The time taken to reach saturation reflects the end point of the transitional stage in the groundwater ridging. This point determines when the pre-event water component will reduce in significance and overland event flow will become dominant in the discharge. In all cases, the simulated transitional stage was found to be short i.e. saturation was reached just a short time after the development of the maximum reversed hydraulic gradient. The highest PEZs coincided with the transitional stage in each simulation, however, percentage values were all lower than many field recorded values (e.g. Pearce et al., 1986: 97%; Sklash, 1990: 75–85%; Sklash and Farvolden, 1979: 60–80%).

In the following sections, *phase* refers to the processes of groundwater ridging identified in Fig. 8,

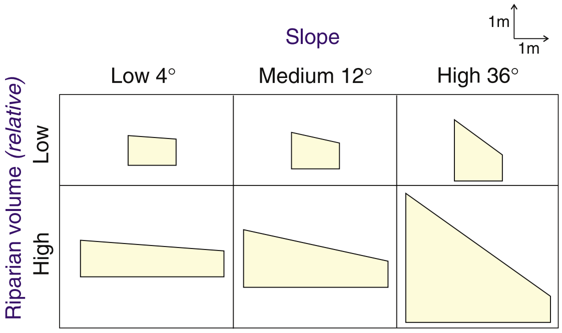
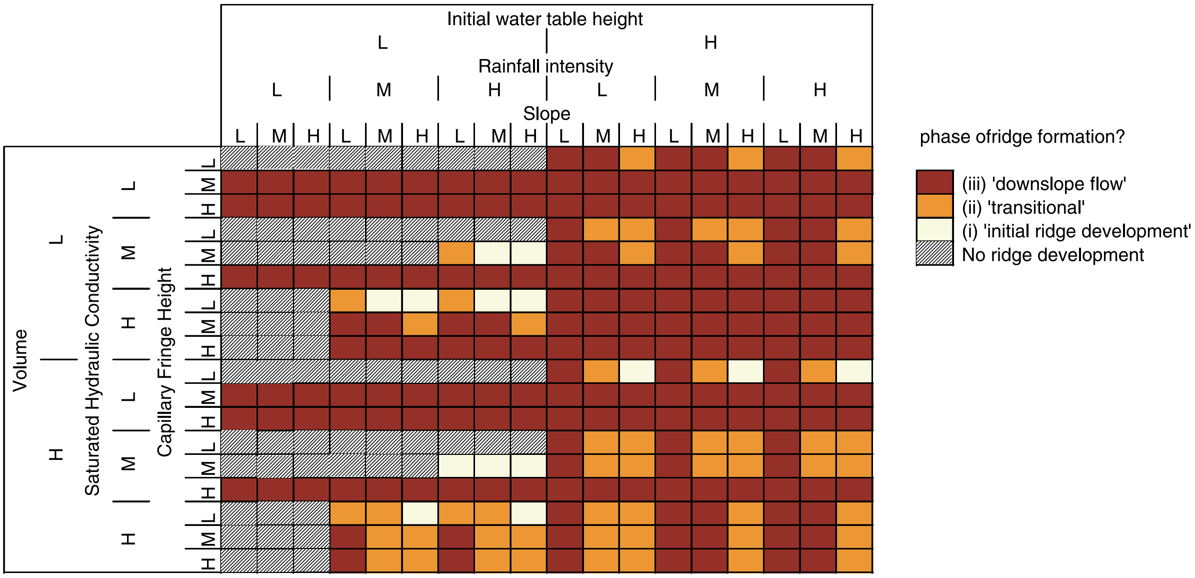


Fig. 9. The domains used in the multivariate analysis. High volume domains are three times the length of low volume domains. Volume = area × 1 m.



