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Case Study

Understanding hydrological flow paths in conceptual catchment models using uncertainty and sensitivity analysis

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ABSTRACT

Increasing pressures on water quality due to intensification of agriculture have raised demands for environmental modeling to accurately simulate the movement of diffuse (nonpoint) nutrients in catchments. As hydrological flows drive the movement and attenuation of nutrients, individual hydrological processes in models should be adequately represented for water quality simulations to be meaningful. In particular, the relative contribution of groundwater and surface runoff to rivers is of interest, as increasing nitrate concentrations are linked to higher groundwater discharges. These requirements for hydrological modeling of groundwater contribution to rivers initiated this assessment of internal flow path partitioning in conceptual hydrological models.

In this study, a variance based sensitivity analysis method was used to investigate parameter sensitivities and flow partitioning of three conceptual hydrological models simulating 31 Irish catchments. We compared two established conceptual hydrological models (NAM and SMARG) and a new model (SMART), produced especially for water quality modeling. In addition to the criteria that assess streamflow simulations, a ratio of average groundwater contribution to total streamflow was calculated for all simulations over the 16 year study period. As observations time-series of groundwater contributions to streamflow are not available at catchment scale, the groundwater ratios were evaluated against average annual indices of base flow and deep groundwater flow for each catchment. The exploration of sensitivities of internal flow path partitioning was a specific focus to assist in evaluating model performances. Results highlight that model structure has a strong impact on simulated groundwater flow paths. Sensitivity to the internal pathways in the models are not reflected in the performance criteria results. This demonstrates that simulated groundwater contribution should be constrained by independent data to ensure results within realistic bounds if such models are to be used in the broader environmental sustainability decision making context.

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1. Introduction

In the natural environment, hydrological flows exist as a continuum throughout the surface landscape and subsurface formations. Hydrological models attempt to capture the dominant processes in a catchment to predict river flows. For practical reasons, this flow continuum is simplified into discrete flow paths to facilitate conceptual understanding, model development and data analysis. The number of flow paths identified can depend on the catchment characteristics and the ultimate objective of the investigation, with two to four flow paths typically representing responses of flow processes reaching a river (e.g. SMARG (Kachroo, 1992; Khan, 1986; Tan and O'Connor, 1996), HBV (Bergström, 1995), NAM (Nielsen and Hansen, 1973) and PRMS (Leavesley et al., 1983, 1996)).

The merits of conceptual, parametrically parsimonious, hydrological models for investigating the dominant pathways and processes in catchments have been widely discussed (e.g. Refsgaard and Henriksen, 2004; Sivapalan, 2003). Model parameter identification is a fundamental challenge for hydrologists (Duan et al., 2006; Sivapalan, 2003). The presence of parameter interactions in conceptual rainfall–runoff (CRR) models can make a priori parameter prediction methods unreliable (Wagener and Wheater, 2006). Ideally, a model should be parametrically parsimonious while still capturing the dominant processes of the catchment with limited parameter interactions. Many hydrological models have been developed and used for decades for both research and operational hydrology. However, new model structures are still being developed to incorporate new conceptual understanding of specific catchment processes and places (Beven, 1999), and to facilitate the demands of new pressures on water resources, including nutrient enrichment (Futter et al., 2014).

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There is a growing body of literature investigating model structure uncertainty (Breuer et al., 2009; Clark et al., 2008; Gupta et al., 2012; Kavetski and Fenicia, 2011; Wagener et al., 2001). The focus is increasingly turning to the internal movement of water within these conceptual models to investigate if each of the simulated processes contributing to the total flows are realistic (e.g. Fenicia et al., 2011; Kokkonen and Jakeman, 2001). This hydrological partitioning is particularly important when coupling flow simulations with water quality, as the flow path can have a significant effect on solute transport and attenuation (Futter et al., 2014; Medici et al., 2012). Typically, particulate phosphorus is delivered via overland flow (Jordan et al., 2005). Nitrate is typically delivered to streams via subsurface pathways, with links between increasing nitrate concentrations and groundwater contributions (Tesoriero et al., 2009).

Sensitivity analysis (SA) is “the principal evaluation tool for characterizing the most and least important sources of uncertainty in environmental models” (U.S.EPA, 2009). The central role of sensitivity analysis for testing and implementing environmental models is widely noted (Refsgaard et al., 2007; U.S.EPA, 2009). Sensitivity analysis of parameters of water quality models has been undertaken using one-at-a time sensitivity analysis (e.g. Morris, 1991) with Latin Hypercube Sampling, for example, for simulating dissolved oxygen with the ESWAT model (Vandenberghe et al., 2001) and nitrogen with the INCA-N model (Rankinen et al., 2013), or other Monte Carlo methods (e.g. McIntyre et al., 2005; Sánchez-Canales et al., 2015). More recently, variance based sensitivity methods have been employed for the parameters of SWAT (Nossent et al., 2011; Zhang et al., 2013).

