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Using a fully coupled surface water - groundwater model to quantify streamflow components

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Abstract: Separation of streamflow components into quickflow and baseflow is usually carried out in two main ways: hydrograph recession analysis and tracer-based methods. In this paper, it is proposed to use a fully coupled surface and subsurface flow and transport model to gain a better understanding of the relationship between physical catchment characteristics (e.g. aquifer hydraulic conductivity) and hydrological response (e.g. stream salinity and flow response) to a rainfall event. This enables an evaluation of the common empirical approaches of recession analysis and baseflow separation in practice. This is achieved by conducting a range of numerical experiments on a hypothetical case study, which is based on a commonly used surface water-groundwater interaction benchmarking problem. A fully coupled, variably saturated surface-subsurface flow and transport model (HydroGeoSphere) forms the basis of the numerical experiments conducted in this investigation. The results indicate that the empirical baseflow separation algorithms failed to reproduce the simulated groundwater discharge to the stream from the theoretical catchment, although it was identified that the surface-subsurface benchmark problem needs to be further developed to produce more realistic hydrograph behaviour before a proper comparison between the two approaches can be made.

Keywords: *Baseflow separation; Surface water - Groundwater interactions; Numerical modelling*

1. INTRODUCTION

The understanding of hydrographs has long been recognised as being very important in catchment hydrology. In particular, the identification of baseflow (presumed to be groundwater discharge for the purposes of this study) and quickflow components of stream flow is necessary for assessing catchment functioning. Historically, the separation of the stream flow hydrograph into baseflow and quickflow has been carried out using empirical methods, which commonly utilise stream flow recession characteristics combined with digital filters or graphical approaches. Alternatively, artificial and environmental tracers can be used in combination with flow measurements to separate the components of stream flow based on their respective chemical characteristics (Jones et al., 2006). A combination of these two approaches is described by Werner et al. (2008), who examined the shape of the stream salinograph (salinity versus time) to assess the recession behaviour of the catchment's flow constituents.

The accuracies of existing baseflow separation methods that use recession analysis and digital filters are difficult to evaluate due to a lack of benchmarking cases that might serve to validate the estimation of baseflow. Inter-comparisons between various empirical methods for baseflow separation highlight the relative accuracy and performance of the tested methods based on usability and objectivity (Nathan & McMahon, 1990; Chapman, 1999). However, there appear to be no studies that attempt to validate the accuracy of baseflow estimation for individual methods by testing against well-defined test cases. In the current study, we hypothesise that a physically based surface-subsurface model can be used to generate synthetic hydrographs with known baseflow and quickflow components to evaluate existing empirical hydrograph analysis techniques. In order to test this hypothesis, we first develop a base-case modelling simulation of streamflow generation, and undertake rigorous diagnostics to evaluate the various flow components of the resulting discharge hydrograph.

Integrated surface-subsurface modelling tools have evolved rapidly in recent years, and are now being applied to the analysis of catchment functioning in real-world settings. Prominent examples include studies by Panday & Huyakorn (2004), Jones et al. (2006) and Werner et al. (2006). The applicability of coupled surface-subsurface models to real-world settings provides evidence of the capacity of these models to produce somewhat realistic catchment behaviour. In this study, a theoretical catchment model based on a common surface water/groundwater benchmarking problem is modelled, in which streamflow components and concentrations are predicted at the catchment outflow, and are utilised to compare against common empirical methods for baseflow separation. This study is carried out considering a small range of hydrograph analysis methods and considers two different soil types for the theoretical catchment.

2. METHODS

The methodological approach used in this study was based around model simulations of a theoretical catchment based on the extension of the tilted V-catchment DiGiammarco et al. (1996) problem published in Panday & Huyakorn (2004). The outlet hydrograph modelled for this theoretical catchment was interpreted using common empirical methods of recession analysis and baseflow separation. The model simulations were used to provide flow and transport information within the theoretical catchment, in order to account for the streamflow components (i.e. baseflow and quickflow).

2.1. Model Simulation

The conceptual model in this study uses Richards' equation for matrix flow and considers a single continuum only (i.e. no macropores or fractures), and the St Venant equations for surface flow.