		Initial water table height	L									H								
		Rainfall intensity	L			M			H			L			M			H		
		Slope	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Volume	Saturated Hydraulic Conductivity	Capillary Fringe Height																		
L	L	L	▨	▨	▨	▨	▨	▨	▨	▨	▨	🟥	🟥	🟧	🟥	🟥	🟧	🟥	🟥	🟧
		M	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		H	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	M	L	▨	▨	▨	▨	▨	▨	▨	▨	▨	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟥	🟧
		M	▨	▨	▨	▨	▨	▨	🟧	⬜	⬜	🟥	🟥	🟧	🟥	🟥	🟧	🟥	🟥	🟧
		H	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	H	L	▨	▨	▨	🟧	⬜	⬜	🟧	⬜	⬜	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		M	▨	▨	▨	🟥	🟥	🟧	🟥	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		H	▨	▨	▨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
H	L	L	▨	▨	▨	▨	▨	▨	▨	▨	▨	🟥	🟧	⬜	🟥	🟧	⬜	🟥	🟧	⬜
		M	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		H	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	M	L	▨	▨	▨	▨	▨	▨	▨	▨	▨	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟧	🟧
		M	▨	▨	▨	▨	▨	▨	⬜	⬜	⬜	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟧	🟧
		H	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	H	L	▨	▨	▨	🟧	🟧	⬜	🟧	🟧	⬜	🟥	🟧	🟧	🟥	🟥	🟧	🟥	🟥	🟧
		M	▨	▨	▨	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟥	🟧	🟥	🟥	🟧
		H	▨	▨	▨	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟧	🟧	🟥	🟥	🟧	🟥	🟥	🟧

phase ofridge formation?

🟥 (iii) 'downslope flow'
🟧 (ii) 'transitional'
⬜ (i) 'initial ridge development'
▨ No ridge development

Fig. 10. A matrix of riparian characteristics and the presence or absence of a groundwater pressure ridge for a continuous rainfall simulation of a 24 h event.

and *PEZ* refers to a categorization of the percentage of pre-event water as identified in Fig. 3. The results of the set of simulations with varying characteristics (the matrix testing) are given in Figs. 10 and 11. Four points are immediately apparent:

(i) The patterns of ridge development are similar in places but generally do not coincide with the patterns of maximum PEZ. The presence of a ridge is not therefore the only determinant of the maximum PEZ value reached.
(ii) A groundwater pressure ridge is formed in the majority of simulations with the exception of low initial water tables.
(iii) Many of the simulations only result in a PEZ level of 1 (pre-event water is insignificant in the discharge throughout the simulation). This is the case even when a groundwater ridge is present, and is especially true for low rainfalls and low hydraulic conductivities (K_s).
(iv) No simulations reached a PEZ level of 6, which means that event water always reached the stream channel and played some part in the discharge.

4.4. The development of a groundwater pressure ridge

The interrelationships between the different riparian characteristics and the presence of a ridge are complicated, but are summarised here, based on the results presented in Fig. 10. If the *capillary fringe* extends to the ground surface, either because the pre-storm water table is high or the soil type is fine-grained, groundwater ridging occurs (to some degree). If the capillary fringe reaches the surface for the whole of the top boundary, when rainfall is added, the system instantaneously becomes a phase (iii) groundwater ridge. Riparian zones with low *water tables* are less likely to experience groundwater ridging, unless the capillary fringe extends to the ground surface. The *rainfall intensity* is important only where the capillary fringe does not reach the ground surface and the K_s is high enough to have rainfall-limited infiltration. Lower *slopes* encourage a rise in ridge phase, but have no other effect on the presence/absence of ridging (as would be expected as the water table position is defined from the bottom of the slope, and thus is the same for all slope gradients). In a similar way, an increase in *volume* tends to a decrease in phase. The development of a positive ridge is dependent on *soil type*: coarse grained

