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Research papers

Integrated surface-subsurface model to investigate the role of groundwater in headwater catchment runoff generation: A minimalist approach to parameterisation

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ABSTRACT

Understanding the role of groundwater for runoff generation in headwater catchments is a challenge in hydrology, particularly so in data-scarce areas. Fully-integrated surface-subsurface modelling has shown potential in increasing process understanding for runoff generation, but high data requirements and difficulties in model calibration are typically assumed to preclude their use in catchment-scale studies. We used a fully integrated surface-subsurface hydrological simulator to enhance groundwater-related process understanding in a headwater catchment with a rich background in empirical data. To set up the model we used minimal data that could be reasonably expected to exist for any experimental catchment. A novel aspect of our approach was in using simplified model parameterisation and including parameters from all model domains (surface, subsurface, evapotranspiration) in automated model calibration. Calibration aimed not only to improve model fit, but also to test the information content of the observations (streamflow, remotely sensed evapotranspiration, median groundwater level) used in calibration objective functions. We identified sensitive parameters in all model domains (subsurface, surface, evapotranspiration), demonstrating that model calibration should be inclusive of parameters from these different model domains. Incorporating groundwater data in calibration objectives improved the model fit for groundwater levels, but simulations did not reproduce well the remotely sensed evapotranspiration time series even after calibration. Spatially explicit model output improved our understanding of how groundwater functions in maintaining streamflow generation primarily via saturation excess overland flow. Steady groundwater inputs created saturated conditions in the valley bottom riparian peatlands, leading to overland flow even during dry periods. Groundwater on the hillslopes was more dynamic in its response to rainfall, acting to expand the saturated area extent and thereby promoting saturation excess overland flow during rainstorms. Our work shows the potential of using integrated surface-subsurface modelling alongside with rigorous model calibration to better understand and visualise the role of groundwater in runoff generation even with limited datasets.

1. Introduction

Understanding streamflow generation is a fundamental challenge in hydrology. The biggest source of uncertainty resides where most of the flow takes place and vegetation taps water for transpiration: the shallow subsurface (McDonnell, 2013; Sklash and Farvolden, 1979). The challenge has been tackled by a plethora of mathematical hydrological models with very different process conceptualisations ranging from parsimonious conceptual models (Bergstrom, 1976; Beven and Kirkby, 1979) to complex and highly parameterised physically-based simulators (Aquanty, 2016; Kollet and Maxwell, 2006) – all working towards constraining the fundamentals of streamflow generation.

Physically-based hydrological models integrating flow processes in the surface and subsurface provide a promising tool to test concepts of runoff generation and have been successfully used to reveal processes responsible for streamflow generation across scales (Frei et al., 2010; Liggett et al., 2015; Park et al., 2011; Weill et al., 2013). One of their main advantages is the ability to make use of various field-based observations in both constructing the models and assessing their performance. Their physically-

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based equations and spatially distributed parameterisation creates a consistent framework not only to mimick observed catchment behaviour, but also to formulate and test hypotheses for potential hydrological behaviour beyond existing measurements (Bolger et al., 2011; Hwang et al., 2015; Jones et al., 2006; Maxwell and Condon, 2016).

While acknowledging their apparent strengths, integrated surface-subsurface models are often criticised for the extensive data needed in parameterisation and numerical complexity leading to long model runtimes and numerical instabilities, which combine to complicate the process of catchment scale model calibration (Beven, 2002; Doherty and Christensen, 2011). Consequently, calibration of such models often resorts to 'manual' trial and error approaches (Ala-aho et al., 2015; Jones et al., 2008; Li et al., 2008), or no calibration at all (Bolger et al., 2011). Recent work has applied parameter optimisation routines, commonly the PEST software suite (Doherty, 2010) to calibrate integrated surface-subsurface models. These studies have calibrated parameters pertaining to subsurface and surface domains of catchment-scale models (Maneta and Wallender, 2013; Verbist et al., 2012; Wildemeersch et al., 2014; Yang et al., 2015) or subsurface and ET domains in more simple model configurations (Brunner et al., 2012; Schilling et al., 2014). To the best of our knowledge, studies incorporating rigorous model calibration that includes parameters from all model domains (surface, subsurface, ET), and thereby explicitly acknowledge the integrated nature of the simulated processes, are extremely rare. Overall, while catchment scale integrated surface-subsurface model applications are increasing, remote data-scarce headwater catchments are under-represented in the literature.

