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The effect of model configuration on modelled hillslope–riparian interactions

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Abstract

The transfer of hillslope water to and through the riparian zone forms a research area of importance in hydrological investigations. Numerical modelling schemes offer a way to visualise and quantify first-order controls on catchment runoff response and mixing. We use a two-dimensional Finite Element model to assess the link between model setup decisions (e.g. zero-flux boundary definitions, soil algorithm choice) and the consequential hydrological process behaviour. A detailed understanding of the consequences of model configuration is required in order to produce reliable estimates of state variables. We demonstrate that model configuration decisions can determine effectively the presence or absence of particular hillslope flow processes and, the magnitude and direction of flux at the hillslope–riparian interface. If these consequences are not fully explored for any given scheme and application, the resulting process inference may well be misleading.

Keywords: Hillslope hydrology; Finite element modelling; Boundary conditions; Riparian zone

1. Introduction

Much research over the last few decades has focused on those hydrological processes that generate the flow of water from the hillslope into the river channel (Bonell, 1998). However, our desire for knowledge about how a particular hillslope system functions vastly outstrips our ability to test these hypotheses rigorously in field situations. The development of high-resolution spatially distributed numerical models for catchment hydrological investigations is now an increasing trend (Brontstert, 1999), and forms an attractive method of hypothesis testing. Complex hydrological situations such as hillslope–riparian interaction require high-resolution formulations to capture the relevant processes. To achieve such high space–time resolutions these schemes are effectively over-parameterised, require the specification of boundary conditions for which no reliable estimates usually exist and for which the parameterisation of soil properties is only at a few known points within the domain (Clayton, 2000). There has been much recent discussion regarding the problems of parameterisation (for example, examining sensitivity

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analysis, multiple realisations and model calibration procedures)—in the context of numerical implementation (Anderson and Bates, 2001). However, these issues acknowledged, high-resolution modelling schemes offer a unique opportunity for hydrological process investigation as they offer an exceptional way to visualise and quantify hillslope–riparian interaction.

Water table position, saturation extent and Darcian velocity vector fields are fundamental aspects of the hillslope–riparian hydrological system. The linkage between water flux from the hillslope and how it may be modulated by the riparian zone en route to the channel is a first order control on stream flow and chemistry (Cirmo and McDonnell, 1997; Hill, 1999; Burns et al., 2001; McDonnell et al., 2001). Our increased ability to run fast simulations presents opportunities to explore such hillslope–riparian hydrology anew. Other complementary fields of ecology and hydraulics demand similar information—such as the near-stream extent of saturated conditions for ecophysiological and ecohydrological processes, and maximum flux and flux vector orientation for flood inundation modelling (Mertes, 1997). Nevertheless, these 'state' variables have yet to form the basis of hydrological model design or the associated field parameterisation in catchment hydrology. Inadequate representation of state variables is possible if they are not the specific focus of the model effort, and a change in their state (for example, a change in the direction of Darcian velocity vectors or an extension of the saturated areas of a domain) will in turn change the hydrological response of the hillslope. This can lead to a model switching 'on' or 'off' what we usually conceive of as a hydrological process or mechanism (for instance, the contribution of old water to the stream channel or some non-linear conversion of tension to pressure saturation, such as the 'capillary fringe effect'). A reliable representation of these key state variables is therefore of extreme importance and must be the principal focus of the modeller.

The first order decisions to be made when modelling hillslope–riparian hydrology are those that define the mathematical problem to be solved: selection of the equation to be solved (in this case the Richards equation); definition of boundary conditions; definition of initial conditions; and selection of the internal algorithms of the model such as the soil moisture algorithm to represent the soil hydraulic properties. Second order decisions are those that describe the methods used to solve the problem. These include the choice of numerical solver, convergence criterion, implicitation coefficient, time stepping strategy, spatial discretisation method (finite difference, finite element, finite volume etc.) and mesh resolution. It is critical to understand first order modelling decisions to enable confidence in the modelling of hydrological fluxes but they are often overlooked. A general observation can be made that various decisions inherent in the internal configuration of numerical models need greater exploration and it is these that will form the focus of this investigation.

There is a clear distinction between model configuration and the subsequent parameterisation, and high-resolution numerical modelling schemes can currently be seen as flawed in both of these respects. Specific decisions regarding model configuration need to be evaluated carefully. The effects of such decisions can propagate through the model as illustrated in Fig. 1 and may have a significant impact on model output in terms of state variable representation. Modellers rarely consider the consequences of these risks. The risks are not explicitly defined in textbooks or user manuals, however, warnings such as… 'correct selection of boundary conditions is a critical step in model design' (Anderson and Woessner, 1992) are ubiquitous in the literature. It is common practice to define boundary conditions and other configuration decisions from 'previous experience' of other modellers, on the basis of numerical efficiency or merely because it is easy to do so ('the model is already set up like that'). This is not satisfactory when important dependencies may exist between sub-model choice and state variable predictions. An overestimation of Darcian velocity or subsurface saturation extension up a hillslope can severely undermine our ability to identify runoff pathways. If a system is simulated based upon incorrect configuration decisions, then the simulation exercise is solving the wrong problem and, by definition, will provide the wrong solution (Franke and Reilly, 1987). Seibert and McDonnell (2003) have commented on this in the context of achieving the right model 'fit' but for the wrong process reasons.