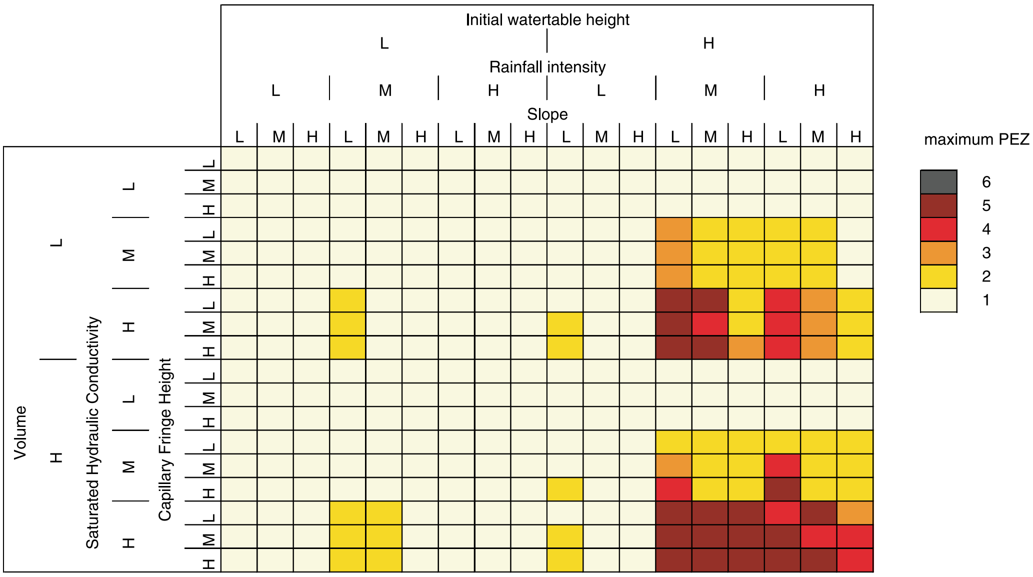


Fig. 11. A matrix of riparian characteristics and the maximum PEZ reached for a continuous rainfall simulation of a 24 h event.

soils are more likely to form ridges than medium grained soils because of the increased infiltration capacity (higher K_s). Fine grained soils are more likely to form ridges than medium and coarse grained soils, because the capillary fringe is larger and more likely to reach the ground surface. The characteristics of water table height, capillary fringe size, rainfall intensity and K_s have the potential to impede the development of a groundwater ridge, as well as changing the phase of development reached in 24 h.

4.5. The maximum PEZ reached

The following is based on the results presented in Fig. 11. The initial *water table* height is a strong control on the maximum PEZ reached. With a low initial water table, for many simulations the water table does not respond within the timescale of the simulation. The *rainfall intensity* controls both the initial ridge development but more importantly the strength of the signature of the pre-event water in the discharge. For low rainfall intensities ($0.036\ \mathrm{mm\,h^{-1}}$), the PEZ is low, which suggests that even with ridge development, the rainfall is limiting further infiltration and thus phase increase. The high rainfall intensity ($360\ \mathrm{mm\,h^{-1}}$) is the value used in the numerical experiments in the preliminary simulations, and the PEZ is low for the majority of simulations because the large event water component that becomes saturation overland flow, masks the pre-event component and dominates the discharge. A medium rainfall ($3.6\ \mathrm{mm\,h^{-1}}$) is high enough to allow phase increase of the groundwater ridge, and low enough to mean that the pre-event discharge can form a significant proportion of discharge as the event component is lower. This is therefore a very sensitive variable and is a major control on PEZ. The lowest *slopes* have the largest PEZ, but this pattern is dominated by other characteristics. Lower slopes have less storage capacity to be filled and have a lower overland flow velocity, and thus have the largest maximum PEZ. Perhaps surprisingly, *volume* does not have a large influence on the PEZ reached. K_s is a controlling variable of the maximum PEZ levels for a simulation. The high K_s values result in high PEZ and low K_s values result in low PEZ. This is most clearly demonstrated in the riparian spaces with a high water table. A high K_s controls ridge development through infiltration, and also discharge capacity. The *capillary fringe* was seen to be a controlling factor in ridge development. However, it has little effect on PEZ values.

For the simulations performed, the transitional phase can be positively linked with a slope's ability to discharge pre-event water. Therefore, variables that lead to high PEZ levels will tend to be those that have a long transitional phase.

5. Discussion

5.1. The areas, times and instances where the groundwater ridging hypothesis applies

The previous simulation results have revealed several important points related to pre-event water discharge:

1. All the characteristics selected do affect ridge development and PEZ values in some way. The sensitivity rankings for these characteristics are shown in Table 4. The sensitivity of the PEZ to the characteristics is different from the sensitivity of ridge development. For example, the initial water table height has the greatest affect on the processes operating. Only wet antecedent conditions will lead to groundwater ridge development and pre-event water discharge dominating. Saturated hydraulic conductivity is also a controlling factor on both the groundwater ridge development and the PEZ. The capillary fringe is a controlling factor of groundwater ridge development but the PEZ levels are not sensitive to this characteristic.
2. High maximum PEZ levels were not related to the presence of the groundwater ridge. Instead the correlation was with the length of the phase (ii) transitional phase when hydraulic gradients act both towards and away from the stream. In this phase, the seepage zone is small and infiltration of event water is high, therefore pre-event water is able to dominate the discharge.
3. In nearly all simulated riparian spaces, high PEZ levels were not sustained and were lower than those found in field studies. PEZ levels are affected by the development of the transitional phase of groundwater ridge development. However, in order to explain the discrepancies between field and simulated values, there must be other processes of pre-event water discharge operating or the hypothetical simulations cannot replicate field scenarios (geometrical effects, etc.).

