Environmental Modelling & Software 80 (2016) 122–131

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Disaggregating the components of a monthly water resources system model to daily values for use with a water quality model

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ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form
3 February 2016
Accepted 23 February 2016
Available online xxx

Keywords:
Water resources system models
Monthly models
Daily disaggregation

ABSTRACT

A model designed to disaggregate the water balance components of a monthly water resources system model to daily time series is presented. The objective of the model is to add value to existing monthly model setups and to provide daily water balance data for a water quality model. The model components include the disaggregation of incremental catchment flows, run-of-river and reservoir abstractions, reservoir releases for users and environmental flow requirements and reservoir spills. While previous studies have demonstrated that the main incremental catchment flow component is fit-for-purpose, the overall model is difficult to validate due to the impacts of imperfect monthly model simulations and the variability in operational practises compared with operational design procedures that form the basis of the model algorithm. Despite these reservations, the model is considered to provide a pragmatic, but useful approach to disaggregating monthly water balance simulations for use within a daily water quality model.

1. Introduction

Monthly rainfall-runoff (Hughes, 2013) and water resources system yield (Basson et al., 1994; Mallory et al., 2008) models have been in practical use in southern Africa for many years. The Pitman (1973) monthly rainfall-runoff model was first used in the early 1970s and has been in continuous use with some modifications (Hughes, 2013) ever since. It has formed the basis of several national water resources assessments of South Africa, including the most recent update (http://waterresourceswr2012.co.za/: accessed on 2 April 2015). However, the use of a monthly time step has attracted criticism during some recent local conferences and workshops (not published information) for not being able to generate daily data that are required for some water resources decision-making objectives. One such objective is the integration of water quantity and quality modelling, while others might include the quantification of environmental flows and detailed routing of reservoir releases for downstream water users in semi-arid areas. There are many different options available to fill the gap in the availability of appropriate modelling tools that can generate simulated daily flows. These include an updated development of a daily version of the same rainfall-runoff model (Pitman, 1976), the use of an existing daily rainfall-runoff model that has been designed for the region (Warburton et al., 2010), the development of an entirely new daily rainfall-runoff model or the use of a tried and tested internationally available model (e.g. the GR4J or HBV models; Perrin et al., 2003; Staudinger et al., 2011). With respect to the objective of integrating quantity and quality, a further option would be to use an existing integrated model (Lindström et al., 2010).

All of these options would have to be associated with the development of a daily version of a water resources system yield model that is appropriate, and aligned to existing South Africa approaches for system yield analysis and planning (Basson et al., 1994 and many Department of Water and Sanitation internal reports available on the DWS website (https://www6.dwa.gov.za/DocPortal/AllDocuments.aspx). This statement is based on the assumption that it would be extremely poor water resources management practise to use a water quality model that was forced by different hydrological simulations than those used for water allocation and system yield management. The consequences, for all of the modelling options referred to above, would be that existing model setups would have to be reproduced within a new modelling environment and that practitioners experienced in the use of both the Pitman rainfall-runoff model and existing yield models would require re-training. Given that there are a large number of such

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http://dx.doi.org/10.1016/j.envsoft.2016.02.028
1364-8152/

model setups that are in current practical use by the DWS, this is likely to be totally impractical and not very popular with many water resources engineering practitioners. This paper refers to the water quantity components of an alternative approach that is currently under development and that involves the disaggregation of simulated monthly flow volumes (either existing or from future applications of the existing models) into daily sequences, which are then used to force a water quality model.

2. Disaggregation approaches

The first important key design issue is that the monthly water volumes of all of the components included within the water resources system model must be preserved within the disaggregated daily flow time series. While it is noted that, in some situations, the monthly systems model may not simulate the real flows very well (Hughes and Slaughter, 2015), it is nevertheless important to maintain consistency in the monthly water mass balance between the two models. Any problems with poor simulation of the monthly volumes (that might impact on the validity and usefulness of the water quality simulations) should therefore be addressed through re-calibration of the monthly model. A second issue is the need to minimise the number of additional parameters that would be needed for the disaggregation process, or at least to link these parameters to information that should be available in most circumstances. It was, however, recognised at the start of the model design process that additional parameters (and some additional data) would be required to achieve effective and realistic disaggregations.

One of the other key issues is that the sites of interest for water quality assessments could be anywhere within the catchment system and therefore, it is important to obtain appropriate disaggregated daily sequences of flow at all points and not just within the catchment inflows that were addressed in the earlier papers of Slaughter et al. (2015) and Hughes and Slaughter (2015). Fig. 1 summarises the main water balance components that require disaggregation and the specific issues associated with, as well as the approaches adopted for, each one are discussed in the following sub-sections. Table 1 summarises the additional parameters and data that are required for the disaggregation components. Within the monthly rainfall-runoff model (or yield model) small farm dams are typically lumped together and dealt with as part of the sub-basin scale hydrological modelling. The only reservoirs that are individually simulated are those at the outlet of sub-basins and are typically quite large (storages greater than about 0.5×10^6 m^3) and for which information can be obtained about their characteristics (see Sections 2.5–2.7, below).