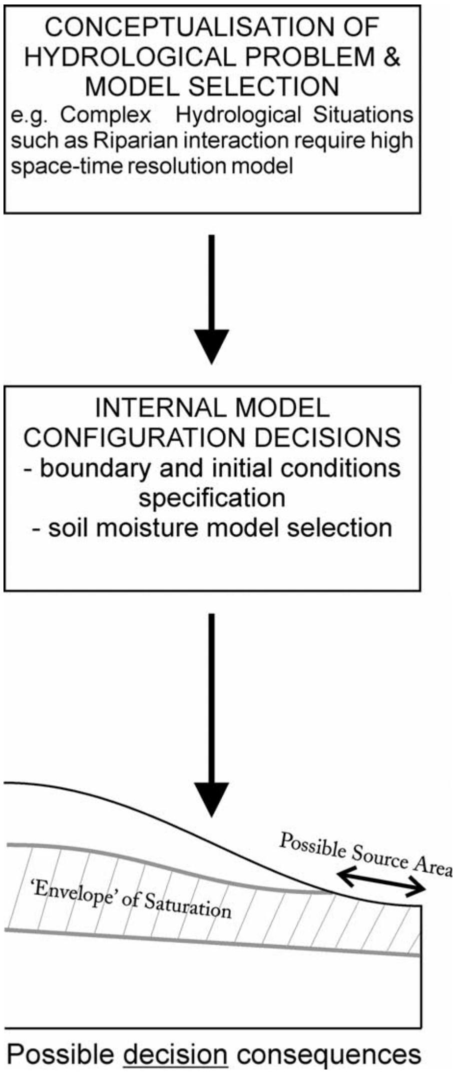


Fig. 1. The envelope of possible saturation resulting from model configuration decisions.

High-resolution hillslope hydrology modelling can be used successfully as a research tool for examining the hillslope–riparian interaction, but only under conditions of 'comprehensive data availability' (Brontstert, 1999) where all relevant processes are accounted for and where we have sufficient knowledge of the conditions at the model boundaries. Ideally, all research modelling would be carried out under these conditions. However, until this is the case, investigations must recognise the effects of internal configurations on model outputs. For the vast majority of potential applications of interest to hydrologists the existing approach of 'unknown' consequences is the only means with which to undertake investigations. It is therefore essential that we attempt to fully understand the consequences of using such models in hillslope–riparian hydrological investigations.

One key impediment to moving forward in high-resolution modelling of hillslope–riparian hydrological interactions is a missing framework for dialogue between the experimentalist (who has some understanding of how the system 'works') and the modeller (who understands how the code 'works'). This dialogue can aid model structural decisions (and subsequent parameterisation) but only after the consequences of the implementation of these decisions are fully understood.

A detailed understanding of the consequences of model configuration is required in order to produce reliable estimates of state variables. The objective of this research is to explore these decision consequences with the aid of four examples, which highlight the important decision dependencies that are evident in this type of modelling. These example scenarios are not comprehensive of the problems that may be encountered, but provide what we consider to be the first appropriate steps in exploring the impact of model configuration decisions on simulated process behaviour. The scenarios presented are: (i)–(ii) a study of boundary condition implementation (lower and upslope); (iii) initial conditions; (iv) soil moisture release algorithm selection. Our objective is accomplished using a typical two-dimensional Finite Element model (ESTEL-2D) to explore the decision consequences that become apparent in these different configuration scenarios.

2. Model platform

ESTEL-2D solves the Richards equation in saturated and unsaturated porous media. It is an example of a finite element scheme that is capable of solving complex hillslope–riparian interaction (Bates et al., 2000). ESTEL-2D has similar capabilities to many other two-dimensional high-resolution spatially distributed numerical models. However, the availability of the source code to the authors has allowed investigation of the consequences of the internal model configuration in a way that would not otherwise have been possible. The model is described fully by Desitter et al. (1998, 2000) and Renaud (2002). 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 (Desitter et al., 2000). The 'mixed' form of the Richards equation is solved:

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

where t is the time (T); θ is the volumetric moisture content ($\mathrm{L^3L^{-3}}$); h is the pressure head (L); K is the hydraulic conductivity tensor ($\mathrm{LT^{-1}}$); z is the elevation (L) and S is a source term ($\mathrm{T^{-1}}$) which can represent additional processes such as evapotranspiration. The model also allows the solution of 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 (2002) gives a full description of how these are implemented mathematically in ESTEL-2D, including the incorporation of a seepage face capability.

The above equation system is solved in time and space. The time discretisation for the Richards' equation is defined using the modified Picard iterative scheme; this is based on a discretisation of the mixed form of the Richards' equation (Celia et al., 1990) and is robust and simple to implement. The finite element spatial discretisation in ESTEL-2D uses the Galerkin variational formulation. The governing equations are solved to give the pressure head, from which values of hydraulic head, Darcian velocity and moisture content can subsequently be derived using additional relationships.

From a mathematical point of view, the Richards' equation is a second-order partial differential equation, and of particular importance in the context of the research reported here is that for a given set of initial and boundary conditions, such an equation has a unique solution (de Marsilly, 1994, pp. 107).

3. Field site and test cases used for the numerical experiments

The objective of this research is to explore the consequences of first-order model decisions in hillslope–riparian modelling. This is achieved in this paper with the aid of four typical hillslope–riparian modelling scenarios. The difficulties encountered in model configuration (boundary and initial condition specification and soil moisture algorithm selection) are seen in a wide spectrum of situations. There are, however, particular input data requirements for numerical models such as ESTEL-2D, and the availability of these data formed the basis for selection of the four examples. Each of the four scenarios presented in this study requires different domain characteristics in order to develop an illustration of the consequences of a particular model configuration. Some decisions will become more important in different domains (soil type and distribution, morphology, etc.). The field site and test cases used for the numerical experiments, in order to illustrate the potential consequences of configuration decisions, are presented here along with a justification for their selection.

3.1. Boundary conditions (lower and upslope)

Many of the hillslope–riparian areas of interest to hydrologists have shallow soils, complicated morphology and exhibit return flow. These features allow easy deflection of subsurface flow vectors. When modelled, this type of domain is thus very sensitive to boundary conditions, because a small change in boundary flow vectors could subsequently affect a large part of the modelled domain. The test site for the boundary conditions numerical experiments needed to be potentially demanding in terms of model representation but where potential hillslope process connections would be clear and unequivocal. The domain needed to be sensitive to boundary condition changes with the result of a deflection of these flow vectors and the possibility of the switching on/off of flow processes. The Sleepers River site fulfilled these broad criteria and hence was selected for study. The Sleepers River Research Watershed in Vermont, USA, is one of five sites for research on Water, Energy and Biogeochemical Budgets (WEBB) under the USGS Global Change Hydrology program. McGlynn et al. (1999) conducted a study in a headwater reach in the intensively instrumented 40.5 ha W-9 catchment. Their study aimed to determine the flowpaths and physical water mixing through riparian and hillslope zones. A transect of nested piezometers enabled the dynamics of the 1996 melt season to be captured both spatially and temporally.