Table 4
Rank of the riparian characteristics which most affect the maximum PEZ levels reached in simulations of 24 h continuous rainfall event

Characteristic	PEZ rank	Ridge development rank
Initial water table height	1 max	1 max
Saturated hydraulic conductivity	2 max	3 max
Rainfall intensity	3 medium	5 max
Riparian volume	4 max	6 max
Slope	5 min	4 min
Capillary fringe height	6 max	2 max

1 (large effect) to 6 (small effect). max/min: maximum/minimum (and medium for rainfall intensity) value of parameter leads to highest PEZ/fastest ridge development.

The groundwater ridging hypothesis, as modelled here, cannot account for the high levels of sustained PEZ seen in field studies. Higher PEZ levels coincide with a long transitional phase of ridge development. The matrix of riparian characteristics have been retested to include the process of transmissivity feedback in the soil characteristics (exponential decline in hydraulic conductivity with depth). A comparison of Figs. 11 and 12 shows that the addition of transmissivity feedback has little effect on the maximum PEZ levels reached. The characteristics that lead to high PEZ levels are thus also those applicable in transmissivity feedback environments, where K_s decreases rapidly with increasing soil depth. This is because any decline in conductivity with depth leads to a slowing of the pre-event water. So although there is less storage at depth (and therefore rapid water table rise), less discharge is enabled. In these hypothetical simulations, the transmissivity feedback hypothesis does not produce high levels of PEZ.

5.2. What is the relationship between capillary fringe, water table response, and hydraulic conductivity?

Riparian zones are complicated hydrological systems, that are site specific and our knowledge of the riparian spectrum remains incomplete. A great deal

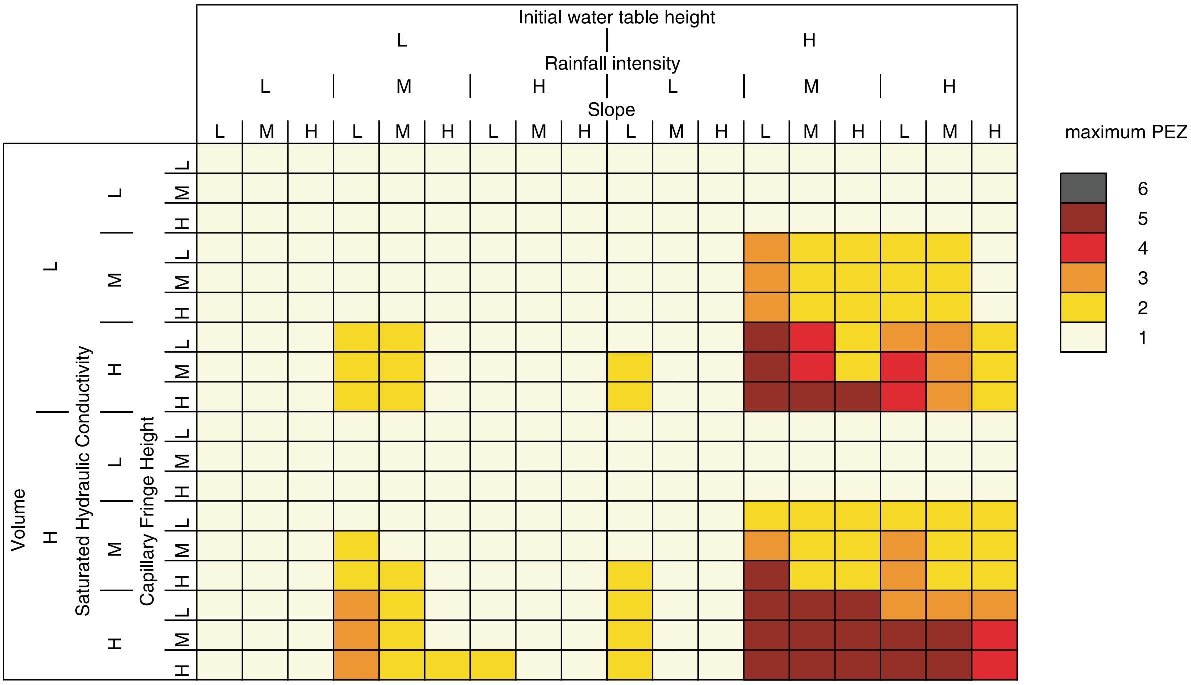


Fig. 12. A matrix of riparian characteristics and the maximum PEZ reached for a simulation of 24 h event. Riparian areas are specified to have a decline in hydraulic conductivity with depth (transmissivity feedback).