Variance based sensitivity analysis (e.g. Sobol, 2001) is recommended as a superior method for which the computational effort is not prohibitive (Saltelli and Annoni, 2010; Tang et al., 2007; U.S.EPA, 2009). For non-linear conceptual hydrological models such as those investigated in this study, variance based methods are ideal to investigate the parameter sensitivities and interactions in the global parameter space (e.g. O'Loughlin et al., 2013; van Werkhoven et al., 2008, 2009; Zhan et al., 2013).

The aim of the study was to identify a suitable hydrological model that can represent the internal flow paths in Irish catchments. In this paper, a new model that was developed with a focus on sub-surface flow paths, SMART, is compared with two well-established conceptual models, NAM and SMARG. The parameters and internal flow paths the three models are compared using (i) an uncertainty analysis and (ii) a variance based sensitivity analysis method. The analysis is carried out on multiple metrics of the three models simulating a 16 year period in 31 Irish catchments.

2. Data

2.1. Catchment data

The majority of Ireland's area (70,000 km^2) has central, gently undulating lowlands of elevations generally less than 150 m above

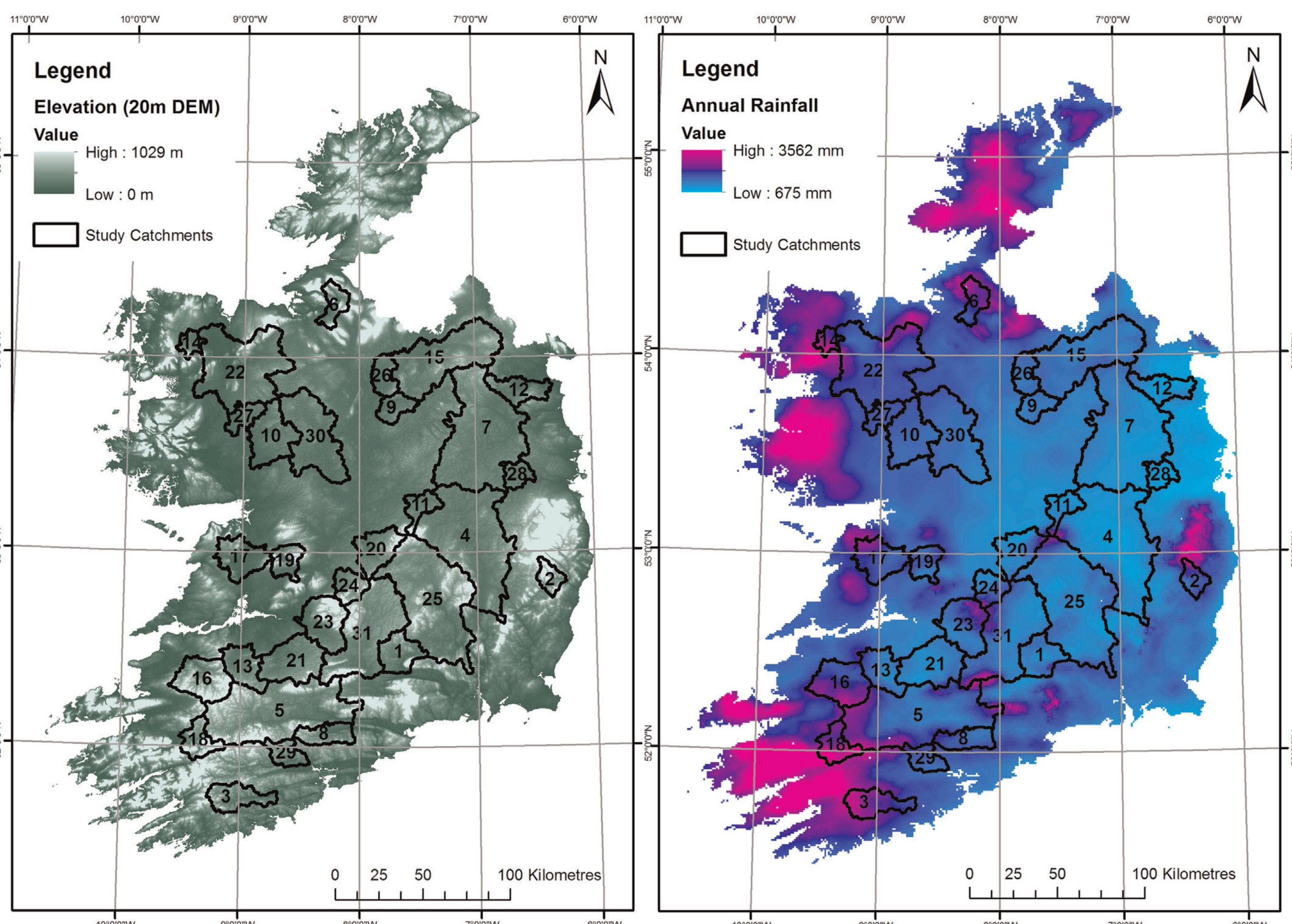

Fig. 1. Locations of the study catchments (numbers relate to Table 1), with the left panel showing the terrain data (DEM source: EPA) and right panel show the annual average rainfall (AAR). Source: Met Éireann (1981–2010).

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