HydroGeoSphere or HGS (Therrien et al., 2009), a fully coupled surface water – groundwater flow and transport code, was used for carrying out model simulations in this study. HGS solves the following modified form of the Richards' equation (Therrien et al., 2009) for subsurface flow:

$$-\nabla\cdot\left(-\overline{K}\cdot k_r\nabla(\psi+z)\right)+\sum\Gamma_{ex}\pm Q=\frac{\partial}{\partial t}(\theta_s S_w) \quad \textbf{(1)}$$

Where $\overline{K}$ is the hydraulic conductivity tensor, k_r is the relative permeability, ψ is the pressure head, z is the elevation head, Γ_{ex} is the subsurface fluid exchange rate with the surface domain, Q is a subsurface fluid source or sink, θ_s is the saturated water content and S_w is the water saturation.

The following form of the St Venant equations (Therrien et al., 2009) are solved for surface flow:

Mass balance: $$\frac{\partial \phi_0}{\partial t} + \frac{\partial(\bar{v}_{x0} d_0)}{\partial x} + \frac{\partial(\bar{v}_{y0} d_0)}{\partial y} + d_0\Gamma_0 \pm Q_0 = 0 \quad \textbf{(2)}$$

Where ϕ_0 is the surface porosity, $\bar{v}_{x0}$ and $\bar{v}_{y0}$ are the vertically averaged flow velocity in the x and y directions respectively, d_0 is the water depth, Γ_0 is the fluid exchange rate with the subsurface, and Q_0 is a surface fluid source or sink.

Momentum equation in x: $$\frac{\partial}{\partial t}(\bar{v}_{x0} d_0) + \frac{\partial}{\partial x}(\bar{v}_{x0}^2 d_0) + \frac{\partial}{\partial y}(\bar{v}_{x0}\bar{v}_{y0} d_0) + g d_0 \frac{\partial d_0}{\partial x} = g d_0 (S_{0x} - S_{fx}) \quad \textbf{(3)}$$

Momentum equation in y: $$\frac{\partial}{\partial t}(\bar{v}_{y0} d_0) + \frac{\partial}{\partial y}(\bar{v}_{y0}^2 d_0) + \frac{\partial}{\partial x}(\bar{v}_{x0}\bar{v}_{y0} d_0) + g d_0 \frac{\partial d_0}{\partial y} = g d_0 (S_{0y} - S_{fy}) \quad \textbf{(4)}$$

Where g is the acceleration due to gravity, S_{0x} and S_{0y} are the surface flow bed slopes in the x and y direction respectively, and S_{fx} and S_{fy} are the surface flow friction slopes in the x and y direction respectively.

HGS solves the above equations simultaneously using either finite difference (FD), control volume finite difference (CVFD) or finite element (FE) methods. The CVFD method was used in this study, utilising its quick execution on regular model grids and superior mass conservation, as compared to FD.

2.2. Hydrograph analysis

The analysis of hydrographs for the purpose of estimating baseflow requires a clear understanding of how baseflow and quickflow are defined;

*"**Baseflow** is the longer-term discharge into a stream from natural storages, notably sustaining flow between rainfall events. Recognising that there can be multiple natural storages in a catchment, the discharge of groundwater to the stream is termed the groundwater component of baseflow.*

***Quickflow** is the direct response to a rainfall event including overland flow* (*runoff*), *lateral movement in the soil profile* (*interflow*) *and direct rainfall onto the stream surface* (*direct precipitation*)" (Connected Water, 2009)

Once defined, the objective of the separation becomes clear. When not defined, it is sometimes unclear as to whether the separation is being performed to understand the quantity of pre-event groundwater contributing to the stream, and in that sense, the nature of the surface/groundwater interaction, or whether it is for the purpose of general catchment characterisation of the rainfall-stream discharge relationship. For instance, in tracer based methods, the separation seems based on quantifying pre-event groundwater discharge as opposed to baseflow as defined above.

In this study a simple recession analysis is applied to determine the baseflow recession constant and then two filters for baseflow separation are applied and the results compared with the simulated baseflow.

Recession analysis

The method for recession analysis used in this study is an approximation of the semi-logarithmic plot of the recession curves as three straight lines of different slope to obtain the baseflow recession constant (Barnes 1940). The recession constant for baseflow was determined for the three rainfall events and averaged.

Baseflow separation

Baseflow separation was carried out using two different digital recursive filters. Graphical methods were not considered as they are difficult to apply in practice to long continuous records of stream flow (Chapman, 1999). Although the simulations in this study do not consist of long continuous stream flow data, the emphasis was on the more common methods used in practice.