of field evidence has pointed to the rapid rise of the near-stream water table in many riparian zones upon the application of rainfall (Ragan, 1968; McGlynn and McDonnell, 2003). It is common for soils to fall between the extremes of 'high capillary fringe with low conductivity' and to 'low capillary fringe with high conductivity'. The preceding investigation gives us some insight into general trends that may be apparent. One question to be answered for 'typical soils' is in what way the soil hydraulic properties such as the capillary fringe height and K_s control the response of the near stream water table. Previous suggestions for the cause of this rapid water table rise have included capillary fringe induced groundwater ridging with its associated pre-event water discharge. The importance of the presence of the capillary fringe intersecting the ground surface for the hypothesised mechanisms to operate has been emphasised in the literature.

The following points describe the simulated riparian water table rise observed in the numerical experiments and the complex relationship between capillary fringe, water table response and hydraulic conductivity in a hillslope–riparian context:

1. The ESTEL-2D model was used to simulate the Abdul and Gillham laboratory setup with a medium sloping riparian area, a high or medium initial water table height and a soil with both a high K_s and Q high capillary fringe. The rapid rise of both the hydraulic head of the groundwater and the water table was seen immediately after the onset of rain, and tension saturated water was rapidly converted into phreatic water. This thereby agreed with the evidence of Sklash and Farvolden (1979) and Abdul and Gillham (1984).
2. The numerical experiments indicated the development of a seepage face (due to the rapidly rising near-stream water table) and followed the expected pattern: all storage was filled in the box near-instantaneously. More complex behaviours of the near-stream saturated zone are found when storage is not immediately filled. Again, the numerical simulations accord with the Abdul and Gillham findings relating to seepage face development.
3. A 'ridge' in the pressure adjacent to the stream does develop in the numerical simulations performed in this paper. However, a particular conceptual model

of the development of a groundwater pressure ridge in the Abdul and Gillham domain has been deduced from model simulations (Fig. 8). This pressure ridge development is not consistent with the hypothesis as originally specified. Three stages of the process of the ridging are identified relating to the hydraulic gradients in the domain: (i) an initial ridge development with one gradient acting from the near-stream zone to the hillslope; (ii) a transitional phase, where gradients exist both into the slope and towards the stream channel; (iii) downslope flow, where the only gradient is from hillslope to stream channel. This conceptual model of the process was developed to incorporate the importance of hydraulic gradients directed away from the stream in the simulations. Further field investigations documenting the absence or presence of a ‘reversed’ hydraulic gradient due to rainfall are strongly advocated.