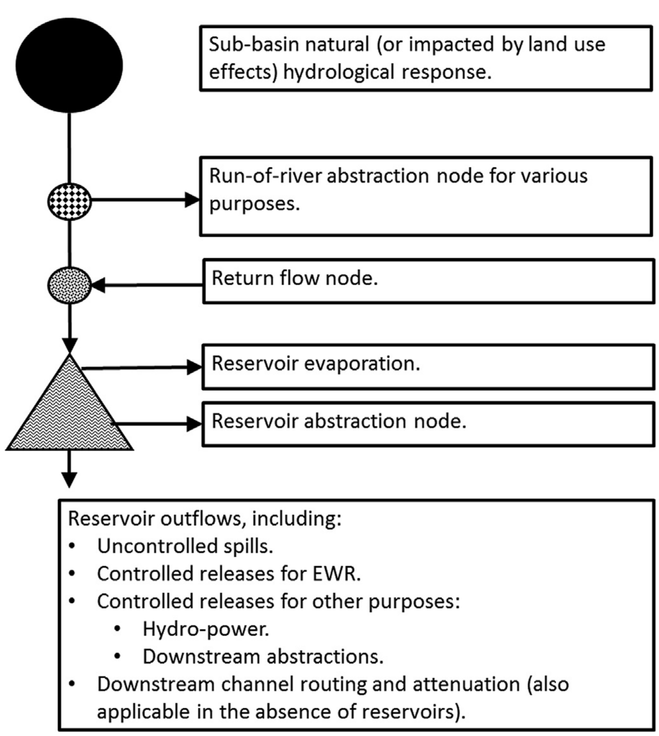

Fig. 1. Water balance components in a water resources system model that require disaggregation.

2.1. Incremental catchment inflows

The incremental catchment inflows are typically (within system models commonly used within South Africa) simulated by a separate rainfall-runoff model and then used as inputs to the systems model. As already noted, the model most frequently used in South Africa is one of the derivatives of the Pitman monthly rainfall-runoff model (Pitman, 1973; Hughes, 2013). These simulations can be based on representing natural flow, but can also represent some land use modification effects such as agricultural water, urban drainage or afforestation. The details of how the catchment inflows are disaggregated are not given here as they have already been published (Slaughter et al., 2015; Hughes and Slaughter, 2015). However, the method and associated parameter values (Table 1) are summarised in this paper for completeness.

The disaggregation approach is based on the earlier work of Smakhtin and Masse (2000), using continuous daily time series of an antecedent precipitation index and a quantile transformation method. The additional data required are time series of catchment average daily rainfall, while there are also a number of additional parameters. There are essentially six steps in the approach:

Step 1: The simulated monthly flow data are used to generate a flow duration curve (M_FDC) of mean monthly flow ($m^3\ s^{-1}$).

Step 2: The mean monthly flow quantiles (at pp %) of the M_FDC are scaled (S_{PP}) to daily values (D_FDC) using a power function with three parameters developed from either available observed daily flow data or regional estimates:

$$\begin{aligned} &\mathrm{D\_FDC}_{pp} = S_{PP} \cdot \mathrm{M\_FDC}_{pp} \\ &\text{with } S_{PP} = A \cdot PP^B + C \text{ (if } S_{PP} < 0 \text{ then } S_{PP} = 0) \end{aligned} \tag{1}$$

Step 3: The daily rainfall (P_i) data are converted to a continuous time series of antecedent rainfall (AP_i) using decay (KD) and threshold (P_{Thresh}) parameters, which are typically calibrated using some observed flow data for the region:

$$\begin{aligned} &API_i = API_{i-1}^{KD} + P_i \\ &(\text{for } P_i \geq P_{Thresh}) \text{ (where 'i' is the day in the time series)} \end{aligned} \tag{2}$$

$$API_i = API_{i-1}^{KD} \quad (\text{for } P_i < P_{Thresh}) \tag{3}$$

Step 4: The exceedance frequency distribution of the antecedent rainfall time series (API_FRQ) is generated.

Step 5: Initial values of the daily flow time series (D_i) are generated from the antecedent rainfall time series (API_i) using a quantile (API_FRQ) − quantile (D_FDC) transformation method.

Step 6: The initial daily flow values (D_i) are volume corrected (DC_i) to ensure the same volume as the monthly flow data (M_j).