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Regional water resources assessments using an uncertain modelling approach: The example of Swaziland

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ABSTRACT

Study region: The 5 river basins that flow through or within Swaziland in southern Africa.
Study focus: A regional water resource assessment using an uncertainty version of the Pitman monthly rainfall-runoff model whose outputs are constrained by six indices of natural hydrological response (mean monthly runoff, mean monthly groundwater recharge, Q10, Q50 and Q90 percentage points of the flow duration curve and% time of zero flows) for each of the 122 sub-basins within the whole of Swaziland. A 2-step approach is adopted where the first step establishes behavioural, but uncertain, model parameter ranges for natural incremental sub-basin hydrological responses, while the second step links all the sub-basin outputs to generate cumulative sub-basin outflows and allows for water use parameters to be included.
New hydrological insights for this region: The analysis of hydrological indices highlights the regional variations in hydrological processes and sub-basin response. The adopted modelling approach provides further insight into all of the uncertainties associated with quantifying the available water resources of Swaziland. The study has provided more insight into the spatial variability of the hydrological response and existing development impacts than was previously available. These new insights should provide an improved basis for future water management in Swaziland.

1. Introduction

Regional water resources assessments are vital for the effective management of the water resources of a country, while in southern Africa adequate measurement of hydrological variables is not possible for various economic or human capacity reasons (Mazvimavi, 2003). It is therefore necessary to rely on what few measurements are available (Seibert and Beven, 2009) and to fill the gaps in the information required for effective management with appropriate models (Pomeroy et al., 2013). In addition, measured stream flow data are rarely completely accurate, nor do we fully understand what they represent, due to non-stationary upstream impacts (Thirel et al., 2015). Hydrological and water resources models are not perfect representations of the real world (Fenicia et al., 2008), are often forced with inaccurate or poorly representative climate data, and are not always applied with appropriate parameters. Beven (2000) also refers to the concept of *uniqueness of place*, how this gives rise to differences in catchment hydrological response and how it limits our ability to generalise hypotheses (Beven, 2012) in approaches to hydrological regionalisation. It is clear, therefore, that regional water resources assessments will always be subject to uncertainties, particularly in regions such as southern Africa where hydrological response is highly

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variable in time and space and where data are scarce (Hughes et al., 2010). While the scientific hydrological community has long recognised this fact and developed appropriate modelling strategies (Sivapalan et al., 2003; Blöschl et al., 2013; Hrachowitz et al., 2013), it appears to be more difficult to adopt uncertainty approaches in practice (Pappenberger and Beven, 2006).

Many hydrological regionalisation approaches (Grayson et al., 2002; Farmer et al., 2003; Wagener et al., 2007; Sawicz et al., 2011) have been based on catchment physical properties (topography, geology, soils, vegetation, etc.), but unfortunately their success is often limited not only by the uniqueness of place concept, but also by deficiencies in the data available to quantify the physical properties, as well as the relatively large spatial scales used in practical hydrological modelling (Kapangaziwiri et al., 2012) and the inherent complexities (McDonnell et al., 2007). The dominant climatic and landscape controls on hydrologic behaviour are also time-scale dependant (Atkinson et al., 2003; Farmer et al., 2003; Son and Sivapalan, 2007). Grayson et al. (2002) argue that observed spatial patterns of hydrological response can be effective discriminators of "behavioural" and "non-behavioural" models and used to constrain model outputs. Hydrologic similarity based on hydrological response is, therefore, the basis for transferability of information and for generalisation of hydrologic understanding (Sawicz et al., 2011). There are therefore two key issues in conducting regional water resources assessments in relatively data scarce areas:

- What information (Beven and Westerberg, 2011) and methods can be used to develop a regionalisation approach based on hydrological models?
- What data (or information) are available to validate and/or constrain the model outputs to ensure that the uncertainties in the results are minimised?

Earlier methods of regionalising the parameters of hydrological models tended to focus on direct methods of parameter estimation from physical basin data (Kapangaziwiri and Hughes, 2008) or the identification of relationships between pre-calibrated model parameters and basin properties (Mazvimavi, 2003; Pokhrel and Gupta, 2009). However, more recently there has been a focus on using measured or estimated basin response characteristics to constrain the ensemble outputs of an uncertain hydrological model, rather than directly estimating parameter values in a single model run (Yadav et al., 2007; Zhang et al., 2008; Westerberg et al., 2011; Kapangaziwiri et al., 2012; Hrachowitz et al., 2014; Tumbo and Hughes, 2014; Westerberg et al., 2014; Nijzink et al., 2016). Others have used similar approaches to assess model structures (Euser et al., 2013). This study builds upon a growing body of literature that addresses the issues of hydrological model uncertainty and quantifying behavioural parameter sets using regionalised indices of sub-basin hydrological response to constrain the outputs of a hydrological model. The geographical context is the river basins that flow through the whole of the small Kingdom of Swaziland in southern Africa. The overall objective of the study is to develop a hydrological model for the whole country that explicitly includes uncertainty in our knowledge of natural hydrological response as well as in existing and future abstractions. The final model is expected to contribute to improved understanding of the regional hydrology of the country as well as to the practical needs of water resources managers for robust estimates of water availability in Swaziland.

2. Modelling methods

The general approach adopted in this study is illustrated in Figs. 1 and 2 and follows similar procedures discussed in Tumbo and Hughes (2015) that were applied to the Great Ruaha River basin in Tanzania. The hydrological model used is an uncertainty version of the semi-distributed, monthly time step Pitman model (Pitman, 1973; Hughes, 2004; Hughes, 2013), but the approach is considered applicable to many other hydrological models that are also based on a sub-basin spatial distribution system. The uncertainty approach is divided into two steps (Fig. 1). The first step simulates the incremental natural flows for all of the sub-basins and links between sub-basins are ignored (i.e. cumulative flows are not calculated). The inputs to the first step are the climate forcing data, a set of ranges (minimum and maximum) defining the feasible parameter space for all of the model parameters that affect the incremental sub-basin natural hydrology (i.e. downstream routing and water use parameters are not included) and a set of ranges defining the indices of hydrological response that are used to constrain the model outputs. There are six constraint indices used in this study, although additional constraints could be included where this is considered appropriate. The indices are mean monthly runoff volume (MMQ in $m^3 * 10^6$), mean monthly groundwater recharge depth (MMR in mm), the 10th, 50th and 90th percentiles of the flow duration curve expressed as a fraction of MMQ (Q10/MMQ, Q50/MMQ, Q90/MMQ) and the percentage of time that zero flows are expected (%Zero). These have been adopted as representing the minimum number of key indices that can discriminate between different hydrological responses.

The model interface allows the user to specify the total number of model runs (typically 100 000), as well as the maximum number of behavioural solutions that are desired (typically 5 000). Each model run is based on independent random sampling of the parameter ranges assuming that the minimum and maximum values define a uniform distribution. If the model results for each sub-basin fall within the ranges of all the constraint indices for that sub-basin, the result is considered behavioural and the parameter set values are saved to a database for use with step two. The model continues to run until either the maximum number of saved parameter sets has been achieved or the maximum number of model runs is reached. A model utility is available to view the distributions of the individual parameter and constraint index values within all of the saved behavioural ensembles. This utility can be used to better align the parameter ranges to the constraints (i.e. shift, reduce or