The transect has a complex vertical distribution of soils (of different texture and hydraulic conductivity) and till (McGlynn et al., 1999). The riparian zone in the study reach (Fig. 2) consists of peat accumulations up to 0.9 m in depth overlying dense clay-silt till, which in turn overlies gravelly till of variable depth above bedrock. This riparian profile grades into a more uniform mineral soil further upslope. The study area is characterised by extensive saturated zones on either side of the stream and moderately sloping hillsides. Claxton (2003) presents a detailed model analysis of water, solute and isotope flux from the hillslope. The experiences in that earlier study allow us to show how seemingly arbitrary model decisions impact process simulations and affect results.

3.2. Initial conditions

Definition of initial conditions requires the specification of a pressure head distribution throughout the system at a given time ($t = 0$). It is widely understood in the hydrological sciences that the use of different initial conditions will lead to different outputs from a model (see for example: Ijjász-Vásquez et al., 1992). A ‘hot-start’ is a mathematically convenient method for the specification of initial conditions. A ‘hot-start’ can be given to transient simulations using an equilibrium (steady-state) run-in period.

The specification of initial conditions for hillslope hydrology modelling has been the subject of detailed research by Wood and Calver (1992). They remark that the ideal of dynamic steady state initial conditions, where domain input fluxes equal output fluxes, is impractical for hillslope hydrology cases which are modelled incorporating an unsaturated zone. Dynamic steady state simulations may not converge to a solution, especially in cases involving pressure distributions with steep head gradients. Hence, recent papers have adopted varying approaches to the question of initial conditions. For example, Ng and Shi (1998) used a static (zero applied boundary flux) steady state analysis to generate a quasi-hydrostatic pore water pressure initial conditions distribution. Tsaparas et al. (2002) specified an assumed water table and pore water pressure distributions about this line. These conditions are probably not in dynamic steady state equilibrium and hence the results from any subsequent hydrology modelling using this starting point could be dominated by the initial pressure distribution (e.g. Beven, 1977). It may take a significant period of start-up time before model results no longer depend significantly on the specified initial conditions.

Initial condition choice is probably of greatest significance on steep slopes where rates of lateral subsurface flow are rapid and so the slope is hydrologically responsive. Initial condition choice on steep slopes may therefore dominate subsequent simulation results (Anderson, 1983). The effect of

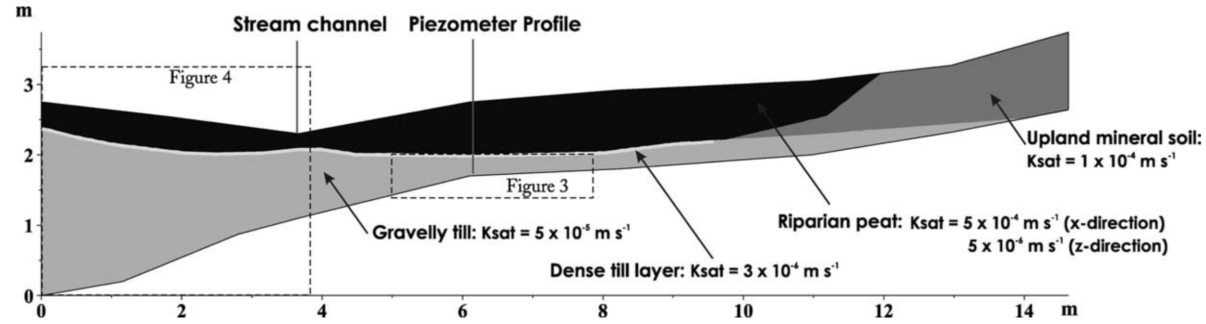


Fig. 2. The Sleepers river domain.

initial condition choice could be masked in the Sleepers River case because of the shallow slope (hydrologically unresponsive) and the complications of the material in the domain (complicated flow pathways as flow vectors are deflected by the different soil layers). In a steep residual soil slope by contrast, the choice of the water table position (zero pore pressure line), within the initial condition definition of the domain, could totally dominate the subsequent pore pressure simulation results. A steep test case was therefore chosen with a 35° slope and single soil type to examine the effects of initial condition selection.

3.3. Algorithm selection

We believe that selection of the soil algorithm (suction–moisture curve representation) has the potential to impact heavily on the saturated areas of a slope shown in model outputs. For the same pressure distribution, the saturation of the slope can vary with soil algorithm, and the lowest and highest saturations produced with different algorithms form an ‘envelope’ of possible saturations (Fig. 1). The saturated wedges that develop on steep slopes are relatively small and a complex soil distribution produces a corresponding complex pattern of saturation within a hillslope. Thus the model domains used previously are not optimal for demonstrating the importance of these saturation ‘envelopes’. However, a slope consisting of a single shallow soil would be of greatest potential concern, because a small increase in saturation could dramatically increase the source areas to the stream. A simple hypothetical shallow domain was therefore constructed in order to enable a complete demonstration of the potential consequences of soil algorithm selection.

4. Analysis of model configuration decisions

The following discussion serves to illustrate the ability of model configuration decisions to impact on state variable output.

4.1. On defining the lower boundary conditions

Lack of information is one of the biggest problems encountered in numerical modelling exercises. We can never feasibly have a complete conceptualisation of every point along all the boundaries of a domain and there will never be adequate field data to support this; and yet numerical modelling requires some conceptualisation of the boundaries to be given. It is common practice to assume that the lower boundary of a modelled hillslope is impermeable rock. Thus the assumption is that the relative saturated hydraulic conductivities of the soil and rock are different enough to provide a no flux (actually a specified flux of zero) Neumann boundary, which will not affect the overall pattern of flow, i.e. an assumption of parallel flow to the lower boundary. However, this ‘impermeable rock’ cannot necessarily be assumed, especially if preferential flow pathways exist (fractured rock) or regional upwelling occurs. These two phenomena are widespread (Torres et al., 1998; Burns et al., 2001) and cannot be assumed to be negligible in a situation with little available data.