The Lyne & Hollick filter is the first filter used (objectively) for performing the baseflow separation in this study. The filter, as in Chapman & Maxwell (1996) takes the form:

$$q_{b(i)} = \frac{k}{2-k} q_{b(i-1)} + \frac{1-k}{2-k} q_{(i)} \quad \textbf{(5)}$$

Where $q_{(i)}$ is the original streamflow for the i^{th}sampling instant, k is the filter parameter given by the recession constant, $q_{b(i)}$ is the filtered baseflow response at time interval i, $q_{b(i-1)}$ is the filtered baseflow response for the previous sampling instant to i.

The two-parameter Boughton algorithm recommended in Chapman (1999) is also applied (subjectively) to filter baseflow from the total stream flow using the following relationship:

$$q_{b(i)} = \frac{k}{1+C} q_{b(i-1)} + \frac{C}{1+C} q_{(i)} \quad \textbf{(6)}$$

Where C is a parameter that allows the shape of the separation to be altered.

3. MODEL SIMULATIONS

3.1. Overview

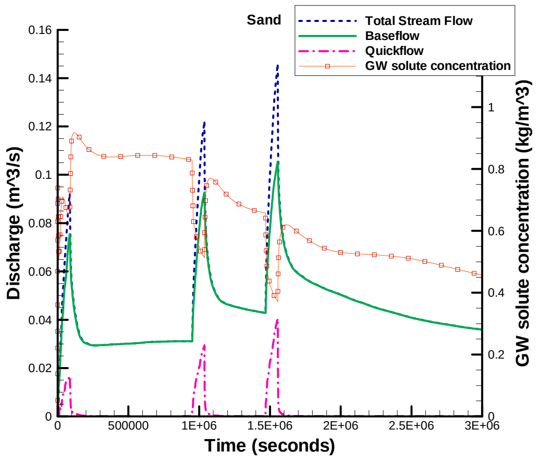
The tilted V-catchment model of Panday & Huyakorn (2004) used in this study extends the DiGiammarco et al. (1996) model to include the subsurface and uses a fully-coupled approach to model the surface/subsurface interaction. This particular model was replicated in HGS (Therrien et al., 2009) for comparison using the Panday & Huyakorn (2004) model as a benchmark, with very good agreeance between the models. This model was extended futher to include transport, in order to infer the pre-event groundwater contribution of baseflow.

Replication of the tilted V-catchment model in HGS is compared with MODHMS simulations (HydoGeoLogic, 2006) of the same catchment using a multi event scenario and shows reasonable agreement between the two. The multi-event simulation consisted of 3 rainfall events, each of 1 day duration with 2 inches of rain and recovery periods after each of 10, 5 and 10 days respectively. The reader is referred to Panday & Huyakorn (2004) for characterisation of the catchment.

The multi event scenario was performed for two soil types. Recession analysis and baseflow separation was applied to the model outputs and compared to the baseflow output from the model hydraulics and the GW component determined by groundwater concentration instream.

3.2. Multiple soil types

Soil types used for this study are given in Table 1. The soils types, corresponding properties and Van Genuchten parameters were taken from Carsel & Parrish (1988), representing two homogeneous soil types. The results from the multi-event simulation using the two soil types are shown in Figure 1. The simulated quickflow and baseflow, as well as groundwater solute concentration, are shown for each soil type.



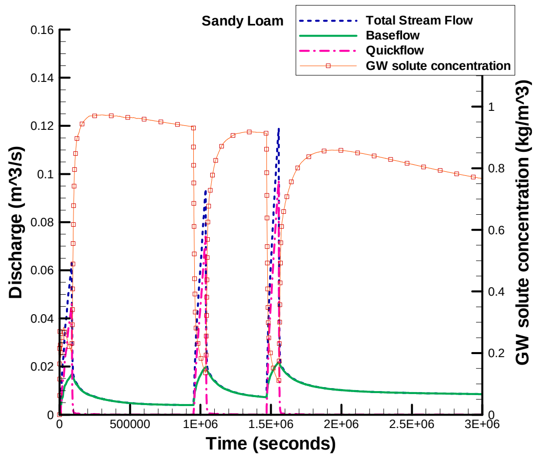


Figure 1. Hydrographs for the two soil types with simulated baseflow and quickflow components.

Table 1. Soil types and properties with Van Genuchten parameters used in model simulations (adapted from Carsel & Parrish 1988)

SOIL TYPE	θ_r mean	K_{sat} mean m/s	α mean /m	N (β) mean
1. Sand	0.045	8.25×10^{-5}	14.5	2.68
2. Sandy Loam	0.065	1.23×10^{-5}	7.5	1.89

4. ANALYSIS

The analysis carried out shows comparison between the inferred nature of baseflow from empirical separation against the output from the model simulations. Whilst the empirical methods are designed around real systems, the conceptual basis (i.e. linear storage-discharge relationship of a catchment) of such empirical methods does not seem to warrant further complexity in the theoretical catchment. Hydrograph behaviour and water balance in the simulation of the sand aquifer is investigated in some detail.

