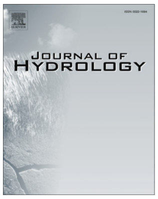
Journal of Hydrology 547 (2017) 124–142

Contents lists available at ScienceDirect

Journal of Hydrology

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



Research papers

Development and application of a large scale river system model for National Water Accounting in Australia

Dushmanta Dutta [a,*], Jai Vaze [a], Shaun Kim [a], Justin Hughes [a], Ang Yang [a], Jin Teng [a], Julien Lerat [b]

[a] CSIRO Land and Water, Canberra, ACT 2601, Australia
[b] The Bureau of Meteorology, Canberra, ACT 2601, Australia

ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form 22 November 2016
Accepted 21 January 2017
Available online 24 January 2017
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Yu Zhang, Associate Editor

Keywords:
Continental scale river model
Water accounting
Australian Water Resources Assessment
AWRA
National Water Account
Water resources management

ABSTRACT

Existing global and continental scale river models, mainly designed for integrating with global climate models, are of very coarse spatial resolutions and lack many important hydrological processes, such as overbank flow, irrigation diversion, groundwater seepage/recharge, which operate at a much finer resolution. Thus, these models are not suitable for producing water accounts, which have become increasingly important for water resources planning and management at regional and national scales. A continental scale river system model called Australian Water Resource Assessment River System model (AWRA-R) has been developed and implemented for national water accounting in Australia using a node-link architecture. The model includes major hydrological processes, anthropogenic water utilisation and storage routing that influence the streamflow in both regulated and unregulated river systems. Two key components of the model are an irrigation model to compute water diversion for irrigation use and associated fluxes and stores and a storage-based floodplain inundation model to compute overbank flow from river to floodplain and associated floodplain fluxes and stores. The results in the Murray-Darling Basin shows highly satisfactory performance of the model with median daily Nash-Sutcliffe Efficiency (NSE) of 0.64 and median annual bias of less than 1% for the period of calibration (1970–1991) and median daily NSE of 0.69 and median annual bias of 12% for validation period (1992–2014). The results have demonstrated that the performance of the model is less satisfactory when the key processes such as overbank flow, groundwater seepage and irrigation diversion are switched off. The AWRA-R model, which has been operationalised by the Australian Bureau of Meteorology for continental scale water accounting, has contributed to improvements in the national water account by substantially reducing accounted different volume (gain/loss).

1. Introduction

With increasing competition for finite and often scarce water resources, water information is a critical underpinning of the water reform process both on which to base decisions and against which to measure progress. Water accounting, a systematic approach of organising and presenting water information relating to the physical volumes of water and how water resources are being used, provides a unique tool for integrated water resources management as well as for economic analysis of water issues. A water-accounting procedure from an irrigation perspective was introduced by Molden (1997) to better understand the impacts of irrigation interventions at a basin scale (Molden and Sakthivadivel, 1999) and applied in the Philippines, Nepal, Pakistan, India, Sri Lanka, and China (IWMI, 1999; Molden et al., 2001; Renault et al., 2001). In Australia, information on water resources has been compiled since the mid-1960s (Vardon et al., 2007). The Australian Bureau of Statistics (ABS) water Accounts (ABS, 2000, 2004a,b) contained supply and use tables that tracked the extraction of water from the 'environment' through to consumptive use, regulated discharges to the environment and reuse. In these reports, data were consolidated from various sources and there were no standards-based national approach to water resources reporting. Through the Water Act 2007, the Australian Bureau of Meteorology (BoM) was given the statutory responsibility for compiling and delivering comprehensive water information across Australia (BoM, 2012a,b) and national water accounts to provide comprehensive and standardised information about the management of Australia's water resources. For producing the national water accounts, the BoM required a river system modelling tool that quantifies water flux and storage terms using a

---

* Corresponding author.
E-mail address: dushmanta.dutta@csiro.au (D. Dutta).

http://dx.doi.org/10.1016/j.jhydrol.2017.01.040

combination of data sets and which is applicable across the continent to provide nationally consistent and robust estimates. The existing river system models used by different jurisdiction in Australia such as the daily Integrated Quantity and Quality Model (IQQM, Simons et al., 1996; Vaze et al., 2011), the REALM model (Perera et al., 2005), the Murray Simulation Model (MSM, monthly) with the daily flow and salinity routing model (called BigMod) (Close, 1996), were not built for continental applications at the required spatio-temporal scale to quantify various fluxes and stores for consistent national scale water accounting (Welsh et al., 2013; Dutta et al., 2013a). One of the key limitations in these models is the lack of explicit representation of several hydrological processes (such as overbank flow and interaction of river with groundwater system). Thus, these river models are not able to simulate several major fluxes and stores for water accounting resulting in large amount of unaccounted water in the total water budget (Van Dijk et al., 2008). For example, New South wales Office of Water (NoW, 2012) reported large unaccounted differences in Murrumbidgee river system water balance study and recommended for consideration of various hydrological processes and anthropogenic water uses in river system modelling to improve overall water balance estimates for river basins. The accounting process of Australia's National Water Accounts in the early years included an unaccounted volume which resulted from unquantified volumes including river, floodplain and other water losses (Chandra et al., 2015).