Fig. 2 shows the modelled Sleepers River hillslope reported by Claxton (2003). The lower boundary in this case is particularly interesting because no data are available to guide the specification: whilst the physical depth to bedrock is well characterised, the hydrological conditions and flow pathways at the lower boundary are not known.

The observed hydraulic head values are poorly represented by the model when using a no-flux boundary condition. Following a sensitivity analysis (Claxton, 2003) it was concluded that this poor representation was not because of uncertainty in the parameterisation, or second order numerics (e.g. mesh resolution) of Sleepers River. In contrast, specified flux boundaries of (i) downwelling at the foot of the hillslope and (ii) recharge to the riparian zone from the bedrock (both guided by the experimental findings of McGlynn et al. (1999) and modeller-experimentalist discussions in this instance), create an upward flux in the central region of the domain that more closely matches the behaviour observed in the field. Both of these boundary conditions are realistic alternatives for the given situation. The question then becomes: how far should we go in specifying an unknown boundary just to fit piezometer data? This change in boundary condition specification forms a distinct binary switch, as the ‘return flow’ is switched on or off. This is demonstrated by the two alternative Darcian velocity vector patterns at the lower boundary

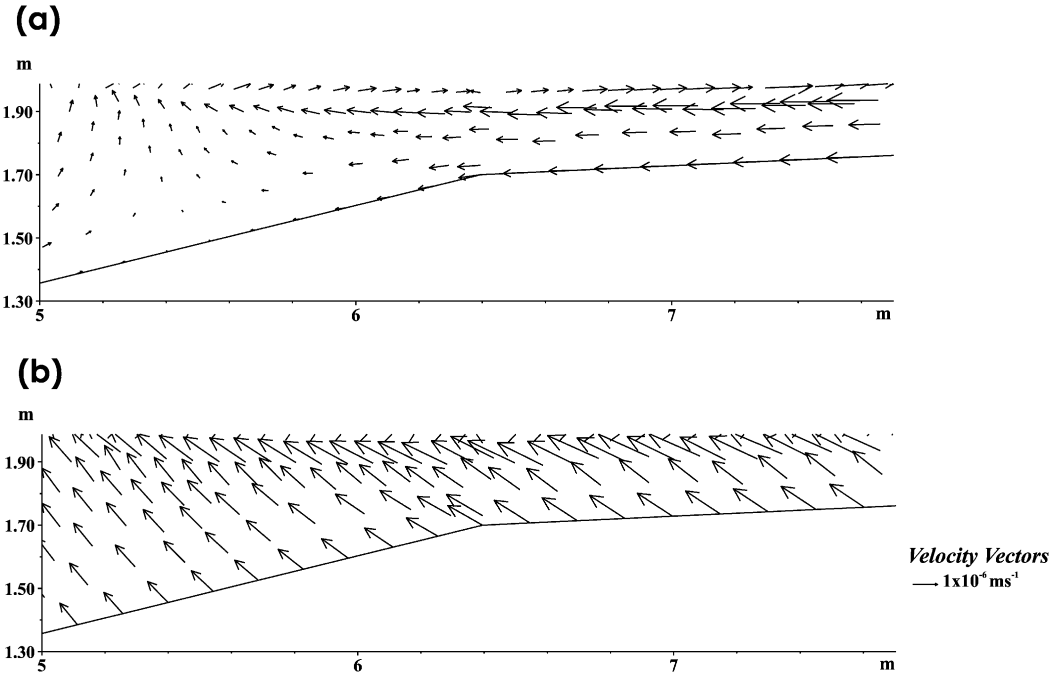


Fig. 3. Velocity vectors at the lower boundary of the Sleepers River domain (see Fig. 2) for (a) no lower boundary flux and (b) incorporating a lower boundary flux.

for a no-flux condition (Fig. 3a) and a specified-flux of downwelling and recharge (Fig. 3b). A no-flux boundary excludes certain flow processes and flow pathways. With a specified flux boundary, the flowpaths implied from the piezometer data are followed. This configuration decision will impact strongly on process behaviour by causing a binary modification of the flow path/process.

4.2. On defining the upslope boundary conditions

The specification of incoming flow from the sides of a modelled domain can prove a very complicated task for the modeller and can significantly affect the hydrological system response. Little information may be provided from the field other than measured pressure heads at particular points. Fig. 4 shows one upslope boundary of the Sleepers River hillslope for the same case as above (defined in Fig. 2). Two head conditions (Dirichlet and Neumann assumptions) were applied at the left hand boundary, both of which are physically reasonable assumptions for the given field data. Fig. 4 shows the difference in resulting pore pressures in the slope segment. A specified head (Dirichlet) representation restricts the hydraulic head along the boundary to a distribution given by the modeller (generally hydrostatic for simplicity, or more complicated functions). Changing to a specified flux (Neumann) creates a more realistic pattern of hydraulic head by generating upward flow at the boundary. Fig. 4 shows the hydraulic head difference in the domain between the specified head and specified flux conditions. The zonal influence of this change in boundary condition extends approximately 2.5 m in the *x* dimension and throughout the *y* dimension. It can thus be seen that effecting this simple modification in the boundary conditions changes both the magnitude and direction of flow in the wider domain.