We propose that one can set up and calibrate a fully-integrated physically based model for a gauged basin with almost equally low data requirements as for any conceptual hydrological model. This is achieved by model calibration using the PEST framework (Doherty, 2010) where we use observations that could be expected in most gauged catchment and which are pertinent to all hydrologically relevant model domains (surface, subsurface and ET). Calibration is facilitated by novel simplifications for subsurface hydraulic and evapotranspiration parameterisation. To test which commonly available hydrological observations data are beneficial to improve simulation results, we perform a sequential calibration with incrementally more data-rich multi-component objective functions (cf. Birkel et al., 2014). We hypothesise that when introducing evapotranspiration and groundwater data in the calibration process, the model performance with respect to these variables would be improved and model parameters pertinent to these domains would be more identifiable. The study aims to achieve the classical proof of hydrological model success: a good hydrograph fit, but simultaneously produce physically meaningful output and an improved understanding of subsurface flow and runoff generation processes with minimum data requirements.

Our specific objectives are:

- To produce a spatially explicit and physically sound conceptualisation of how the subsurface operates in sustaining and generating streamflow in a glaciated headwater catchment.
- To do so by establishing a simple, novel, parameterisation inclusive of surface, subsurface, and ET domains of a fully-integrated model to facilitate a rigorous model calibration.
- Reveal and compare parameter sensitivities across all model domains (surface, subsurface, ET) for an integrated surface-subsurface model, an exercise not done before.
- Determine what data are useful to include in model calibration by examining changes in model responses and parameter sensitivities for different calibration objective functions.

2. Materials and methods

2.1. Study site

The study catchment, the Bruntland Burn, is a montane catchment (3.2 km^2) in the Scottish Highlands. The annual average precipitation approximates 1000 mm, with low seasonality, partitioning to around 600 mm annual runoff and 400 mm evapotranspiration. The catchment has an annually reoccurring but usually minor snow influence; typically accounting for<5% of annual precipitation. Recent work at the site has developed an understanding of the water storage distributions, flow paths and mixing processes by successfully combining tracer studies, hydrometric measurements and conceptual modelling approaches of various complexities (Birkel et al., 2011a,b; Blumstock et al., 2015; Huijgevoort et al., 2016; Soulsby et al., 2015). The above mentioned references contain detailed descriptions of the catchment characteristics, with a brief summary provided below.

Topographic relief in the catchment spans from 250 m (above sea level) at the outlet to 530 m at highest point on the southeast hilltop. Bedrock geology is low permeability unweathered granite and metamorphic rocks. Unconsolidated material overlying the bedrock covers $\sim$ 70% of the catchment and consists of glacial drift deposits, primarily undifferentiated till with a silty and sandy matrix. The glacial legacy of the area has left the catchment with a flat and wide valley bottom (slope < 3^o) where geophysics estimate the drift deposits to reach 30–35 m depth, thinning out towards the steeper hillslopes (slopes > 8^o). In the valley bottom riparian areas, mineral sediments are covered by organic peat soils along with shallower peaty gleys. The soils on the hillslopes consist of podzols. Vegetation on the hillslopes is dominated by heather (*Calluna* sp. and *Erica* sp.) moorland with minor scots pine (*Pinus sylvestris*) coverage. Riparian peatland areas are dominated by *Sphagnum* spp. mosses and some grasses (*Molina caerulea*).

2.2. Integrated surface-subsurface model setup

2.2.1. Conceptual model

Based on previous work, this study simplified the landscape into two units: organic peat soils covering the riparian areas and mineral glacial drift soil/sediments mantling the hillslopes and underlying the peat soil in the valley bottom. Within the numerical model this partitioning was used to parameterise (1) the overland flow domain differently in the riparian peatlands and hillslopes and (2) subsurface flow domain differently to mineral glacial drift sediments and organic riparian peat soils. Bedrock underlying the glacial drift was assumed impermeable and comprised a hydrologically inactive no-flow boundary.

2.2.2. Simulation code HydroGeoSphere

We chose HydroGeoSphere (HGS) as the physically based simulation code because of its capabilities in representing the main hydrological processes of interest in our study – surface and subsurface flow and evapotranspiration – in a physically based manner (Aquanty, 2016). HGS uses a control-volume finite element approach to solve the interconnected flow equations in the surface and subsurface simultaneously for each time step. Flow in the subsurface is solved by a variably saturated Richard's equation and surface flow with a diffusion-wave approximation of the Saint-Venant shallow water flow equations. The model also integrates an evapotranspiration module to simulate water uptake from model nodes closest to the ground surface. The model allows water to be exchanged freely between the different flow domains allowing hydraulic gradient throughout the model to govern the flow processes. To solve the equations above, the model domain needs