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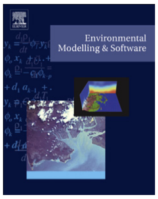

Performance assessment and improvement of recursive digital baseflow filters for catchments with different physical characteristics and hydrological inputs

Li Li [a,1], Holger R. Maier [a,2], Daniel Partington [a,1], Martin F. Lambert [a,*], Craig T. Simmons [b,3]

[a] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide 5005, South Australia, Australia
[b] National Centre for Groundwater Research and Training and School of the Environment, Flinders University, GPO Box 2100, Adelaide 5001, South Australia, Australia

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ABSTRACT

Recursive digital filters (RDFs) are one of the most commonly used methods of baseflow separation. However, how accurately they estimate baseflow and how to select appropriate values of filter parameters is generally unknown. In this paper, the output of fully integrated surface water/groundwater (SW/GW) models is used to obtain optimal parameters for, and assess the accuracy of, three commonly used RDFs under a range of physical catchment characteristics and hydrological inputs. The results indicate that the Lyne and Hollick (LH) filter performs better than the Boughton and Eckhardt filters, over a larger range of conditions. In addition, the optimal values of the filter parameters vary considerably for all three filters, depending on catchment characteristics and hydrological inputs. The dataset of the 66 catchment characteristics and hydrological inputs, as well as the corresponding simulated total streamflow and baseflow hydrographs obtained using the SW/GW model, can be downloaded as Supplementary material.

1. Introduction

The estimation of baseflow plays an important role in the management of many environmental systems, including water supply (Linsley et al., 1988), low flow hydrology (Nathan and McMahon, 1992; Smakhtin, 2001), flood hydrology (Murphy et al., 2009), contamination investigation (Smakhtin, 2001) and stream ecology (Price, 2011). There are various definitions of baseflow, including groundwater discharge (Chapman, 1999; Freeze, 1972), slow flow and sustained flow (Hall, 1968). In this study, groundwater discharge from aquifers represents the baseflow contribution to streamflow.

Due to the difficulties associated with the estimation of baseflow in the field (Li et al., 2013; Partington et al., 2012), various graphical and automated techniques have been developed for baseflow estimation from gauged streamflow data since the early twentieth century. Among these, recursive digital filters (RDFs) are one of the most commonly used methods for estimating baseflow in practice, due to their simplicity and ease of implementation (Arnold et al., 1995; Nathan and McMahon, 1990). The basic principle underpinning these RDFs is that streamflow hydrographs consist of a high frequency signal (i.e. quickflow) and a low frequency signal (i.e. baseflow) and that by applying a filter to the total streamflow hydrograph, the quickflow component can be removed, leaving the baseflow component. Many different RDF configurations have been proposed in the literature in order to achieve this, including the Lyne and Hollick (LH) filter (Nathan and McMahon, 1990), the Chapman one parameter algorithm (Chapman and Maxwell, 1996), the Boughton two-parameter filter (Boughton, 1993; Chapman, 1999) and the Eckhardt filter (Eckhardt, 2005). A common feature of all of these RDFs is that the baseflow hydrographs obtained are a function of one or more user-defined filter parameters. For some RDFs (Eckhardt, 2005; Nathan and McMahon, 1990), fixed values of the filter parameters are used, while for others (Chapman, 1999; Eckhardt, 2005; Meynink, 2011), values of some or all of the filter parameters are selected based on various catchment and/or streamflow characteristics.

A number of studies have compared the performance of different RDFs (Chapman, 1999; Eckhardt, 2008; Evans and Neal,

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[*] Corresponding author. Tel.: +61 (0)8 8313 4320; fax: +61 (0)8 83034359.
E-mail addresses: l.li@alumni.adelaide.edu.au (L. Li), holger.maier@adelaide.edu.au (H.R. Maier), daniel.partington@adelaide.edu.au (D. Partington), martin.lambert@adelaide.edu.au (M.F. Lambert), craig.simmons@flinders.edu.au (C. T. Simmons).
[1] Tel.: +61 (0)8 8313 4323.
[2] Tel.: +61 (0)8 8313 4139.
[3] Tel.: +61 8 8201 5509; fax: +61 8 8201 7906.