4.3. On defining the initial conditions

Many hydrological modellers find using a ‘hot-start’ to generate initial conditions a difficult task. Firstly, we show that there are particular consequences of assuming particular initial conditions from given field information when not using a steady-state run-in period. Secondly, we demonstrate that even if

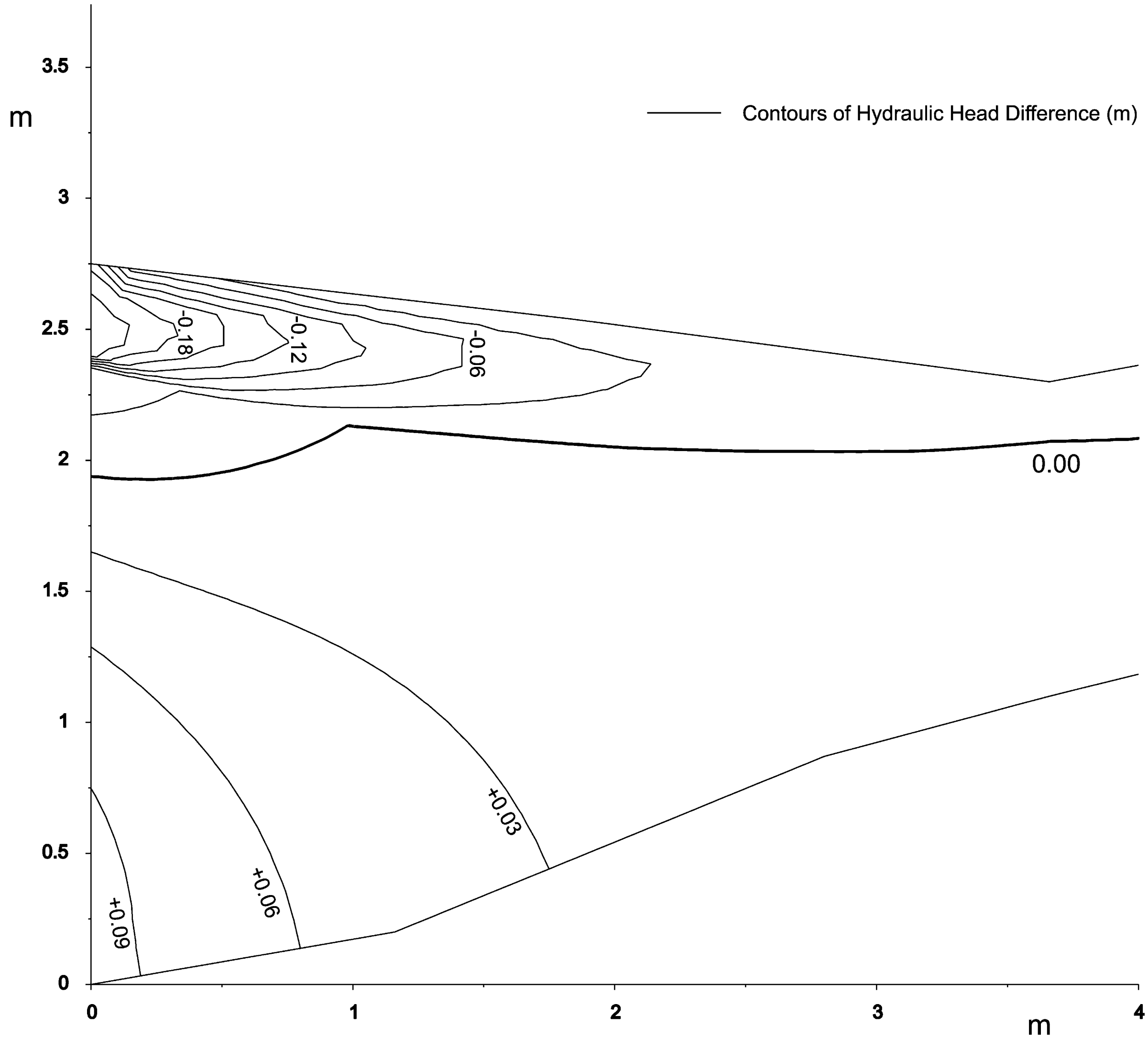
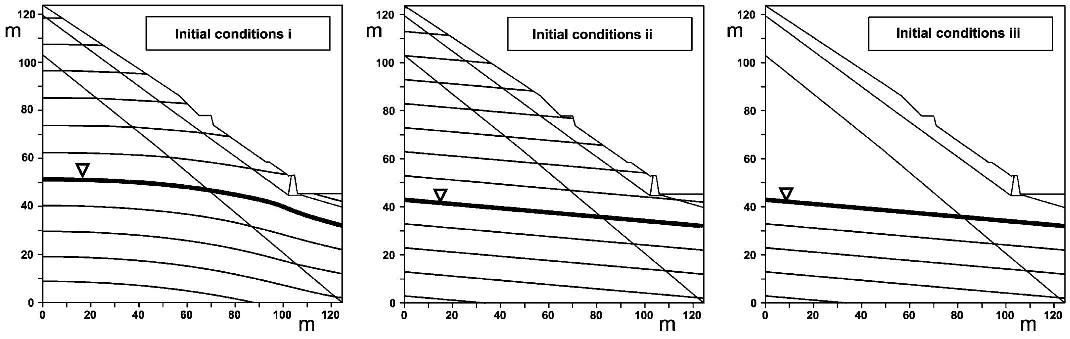


Fig. 4. Left hand boundary of the Sleepers River domain (see Fig. 2). Contours (m) of hydraulic head difference are derived from simulations using (i) specified head and (ii) specified flux boundary conditions on the left hand boundary.

a 'hot-start' can be achieved, it is a very complicated and computationally expensive process.

For a given set of field information certain initial conditions distributions are commonly assumed, each of which may be a physically reasonable conceptual model of the system. Three such commonly assumed initial conditions are illustrated in Fig. 5: (i) hydrostatic curvilinear water table; (ii) hydrostatic linear inclined water table; and (iii) hydrostatic pressure below linear water table with non-hydrostatic conditions above the water table. The water table in each case is in approximately the same position as determined by point field data. Identical transient simulations with constant boundary conditions have been applied to each of the initial condition distributions for the 35° slope given in Fig. 5a. The constant boundary conditions used were: (i) surface boundary-specified infiltration flux of 1.0×10^{-6} m s^{-1}; (ii) left and bottom boundaries—no flux; and (iii) right boundary-specified hydrostatic head, with zero pore water pressure at 32 m height. Varying boundary conditions (e.g. different