4.1. Recession analysis and Baseflow Separation

Recession analysis, proved difficult due to the recession behaviour of the hydrograph in the theoretical catchment. This was because the recession periods were small, making it difficult to determine the baseflow recession constant confidently. Filter parameters k (recession constant) and C (Boughton filter parameter) determined from the hydrograph are summarised along with performance of each of the filters in Table 2. The percentage difference of estimated baseflow as compared to simulated baseflow for each empirical method is shown for the two soil types in Figure 2. Only the second and third rainfall event is shown for the hydrographs in order to make clear the differences in estimated and simulated hydrograph shape. The percentage difference between estimated and simulated baseflow is quantified using the relationship:

$$difference\_(\%) = \frac{Q_{Bsim}/Q_T - Q_{Best}/Q_T}{Q_{Bsim}/Q_T} \times 100 \tag{7}$$

Where Q_{Bsim} and Q_{Best} are the simulated and estimated baseflows respectively and Q_T is total stream flow.

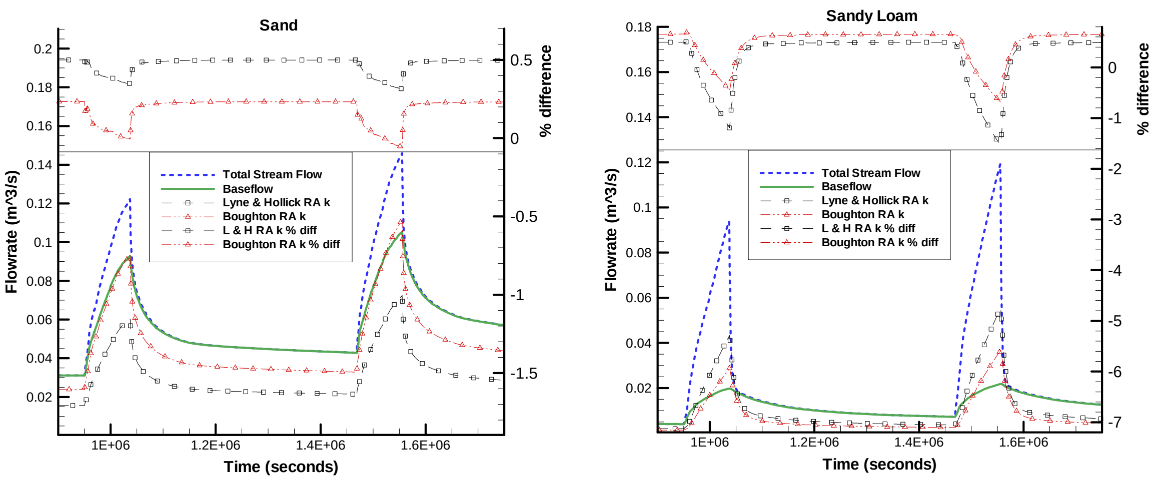


Figure 2 Baseflow estimations and differences relative to baseflow/streamflow ratio for each soil type.

Performance of both the Lyne & Hollick and Boughton filter was reasonable for estimating the proportion of baseflow for the sand and sandy loam, although clearly the filters are underestimating baseflow in the longterm (not during events) and are not able to account for variations that occur in the baseflow-streamflow relationship. In the case of the sand, most of the rainfall infiltrates, leading to recharge with only a small proportion being quickflow. However, in the sandy loam, the proportion of quickflow is much higher with less infiltration and a resulting smaller baseflow component. The filters fail conceptually in their ability to be widely applied as the filters are reliant only on the recession relationship of baseflow and the nature of the total hydrograph. As can be seen in Figure 2, the largest difference which isn't too high (0.5% and -1.4% for the sand and sandy loam respectively), occurs during rainfall events where it might be most important to understand the baseflow-streamflow relationship.

Table 2 Filter parameters and the filter performance for each soil.

SOIL TYPE	K mean	C	Lyne & Hollick performance	Boughton Perfromance
Sand	0.8477	0.5	Poor	Good
Sandy Loam	0.9519	0.025	Poor	Average

4.2. Hydrograph behaviour, boundary condition effects and model limitations

Hydrograph behaviour of the two different soils (Figures 1 & 2) shows clearly differing recession characteristics. It is noted that in comparison to a classical hydrograph, the simulated hydrograph does not behave exactly as expected. In particular, this is evident in the falling limb and peak hydrograph shape. This is a current limitation in the realm of fully coupled surface water-groundwater models. However, whilst not perfect, the processes conceptualised in this model can clearly be accounted for within the water balance.