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2005; Murphy et al., 2009; Tan et al., 2009). However, determining the relative performance of different filters in terms of their ability to estimate baseflow accurately is not easy, primarily because it is extremely difficult to measure baseflow in the field (Dukic, 2006; McCallum et al., 2010), thereby making it almost impossible to determine an appropriate benchmark against which filter performance can be assessed. In order to overcome this problem, a number of different approaches have been used. Nathan and McMahon (1990), Chapman (1999), Eckhardt (2008) and Schwartz (2007) subjectively used the physical plausibility of the resulting baseflow hydrographs to evaluate RDF performance. Szilagyi (2004) and Ferket et al. (2010) applied the outputs of lumped and semi-distributed catchment models as a basis of comparison. Other authors have used process-based models as a performance benchmark. For example, Furey and Gupta (2003) used a process-based model of a hill-slope to evaluate the physically-based baseflow separation method developed by Furey and Gupta (2001). Most recently, Partington et al. (2012) used the baseflow simulated from a fully integrated surface water and groundwater (SW/GW) model at the catchment scale in order to evaluate the performance of simple automated baseflow estimation methods. While significant research efforts have been devoted to the assessment of the overall performance of different RDFs with commonly used values of filter parameters, there has been limited research on the impact of the values of the filter parameters on RDF performance.

In order to address this shortcoming, Li et al. (2013) developed a calibration framework for RDFs. As part of this framework, optimal values of filter parameters can be obtained by minimising the difference between the baseflow hydrograph predicted by the RDF under consideration and the baseflow hydrograph obtained from a fully integrated SW/GW model using a particular error measure. This assumes that fully integrated SW/GW models can provide reasonably accurate estimates of actual baseflow. They also tested this framework on a synthetic catchment with different soil properties in order to determine optimal values of these filter parameters and to assess the impact these values have on filter performance for various catchments with different soil properties. They found that there was a strong relationship between the optimal filter parameter value and saturated hydraulic conductivity (K_s). Also, the optimal values of the filter parameter obtained using the framework for various catchments with different soil types were quite different from the commonly used constant value suggested by other researchers. Their findings showed that the proposed framework has promise in terms of enabling optimal filter parameter values to be selected *a priori* based on physical catchment characteristics. However, Li et al. (2013) only tested their calibration framework on a single RDF, the most commonly used LH filter, and did not consider a range of catchment characteristics that are likely to have an impact on optimal filter parameter values, such as catchment size, slopes, aspect ratio and van Genuchten parameters α and β. In addition, Li et al. (2013) only tested their approach on a single hydrological record and did not consider the impact of evapotranspiration (ET), which could affect the seasonal and longer term trends in baseflow (D'Odorico et al., 2005). While other studies have attempt to predict certain baseflow properties as a function of catchment characteristics (e.g. (Lacey and Grayson, 1998; Longobardi and Villani, 2008; Mazvimavi et al., 2005; Mwakalila et al., 2002)), they have focused on summary statistics, such as the baseflow index (BFI), rather than the optimal parameters of RDFs.

In order to overcome the shortcomings of previous studies outlined above and to test the generality of the results obtained by Li et al. (2013), the objectives of this paper are (i) to determine optimal values of the filter parameters for, and assess the overall performance of, different RDFs under a wider range of physical catchment characteristics (e.g. catchment slopes, area, aspect ratio and soil properties) and hydrological inputs (e.g. rainfall and ET) using the frameworks developed by Li et al. (2013), and (ii) to develop regression relationships that will enable the suitability of different RDFs and the optimal values of filter parameters to be determined based on physical catchment characteristics and hydrological inputs. The remainder of this paper is organised as follows: the methodology is presented in Section 2, followed by the results and discussion of the study in Section 3. A summary and conclusions are given in Section 4.