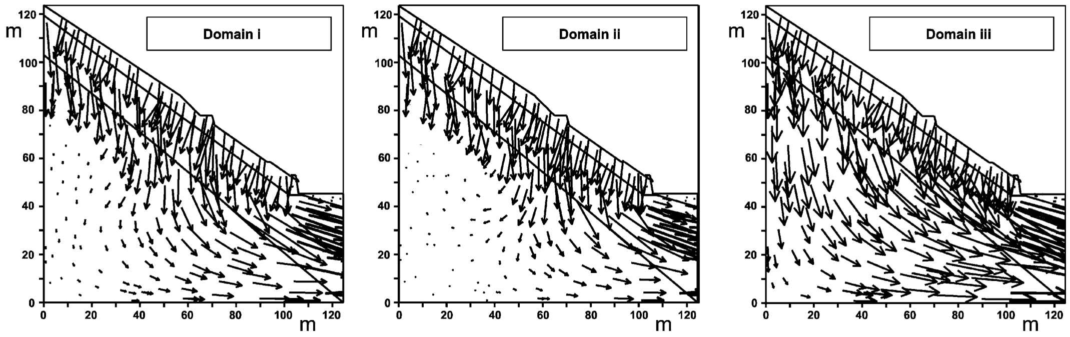
(a) Conceptualised initial conditions



Isolines shown at 10m intervals

i positive & negative pressure = quasi-hydrostatic
ii positive & negative pressure = hydrostatic
iii positive pressure = hydrostatic; negative pressure = non-hydrostatic (0 to -3m negative pore water pressure)

(b) Darcian velocity vector fields at 90 days



(c) Run to equilibrium

Equilibrium results

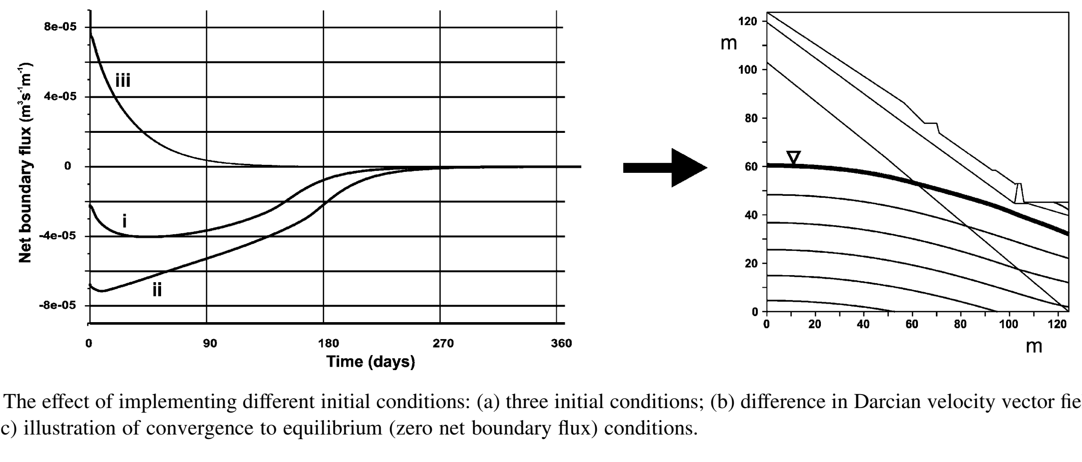


Fig. 5. The effect of implementing different initial conditions: (a) three initial conditions; (b) difference in Darcian velocity vector fields at 90 days; (c) illustration of convergence to equilibrium (zero net boundary flux) conditions.

infiltration fluxes over time) were not used in this illustration as they could mask the differences in the processes and their timings, which are a consequence of the specific initial conditions. However, it should be noted that in reality, this type of flux equilibrium rarely occurs except perhaps during extreme duration events and times of constant influx of water such as snowmelt (Ogden and Watts, 2000). At a period of 90 days (Fig. 5b) the hydrological processes within the domain, here demonstrated by Darcian velocity vector fields, are noticeably different. It can be deduced from Fig. 5 that the selection of a particular set of conceptualised initial conditions from field data can result in vastly differing results for subsequent transient simulations i.e. there is a process dependency on initial conditions. The differences cause process offsets and can significantly affect the results of any hypothesis testing and flow pathway determination using the model framework.

User specified or static steady-state initial conditions are inadequate for hydrological modelling. Blake et al. (2003) have shown that dynamic steady state initial conditions can be generated with ESTEL-2D. However, the process is difficult to achieve and computationally expensive. Using the conceptualised conditions given in Fig. 5a, each simulation was run until equilibrium was attained. This means that for the given set of conditions, the constant rate infiltration influx equals the outgoing flux from the control surfaces (in this case the right boundary). Fig. 5c shows the very long length of time required for all three of the conceptualised conditions to reach equilibrium (i.e. ~180 days for case (iii) as defined above; 270 days for case (i); and 330 days for case (ii)). The similarity between the conceptualised conditions (Fig. 5a) and the final dynamic steady state condition (Fig. 5c) will determine the length of time required to reach equilibrium, but this is not known a priori when conceptualised conditions are specified with limited field data. In addition, it can be seen that if a 'hot-start' is not used, and a simulation was performed using one of the conceptualised conditions (Fig. 5a) as initial conditions, then the subsequent simulations would be affected for several hundred days (Fig. 5c).

If possible (if the modelling code achieves convergence of the solution) it is sensible to 'hot-start' simulations using an equilibrium (steady state) run-in period for transient simulations. When this is not possible an exploration of the consequences of different possibilities for initial conditions is required if model results are to be useful.

4.4. On algorithm selection

Numerous recent studies have shown that the riparian zone controls chemical signature of the hillslope that is expressed in the channel during events (Burns et al., 2001), modulates the flux of mobile water from the hillslope to the stream and controls the mixing of water and solutes at the catchment scale (McGlynn et al., 2002). This zone is in or near a saturated state due to its proximity to the river channel, and the combination of a large upslope accumulated area and the low slope angle which favour saturated conditions. Representation of saturation/near saturation conditions within any numerical model is therefore of vital importance. One of the major components for saturated–unsaturated soil hydraulic property configuration is the selection of an appropriate suction–moisture curve representation, and the resulting relative hydraulic conductivity description.