The boundary condition of fixed head at the top of the model plays a critical role in the baseflow for this model. The fixed head directly affects the recession of the hydrograph by not only increasing groundwater in low water table periods, but also removing subsurface water from the system during rainfall events, as recharge is prevented above the fixed head near the boundary. This would most likely influence the baseflow as the water table is effectively forced to some degree by the fixed head. The rainfall boundary condition is applied in a non realistic fashion with steeper rising and falling limbs than observed in most real hydrographs. In taking a close look at the water balance for the sand in Figure 3 (looking closely at the second event in this simulation), some interesting aspects of the water balance arise that help explain some of the hydrograph behaviour discussed above.

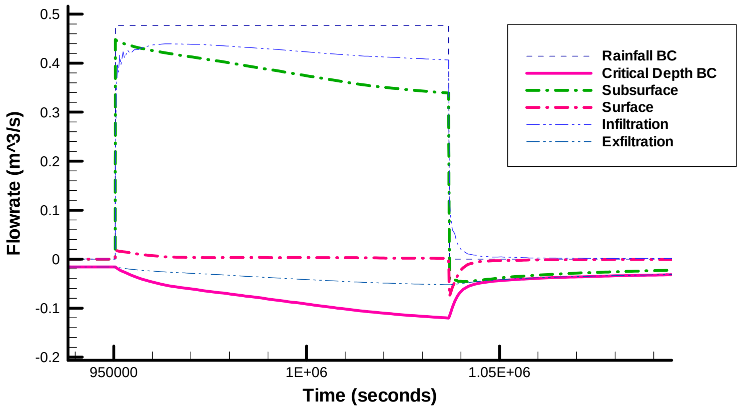


Figure 3 Water Balance for second rainfall event in the initial multi-event simulation

Considering first the rainfall boundary condition, this is a square pulse representing 2 inches of rainfall over a day and has implications as discussed above. The rainfall boundary is a forcing function causing accumulation in the surface and subsurface domains of the model.

The critical depth boundary (negative in the water balance, as it is flow out of the model domain) applied at the endpoint of the stream, shows an increase in discharge during the rainfall event and a decrease after the rainfall event as expected.

Inspection of the subsurface line (rate of accumulation) in Figure 3, demonstrates that most of the rainfall is infiltrating, which is also evident in the infiltration line. The relatively small accumulation in the surface domain indicates almost no direct runoff, as would be expected for a sandy aquifer. On close inspection the accumulation rate in the surface domain shows a sudden increase at the start of the rainfall event with a gradual decrease thereafter. However, in reality, due to preferential flow it would be expected that infiltration would be very high at the start of the low intensity rainfall event on a sandy aquifer. This is particularly significant because it highlights the limitation of the model to simulate infiltration as it tends to occur in the real world. It would be expected that the rate of accumulation in the surface domain would have a gradual increase from zero from the start of the rainfall event. The fact it doesn’t in this model could be attributed to the use of Richards' equation for subsurface flow. This is because prior to the start of the rainfall event, the soil at the surface is very dry. Based on Richards' equation, the hydraulic conductivity will be very low, almost preventing all infiltration. As time progresses and the soil saturates, the hydraulic conductivity will increase and therefore infiltration will increase. This suggests improved modelling is required of infiltration for this case.

5. DISCUSSION AND CONCLUSIONS

This study provides a platform for objectively comparing different empirical baseflow separation methods. Whilst there are limitations to the conceptual model for the theoretical catchment, it seems very promising for objective testing of empirical methods or hypotheses that cannot be determined in the laboratory or field. The failure of the empirical methods to match the simulated baseflow accurately in this study, warrants further investigation into where and when such methods are applicable.

It is recommended that further research be carried out in objectively assessing empirical methods for baseflow separation by: a) Considering a larger parameter set for the theoretical catchment; b) Including other processes such as evaporation, transpiration and preferential flow. In particular with preferential flow, this may address issues related to infiltration with Richards' equation flow; c) Considering a range of boundary conditions for fixed head/flux, longer simulation periods and a more realistic rainfall pattern, in such a way that highlights any forcing that might exist with particular boundary conditions; and d) considering more recession analysis and baseflow separation methods to provide a broader comparison of existing empirical methods.

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