4. The development of groundwater pressure ridges can be identified from the model simulations. Sklash and Farvolden (1979) have suggested that the formation of this ridge in response to a rain event has a *brief* lag time which is related to the near-stream unsaturated zone thickness. From the results of the numerical experiments performed here, antecedent moisture (initial water table height) can be seen to be a controlling factor of near-stream water table rise. For soils with a high conductivity and a high capillary fringe, this lag time may indeed be brief (in the order of minutes in the Abdul and Gillham box). However, for many other soils, lower initial water tables preclude the rapid rise of the near-stream water table as infiltrating water cannot reach the water table, and thus no groundwater ridging or seepage face development is seen.
5. The numerical experiments have shown that where the capillary fringe does intersect the ground surface, an instantaneous rise in the water table is enabled with the application of a small amount of rainfall. However, if the water table is lower and the capillary fringe is near the surface but not intersecting, the response of the water table is determined by the K_s of the medium. In addition, the size of the capillary fringe is inversely related to the K_s of the material. Numerical experiments have confirmed that the greater the propensity for capillary fringe rise the less likely it is that rapid Darcian flux of groundwater can occur even with steepened hydraulic gradients to the near-stream zone (Zaltsberg, 1986). In the sandy soils studied by Sklash and Farvolden (1979) and Abdul and Gillham (1984), a combination of high K_s and high capillary fringe led to the initial specification of the hypothesis of groundwater ridging. The capillary fringe is thus seemingly only a controlling factor on rapid water table response and groundwater ridging in these particular cases.
6. The simulations have shown that only soils with the highest possible K_s values contribute to rapid water table rise (and pre-event water discharge) in the absence of a significant tension saturation and non-Darcian mechanisms. Even where a significant capillary fringe does exist, K_s may still be the controlling factor. For any slope/soil system, the rapid Darcian response of the water table can only be supported with a high K_s, unless the capillary fringe intersects the ground surface. Above a certain value of K_s, there is a range of conductivities for which the response is highly lagged. Below this value the water table does not respond. The threshold value is offset if the capillary fringe is acting. K_s is also notoriously difficult to measure in the field. K_s is suggested here to be the controlling factor in rapid water table rise and should thus be the focus of field investigations of this phenomenon.
7. The riparian characteristics of initial water table height, capillary fringe height and K_s interact in a complicated way to control the timing and magnitude of the response of the water table adjacent to the stream channel. The general relationship is that high values of each variable are positively related to the rapidity of the development of a groundwater ridge. However, for any given riparian configuration, pressure ridge formation is unlikely when infiltrating water cannot meet the tension saturated zone within the event timescale. This occurs when the water table is too low, the K_s is too low and to a lesser extent when the capillary fringe is too low. The capillary fringe is inversely related to conductivity and so its effects may be cancelled out by this feedback. Its position is determined by the water table position. The relationship between water table response and soil type is therefore greatly affected by antecedent moisture. Field estimates of water table response are

similar in studies with and without a capillary fringe (McDonnell and Buttle, 1998).

We suggest that the role of the capillary fringe in the response of the water table to incident rainfall may have previously been overstated in relation to the hypothesised process of groundwater ridging. Gillham and colleagues clearly stated that the conclusions from their work were applicable only to the specific laboratory and field conditions tested, and the wider applicability was uncertain. However, the myth of the widespread operation of the capillary fringe groundwater ridging hypothesis has led to this process being accredited with the discharge of pre-event water in the general case. We suggest that instead of focussing on the capillary fringe, the importance of other soil hydraulic properties such as the K_s of the soil should be emphasised as controlling factors (e.g. as noted by Beven, 1977) on their own merit, but also in the interactions with other controlling factors such as water table height and capillary fringe height. Importantly, it should be noted that near-stream water table response does not necessarily lead to the operation of the groundwater ridging mechanisms as large and rapid pre-event water discharge may be absent even if a groundwater ridge is present. This will be discussed further in the next section.

5.3. How important is riparian groundwater ridging in the displacement of pre-event water to the stream channel?

The consequent conditions for the operation of the groundwater ridging hypothesis are the development of a pressure ridge adjacent to the stream channel in response to the onset of rainfall and a coincidental rapid discharge of pre-event water, which dominates the hydrograph. The following points describe this process as it is simulated by ESTEL-2D and its importance as an explanatory hypothesis of the rapid mobilization of pre-event water.

1. Sklash and Farvolden (1979) and others including Abdul and Gillham (1984) have suggested that a rapid rise in the near-stream water table and consequent groundwater ridge formation generates hydraulic gradients toward the toe of the slope. Numerical experiments have shown that the development, magnitude and direction of the simulated hydraulic gradients control the respective proportions of event and pre-event water in the discharge.
2. For the limited set of simulations performed here, it has been established that a pressure ridge forms under a variety of conditions. However, the connection between the formation of a pressure ridge and the subsequent discharge of pre-event water requires an explanation of the hydraulic gradients acting. Such a connection between cause (groundwater ridge) and effect (pre-event water discharge) is often glossed over in field studies, with the presence of a ridge assumed to account for any pre-event water mobilized. The logic of the connection between the two phenomena should be emphasised, if the process is to be said to ‘operate’. This connection requires the observation of pre-event water mobilized towards the stream channel as a direct consequence of the pressure ridge formation. The evidence from the results presented here did *not* show this connection for the majority of cases.
3. The numerical experiments performed here suggest that, from this limited set, most riparian zones do not reach high pre-event water proportions; those cases that do, involve high water tables and high K_s values. Groundwater pressure ridges formed for many more of the simulations than those that displayed high pre-event water proportion in the discharge. If this result holds true for the general field case, the hypothesis of groundwater ridging should thus be replaced by a ‘continuum’ approach similar to that advocated by Bishop (1991). Rapid rise of the water table, formation of a complex set of hydraulic gradients and discharge of pre-event water can in this way be seen not as part of a ‘mechanism’ but instead as dynamic phenomena which occur with different magnitudes in different riparian spaces.
4. The eventual dominance of overland flow over the extended saturated source areas (Sklash and Farvolden, 1979) is clearly seen in the simulations. This is the most widely applicable part of the groundwater ridging hypothesis for this set of simulations. The rapid water table rise near the stream and the pressure ridge formation is found in many cases, although not all (e.g. soils of low K_s). Elevated proportions of pre-event water in