Field suction moisture curves exhibit considerable variability. Soil moisture algorithms attempt to reflect these shapes accurately often with the use of shape/inflection parameters. The smoothed approximate functions that result are different in shape, especially in the near-saturation zone (for example, air entry pressure—Vogel et al, 2000). It has become accepted practice to choose one or other of the algorithms because it is easy to do so (for convenience or for numerical performance). Researchers commonly follow a 'usual' method that can be internally built into models (e.g. as an option in model setup procedures of HYDRUS 2D). Exploration of the consequences of these choices is rarely made. There are insufficient alternatives to using such algorithms, especially when little field data are available to determine the nature/shape of these curves.

The shape of the suction moisture curves, especially near saturation, is critical in the investigation of hydrologic processes and responses. For example, a curve which exhibits a rapid change in suction with a very small change in moisture content near saturation (i.e. displays an air entry value), is likely to have a very different effect on numerical predictions of pore water pressures than a curve which does not exhibit such a phenomenon. Moisture content/pressure head differences will in turn affect water table levels and associated hydrological flow pathways displayed in model outputs. So there is a specific risk involved in the choice of a single moisture algorithm to represent the soil hydraulic properties of a medium. Chen and Wheater (1999) have recognised that 'structural errors are…always present in soil water retention models and hence assessment of model structures and uncertainties becomes essential in model identification'. The effects of structural differences can propagate through the numerical model to produce strong variations in state variables at the model output stage. The generation of 'false' processes is possible due to the saturation differences resulting from the use of different soil moisture methods. For example, the modelled system can respond very differently in terms of the hydrological connection to the stream because of the reduced storage capacity. This has important implications for streamflow generation problems. An exploration of the likely process behaviour invoked by the shape differences produced by these curves is required. In high resolution numerical hydrological models such as ESTEL2D, these influences and effects must be fully tested before near saturation studies can be relied upon. Hillslope hydrological process understanding can be advanced through simulated process exploration and quantification of water transfers. However, it is very difficult to completely conceptualise the near saturation suction moisture curve for each individual set of soil hydraulic properties for each particular modelled case. Therefore the choices available to the modeller must be clearly considered.

Due to the impossibility of strict validation of water retention models (Chen and Wheater, 1999), it is desirable to test several models with different structures against the same data so that the differences in these structures can be highlighted. Fig. 6a shows three different suction moisture curves generated for the same Silty Clay field data with the aid of the parameter generation program RETC (van Genuchten et al., 1991). These data are sparse near saturation, as is often the case with field data sets. The soil moisture algorithms used to produce suction–moisture relationships and the associated hydraulic conductivity curves are the Brooks–Corey method—BC (Brooks and Corey, 1964), the Millington–Quirk method—MQ (Millington and Quirk, 1961) and the van Genuchten method—VG (van Genuchten, 1980). The structural differences, especially near saturation can be seen clearly. The soil moisture curve produced by the use of the VG model has a characteristic smooth shape, whereas that produced by the BC has a distinct air entry pressure 'cut off' (Fig. 6a). The MQ method is determined by the tabular data input. The shapes of the generated curves will always be determined by the underlying soil information input. However, the fundamental differences in the near saturation shape have the potential to create large deviations between process estimates produced by different models for the same case. It can be seen in Fig. 6a that for a suction of 0.28 m, the BC algorithm gives a saturation of 100%; the MQ algorithm gives a saturation of ~93% and the VG algorithm gives a saturation of ~87.5%.

Fig. 6b shows a simple hypothetical hillslope domain. The results presented demonstrate the 'envelope' of possible saturation levels resulting from the use of different suction moisture curves algorithms for the same data. Importantly, we should note that, as this example illustrates, in shallow regoliths on shallow gradient slopes, this envelope of 'uncertainty' may extend throughout much of the depth of the profile and may also determine source area development. The choice of different suction moisture curves algorithms thus produces a complex effect on the model output that cannot be classified as a simple 'switch'. Parameterisation of the soil moisture algorithms and spatial variations in these parameters, further complicate model outputs. This parameterisation is another layer to the problem and could cancel out the effects of the variations in soil algorithm. The algorithm and its parameters can thus be seen as a multi-dimensional switch, which may be self-cancelling.

5. Discussion: process implications of model configuration decisions

Different classes of process behaviour, which can be generated by model configuration decisions, can therefore be identified:

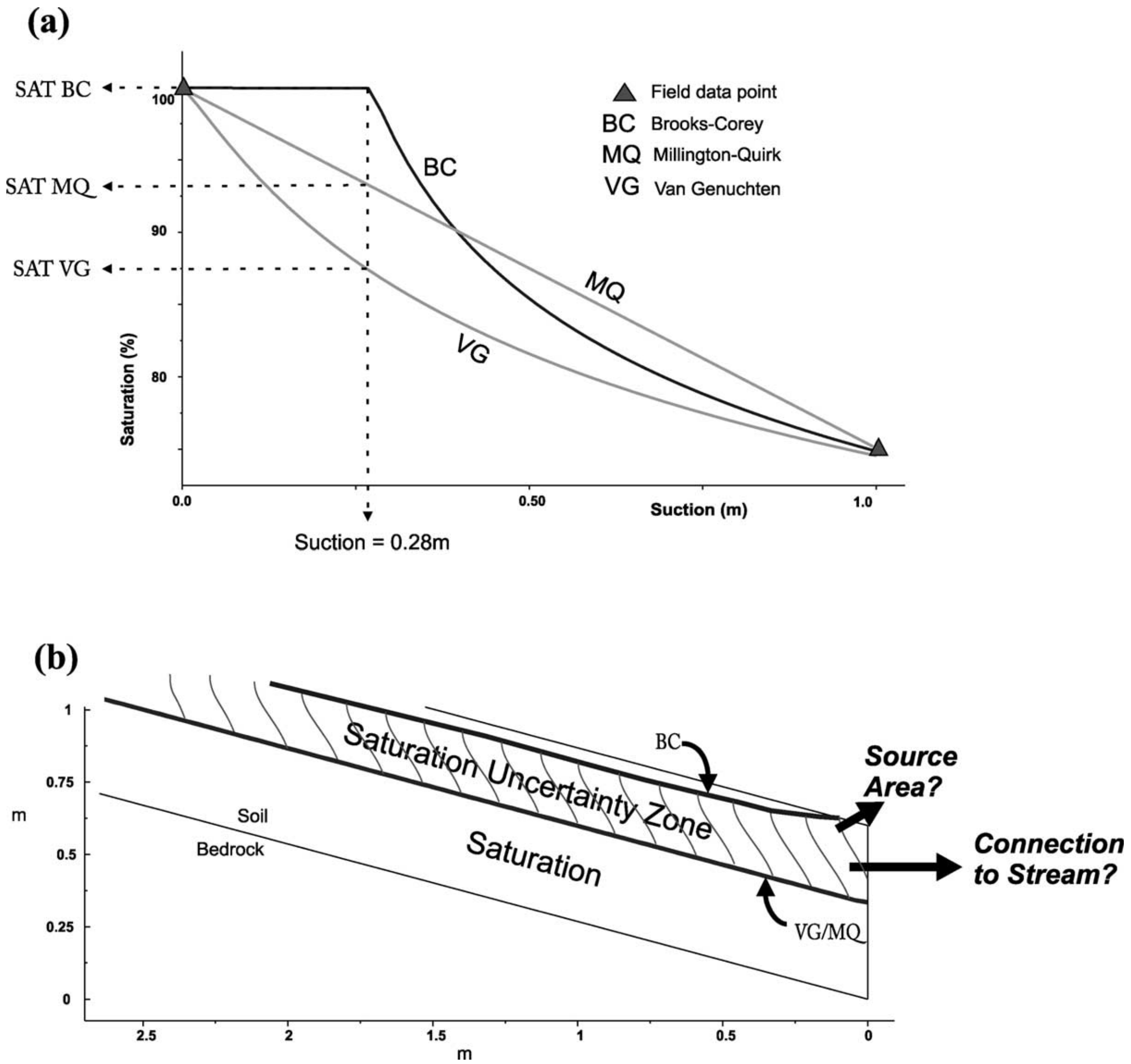


Fig. 6. (a) Three different suction moisture curves—the different saturation levels (SAT) at a suction of 0.28 m are shown and (b) the resultant uncertainty envelope of hillslope saturation.

(i) processes are directly switched 'on or off'— a simple binary change of the flowpath/process demonstrated by the example of the lower boundary condition specification (Fig. 3); 'return flow' is switched on or off.

(ii) processes are occurring but will be modified in magnitude and/or direction—this was demonstrated by the example involving the modification of the upslope boundary condition (see Fig. 4); different side slope boundary conditions yield different pore pressure regimes—such differences are seen to be spatially significant.

(iii) the process is offset in some form by certain configuration decisions. This can be revealed through the example of specification of initial conditions (see Fig. 5); there is a significant spatial offset in terms of infiltration/groundwater connectivity.

(iv) process representation is implicitly specified by the selection of particular within-model algorithms. The example used in this paper was that of the suction moisture curve configuration impacting on the envelope of possible hillslope saturation zones and hence hillslope–stream connectivity domain (see Fig. 6).

The above points should be interpreted as tests that need to be applied to a numerical model prior to establishing process inference from the scheme. Since it is process behaviour (e.g. groundwater ridging and soil layer influences on hillslope–riparian zone mixing) that needs to be correctly depicted in the scheme—this is the critical question. Subsequently, the numerical behaviour of the scheme and the numerics of the process out-turns are of interest; these will be afforded greater weight once the model has passed the 'tests' to which we refer.

The above numerical tests provide illustrations of model decision effects. Such a preliminary investigation needs to be followed by a much more extensive range of tests on a range of slope morphologies in order that some specific guidance may be forthcoming for those circumstances where model decisions are likely to have the greatest 'distorting' impact on process inference.

Having identified the classes of process-model decision interaction above, it is worth broadening and extending the discussion to reaffirm the explicit need for modeller–experimentalist linkages. Once the general consequences of model decisions are understood then consideration of parameterisation can be addressed. The experimentalist has a key role to play in this regard and this study begins the process of defining the precise context for that input.

As a general rule the dialogue between experimentalist and modeller in hydrology is minimal. While many papers have called for such improved dialogue (Klemes, 1988; Dunn, 1983) little progress has yet been made. One reason may be that the psychology of model development in hydrology is not about rejection, but about continuous refinement and commitment to model structures (Hooper, 2001). This may be particularly true for numerical modelling schemes where after considerable time and financial investment, the developer has no interest in trying to falsify (the way of science) but rather continue to modify and 'use' the code. While perhaps seen as a dilemma by some (Beven, 2001), we advocate an approach whereby the modeller engages the experimentalist in decision making early on in the process—at the stage of defining initial conditions and appropriate boundary conditions. If the tests we have outlined above are undertaken, then this will perhaps actually evolve into the closer liaison between modellers and experimentalists that has been called for so many times before.

In the meantime we need to be cautious about the conclusions that we draw from numerical modelling studies, until that is we have a more explicit understanding of the consequences of model configuration on our simulations.

6. Conclusions

This paper has attempted to highlight the importance of the internal configuration of high-resolution models for hillslope hydrology. Model configuration decisions are most important when there is a lack of field information available to the modeller. The large number of options in conceptualising complex hydrological systems requires dialogue between the experimentalist and modeller as uncertainties are high. The implications for model design are that these decisions need to be assessed carefully, especially in the highlighted cases of the selection of boundary conditions, initial conditions and the soil algorithm. The potential consequences of particular decisions are greatest and most quantifiable if there is a simple binary 'on/off' switch of the process. The consequence is more complex, multi-dimensional and possibly self-cancelling, if a number of parameters are variable. The different classes of decisions should be assessed in terms of their effects on the state variables of the system to which the modelling is directed. The discussions presented herein emphasize the importance of selecting appropriate internal model configurations for the numerical representation of hillslope hydrological processes and moreover suggest that there is compelling evidence that such model architecture decisions need to be explored fully prior to numerical hillslope models being used for process inference. Further model developments should include the testing of these configuration decisions over a range of scenarios.

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