2. Methodology

As stated in the introduction, in order to obtain optimal values of the filter parameters and assess overall RDF performance under a range of physical catchment characteristics and hydrological inputs, the calibration and assessment framework introduced by Li et al. (2013) is used, as shown in Fig. 1. As part of the framework, a fully integrated SW/GW model is used to generate streamflow and baseflow hydrographs for a catchment with particular physical properties, given a particular hydrological input. Both of these hydrographs are assumed to provide the best possible representation of the actual streamflow and baseflow hydrographs, as discussed in Li et al. (2013). It should be noted that in order to obtain the most accurate estimate of the baseflow hydrographs, the hydraulic mixing cell (HMC) method developed by Partington et al. (2011) is used.

The streamflow hydrograph obtained from the fully integrated SW/GW model (q) is used as the input to the RDF and the baseflow hydrograph obtained from the fully integrated SW/GW model using the HMC method (q_b^{sim}) is used as the benchmark for the calibration of the filter parameters and the assessment of overall RDF performance. As part of the calibration of the RDF filter parameters, an appropriate error measure between the baseflow hydrograph obtained using the fully integrated SW/GW model (q_b^{sim}) and that obtained using the RDF (q_b^{filter}) is minimised by adjusting the RDF filter parameter(s) using a suitable optimization algorithm. This minimised error measure is also used to assess the overall performance of the calibrated RDF.

As part of this study, the above process is repeated for different combinations of (i) physical catchment characteristics, including the saturated hydraulic conductivity (K_s) and van Genuchten parameters α and β (van Genuchten, 1980) of the soils, the area and aspect ratio of the catchment and the slopes along and perpendicular to the channel, and (ii) hydrological inputs, including rainfall and ET. Given the large number of possible combinations of the different catchment characteristics and hydrological inputs investigated and the long computer run times associated with each simulation of the fully integrated SW/GW model, a suitable sampling strategy (Fig. 1) is used in order to obtain representative combinations of the catchment characteristics and hydrological inputs considered, while keeping the total computational effort to a manageable level. After obtaining optimal filter parameter values and corresponding RDF performances (i.e. error measures), regression models are developed for predicting optimal filter parameter values and filter performance based on catchment characteristics and hydrological inputs. The calibration, assessment and regression model development procedure is repeated for three different RDFs, including the LH filter considered by Li et al. (2013), as well as the Boughton two-parameter and the Eckhardt filters. Details of the various steps in the methodology are given in the subsequent sections.

2.1. *Selection of catchment characteristics and hydrological inputs*

2.1.1. *Synthetic catchment description*

In this study, a synthetic catchment, which is loosely based on a benchmarked integrated surface-subsurface hydrology problem, the tilted V-catchment test case (Fig. 2), is used (Panday and Huyakorn, 2004) (P&H). The P&H case has the same surface geometry features as diGiammarco et al. (1996). In this study, modifications are made to the P&H case as follows: The original roughness coefficients used for the hill-slope and channel domains cause overland flow to be preponderant parallel and adjacent to the stream, rather than in the stream (Gaukroger and Werner, 2011), which was also mentioned as unrealistic by Panday and Huyakorn (2004). Thus, the same roughness coefficient (0.015 s/m$^{1/3}$) is used for both the overland flow and channel domains. Furthermore, the horizontal water table used in the P&H case represents an unrealistic (overly dry) initial condition (Partington et al., 2012). To start the model from more realistic initial conditions, the catchment is fully saturated and allowed to drain with a long time series of representative rainfall and ET events until the average annual discharge is stable (Partington et al., 2012). In order to reduce the influence of the coarse discretisation on the surface and subsurface flow, the unsaturated subsurface domain should have a finer discretisation. As a result, the original discretisation of the subsurface domain of the P&H catchment model is changed from 11 layers to 41 layers, with the top 20 m being formed with 40 uniform permeable layers of soil. Similar P&H case problems and the corresponding modifications are discussed in Gaukroger and Werner (2011), Partington