the stream are rarely detected. These initial results help to confirm McDonnell and Buttle (1998) supposition that there is a need to consider alternative hydrological processes such as macropore flow or kinematic waves, when attempting to explain elevated proportions of pre-event water discharge, and therefore that the hypothesis of capillary fringe induced groundwater ridging is inadequate to explain the levels of pre-event water discharge to the stream found in the field. The Abdul and Gillham laboratory experiment was valid for the specialised case constructed in the laboratory, but we argue that these findings may not be transferable to other riparian spaces.

There are several conceptual and practical limitations to the Abdul and Gillham box. While it characterises a particular riparian area with a particular slope and volume, the rainfall intensity may be so high as to mask the processes of pre-event water discharge that may be more dominant at lower intensities. In addition, the volume of the box is restricted and in many cases is instantaneously saturated, and thus more dynamic phenomena and variations in hydraulic gradients cannot be accounted for in this model domain. The height of the capillary fringe compared to the dimensions of the box is a strongly limiting factor. However, in the limited cases simulated in these numerical experiments, the occurrence of the process of capillary fringe induced groundwater ridging is very rare. Further investigation is required in order to relate these findings to natural hillslopes.

6. Conclusions

This paper has critically addressed the question 'what are the areas, times and instances where one might need to consider groundwater ridging?'. For the limited set of simulations performed, we conclude the following:

1. Groundwater pressure ridges, through rapid water table rise, form in many environments, and the behaviour of the ridge development is determined by the sequence of hydraulic gradients that develop. The development of a pressure ridge does not necessarily lead to pre-event water contribution to discharge. A threshold in the hydraulic gradients must be reached (our so-called phase (ii) transitional) before pre-event water discharge can become important. Proportions of pre-event discharge are determined by the length of the transitional stage of ridge development with a long transitional stage leading to a high pre-event water proportion. A continuum approach considering the dynamic development of hydraulic gradients is advocated.
2. For the riparian characteristics simulated, high pre-event proportions in discharge were related to the complex interactions between characteristics. Water table height and K_s were found to have the largest control. The capillary fringe has little control on the pre-event discharge, even though the capillary fringe is an important control on pressure ridge development. This forms a central piece of evidence for the revision of the traditional theory of groundwater ridging and pre-event water generation.
3. High and sustained proportions of pre-event water, such as the $\sim 75\%$ often found in the field (from the review of Buttle, 1994), are rarely found in the riparian spaces simulated in this investigation. This could be indicative of other processes operating in field environments, such as non-Darcian pressure waves or preferential flows. McDonnell and Buttle (1998) challenged Jayatilaka and Gillham (1996) regarding the widespread application of capillary fringe induced groundwater ridging as a mechanism of streamflow and suggested that alternative mechanisms operate and rapid water table responses are seen in the absence of a capillary fringe. The results of this investigation support McDonnell and Buttle (1998) by showing that the capillary fringe does not have a controlling role in the discharge of pre-event water to the stream, and groundwater ridging related pre-event water discharge cannot account for the high proportions seen in the field.
4. Only certain geometries have been simulated in this investigation, based on the Abdul and Gillham box. Most field environments have complex geometries and other characteristics. The simulation of such complexity is beyond the bounds of this investigation. Future simulations should consider alternative riparian

configurations, water table 'topographies', convergence and divergence, and vegetational effects. In addition, we advocate field testing of the findings of our simulation set.

Finally, we suggest that the groundwater ridging hypothesis as widely understood may require revision, and may be more complex than a simple displacement mechanism. We advocate a continuum approach for understanding riparian dynamics based on the development of dynamic hydraulic gradients in the near-stream zone. We would like to remind the reader that for any investigation based on small-scale and artificial characteristics, the practical significance of the results must be carefully evaluated, preferably in the field.

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