Over the past two decades, several river models have been developed for application over a large geographic domain. Most of these models are either continental scale or global scale stream flow routing models designed as part of land surface or global climate models. The first conceptually-based macro-scale model, developed by Vörösmarty et al. (1989, 1996), was a monthly water balance model, operating on a spatial resolution of $0.5° \times 0.5°$, with parameters derived from gridded soil texture and vegetation data bases. The model routed water from cell to cell, and accounted for inundation and loss of water through evaporation from wetlands and flooded areas. The variable infiltration capacity (VIC) model, which operates at a daily time step, has been used to simulate patterns of streamflow over large basins for water resource estimation purposes across the globe (Wood et al., 1992; Stamm et al., 1994; Liang et al., 1994; Abdulla et al., 1996; Nijssen and Lettermaier, 1997; Zhao et al., 2012; Wu et al., 2014). Arora (2001) used a variable velocity algorithm to perform stream flow routing at 3.75° grid resolution in CCCMA. Some of the other continental or global scale rive routing models are TRIP (Oki and Sud, 1998), VIC-2L (Lohmann et al., 1998), RNN (Renssen and Knoop, 2000), RAPID (David et al., 2013) and MOSART (Li et al., 2013, 2015). All the global or continental scale river routing models are gridded model with relatively coarse resolution grids (about 10 km for continental scale, 50 or 100 km for global scale) mainly because of computational limitations. Based on a comprehensive survey and review of existing large-scale models, Nazemi and Wheater (2015a,b) concluded that current capability of large-scale models to represent anthropogenic demands is rather limited and they emphasised the need of process representations related to both natural and anthropogenic in such models. In recent years, there have been some attempts to incorporate some of these processes in global or continental scale models. For example, Wu et al. (2014) developed the Dominant river tracing-Routing Integrated with VIC Environment (DRIVE) model for global streamflow and flood modelling by coupling the VIC model with a physically-based hierarchical Dominant River Tracing (Wu et al., 2011) based runoff-Routing (DRTR) model. Through representation of various hydrological processes and anthropogenic water use in WaterGAP model, Müller Schmied et al. (2014) demonstrated better simulated river discharge at a global scale. Hanasaki et al. (2006), Voisin et al. (2013), and Zhou et al. (2016) emphasised importance of reservoir operation in streamflow modelling and introduced a reservoir operation scheme for different global streamflow routing models. Yamazaki et al. (2011) introduced floodplain inundation modelling capability in a global river routing model. While the model performance improved with the reservoir and floodplain routing in continental scale analysis, such models are not suitable for water accounting at a river basin scale. In addition, many hydrological processes (e.g., floodplain inundation, groundwater fluxes), regulated storages and anthropogenic withdrawals (irrigation and urban water supply) and water management are operated at a much smaller scale (Dutta and Nakayama, 2009; Nazemi and Wheater, 2015a,b). Appropriate representation of these processes is critical to provide reliable estimates of water balance fluxes and stores for water accounting at a river basin scale as they can account for substantial proportion of the total water especially in heavily regulated river systems. However, explicit representation of such processes in existing continental and global scale gridded models at required spatial resolution is difficult (Wood et al., 2011; Nazemi and Wheater, 2015a,b).

This research, undertaken as a collaborative project between CSIRO and the BoM, aimed at building a large scale river system model (AWRA-R) using the node-link architecture (which is used in basin-scale river modelling) with explicit representation of key hydrological processes and anthropogenic water uses to quantify various surface water fluxes and stores at high spatio-temporal resolution enabling continental-scale water accounting with minimum unaccounted water volumes. The key science challenge addressed in this research was to reduce uncertainty in large scale river system modelling by incorporating appropriate and relevant hydrological processes for reducing unaccounted water. The main hypothesis was that key hydrological processes and anthropogenic water use were needed to be incorporated at a river reach scale in river modelling to reduce unaccounted water. This is an important requirement to produce reliable and robust estimates of various fluxes and stores for improving water accounting in a river system. The model is one of two major components of the continental scale modelling system representing the Australian terrestrial water cycle, called Australian Water Resource Assessment (AWRA). The other component of AWRA is AWRA landscape (AWRA-L), which is a daily grid-based biophysical model of the water balance between the atmosphere, the soil, unsaturated zones and confined and unconfined groundwater stores. The modelling concepts, algorithms and application results of AWRA-L across Australia are described in details in Viney et al. (2015). Fig. 1 shows a schematic representation of the AWRA modelling system. In AWRA simulation, fluxes between AWRA-L and AWRA-R are transferred at every time step (daily) as shown in Fig. 2. The inputs from AWRA-L to AWRA-R are the runoff, potential evaporation and groundwater store data. Simulated seepage from river and groundwater recharge from floodplain and irrigated area for every AWRA-R sub-catchment are transferred to AWRA-L. In the process of transferring fluxes between the two models, the spatial resolutions (gridded outputs from AWRA-L and sub-catchment scale outputs from AWRA-R) are adjusted as required.

This paper presents the development, application, evaluation and operationalisation of the AWRA-R continental scale river system model. The paper is structured as follows. Methods used for building different components of AWRA-R are presented in Section 2. A brief description of the study area is then provided and data collation process is explained. Sections 5 and 6 provide the results and a discussion, respectively. Section 7 discusses the operationalisation of AWRA-R for national water accounts. The conclusions of the study are presented in Section 8.