Journal of Hydrology 504 (2013) 12–28

Contents lists available at ScienceDirect

Journal of Hydrology

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

Storage-based approaches to build floodplain inundation modelling capability in river system models for water resources planning and accounting

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ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form 23 August 2013
Accepted 22 September 2013
Available online 29 September 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ioannis K. Tsanis, Associate Editor

Keywords:
Flood plain inundation modelling
River system model
Murray–Darling Basin
LiDAR DEM
Water resources planning
Water resources accounting

SUMMARY

Two conceptual storage-based approaches have been developed for incorporating floodplain inundation modelling capability in two water resources planning models. Approach one is a simple method suitable for data limited environment, in which, flow in a river reach within a floodplain is partitioned into two components, in-stream and overbank flow, based on the in-stream capacity. A flood volume–area relationship derived from the flood inundation time series, which is generated by analysing daily MODIS imagery, is used to estimate flooded area for the overbank flow. The losses due to evaporation and groundwater seepage from floodplain are calculated using the estimated flooded area. This approach was implemented in the floodplain area of the Murray–Darling Basin in Australia. The simulated flow was compared with gauged data in 216 stations. The model has produced daily time series of floodplain stores and fluxes. The mass-balance analysis shows that the long term mass balance error was negligible for all floodplain reaches.

Approach two is more comprehensive and suitable for areas with high resolution topography data. LiDAR data is used to divide a floodplain into multiple storages based on pre-defined threshold of floodplain inundation heights. The storage characteristics including disconnected storage volume (or, dead storage) and hydraulic connectivity between floodplain storages and a river reach are derived from the LiDAR data using a spatial data processing technique. This information is used to estimate floodplain inundation area for overbank flow. Approach 2 successfully simulated inundation depths, duration and extents in two reaches of Murrumbidgee floodplain. The performance of Approach 2 is highly satisfactory in terms of flood extent, depth and duration at a very high spatial resolution.

The key limitations of Approach one are that this approach is unable to produce the spatial variability of floodplain inundation depth and extent and it does not incorporate dead storage. These limitations can be overcome by integrating it with Approach two. A key advantage of Approach two is the quick run time compared to a two dimensional hydrodynamic model. This makes the approach highly suitable to be incorporated in river system models for various scenario analyses for planning and management, which requires the model to run for over 100 years at a daily time step. The limitations of this approach are the requirement of very high resolution topographic data and the inability to produce flood velocity.

1. Introduction

Floodplains and wetlands are a critical part of natural environment and they play important ecological and hydrological roles in river basins. The role of floodplains and wetlands to provide for stable water supplies, improved water quality and a range of ecological benefits has been demonstrated in a number of recent studies (Richardson et al., 2012; Borin et al., 2001; Moore et al., 2002; Mitchell et al., 2002; Kazezyılmaz-Alhan et al., 2007). For example, the Murray–Darling Basin (MDB) in Australia has over 30,000 wetlands (MDBA, 2011). Many wetlands located across the MDB are of national and international significance and listed in the Ramsar Convention as the wetlands of international importance and provide a range of ecological benefits (EA, 2001). The Murray–Darling Basin Authority (MDBA) has recently developed a basin plan with the aim to return MDB to a healthy, working condition so as to have a sustainable and productive economic future (MDBA, 2012). One of the main objectives of the basin plan is to make sure that the key environmental assets (including wetlands and floodplains) are protected and progressively improved, and there is adequate water to sustain their ecological resilience during periods of drought. Floodplain wetlands rely on inflow from catchments to maintain the flooding and drying cycles critical to their ecological

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http://dx.doi.org/10.1016/j.jhydrol.2013.09.033

integrity (Powell et al., 2008) and a key determinant for habitat quality and the ecological integrity of floodplain wetlands is how the wetland is hydrologically connected to the main river channel over time (Junk et al., 1989; Paterson and Whitfield, 2000; Tockner et al., 2000; Bunn and Arthington, 2002; Frazier and Page, 2006). The environmental benefits of water flowing into wetlands and over floodplains depend on the extent, depth, duration and frequency of the inundation. Water management authorities and river managers need to predict the dynamics of wetting when they plan environmental flows so that they can optimise the environmental benefits to the riparian ecosystem. Thus, development of a detailed understanding of wetland hydrology and inundation characteristics is imperative for effective environmental management.

In-situ measurements of flood extent and depths, while very useful, are generally difficult to obtain for large floodplain problems that are of practical interest for environmental management. For most rivers in MDB sufficient observations of flood inundation extent are not available to determine such areas. Several research projects were undertaken in the past several years to develop detailed understanding of wetland inundation characteristics in different parts of MDB using mainly two approaches: satellite imagery based approach and hydrodynamic modelling.

Satellite and airborne platforms provide useful flood inundation maps that can act as validation data sets for hydraulic flood inundation models. Monitoring and mapping of wetlands using satellite imagery has been undertaken over a range of temporal and spatial scales (Shaikh et al., 2001; Kingsford and Thomas, 2002; Overton et al., 2006; Powell et al., 2008; Colloff et al., 2010). Bates et al. (1997) and Smith (1997) present a good review of the active and passive remote sensing studies of flood inundation. Shaikh et al. (2001) classified wetlands of the Lower Darling River in southeastern Australia based on broad commence-to-flow discharges and the inundation effects at different discharge magnitudes. To date, remote sensing of floodplain inundation from satellite platforms has not offered solution to the dynamic flood inundation processes because multiple images at fine resolution are generally not available (e.g. 35 days for ERS1 and ERS2 satellites, 16 days for Landsat, 7 to 10 days for RADARSAT). The satellite imagery based approach has several limitations including the inability to develop detailed understanding of floodplain hydrology (such as water balance) and hydraulics (e.g., changing floodplain dynamics). Nevertheless, these techniques indeed provide very useful direct observations that can be used for during or post event mapping (Brakenridge and Anderson, 2006; Pulvirenti et al., 2011) and calibration data sets for the flood inundation hydraulic models that can simulate a variety of historical and likely future conditions.

Both one and two dimensional hydrodynamic model are used for simulation of floodplain inundation (Horritt and Bates, 2002; Bales et al., 2007). The representative hydrodynamic models include MIKE21 (DHI, 2012), HEC-RAS (Horritt and Bates, 2002; Pappenberger et al., 2005) and LISFLOOD-FP (Bates et al., 2010). These models require an accurate high resolution DEM, cross-sections of channels and cross-sections of floodplains. The strength of these models includes use of water equilibrium equations, such as St. Venant's equations, to model water movement in river channel and floodplain and to estimate inundation extent, velocity, duration, depth and frequency of wetting. They can also be used for analyzing impacts of modification of control structure such as levee banks. But, they are computationally expensive and need detailed parameter information (for each grid cell) for model calibration. Within MDB, several previous studies on modelling river flow and inundation have been undertaken for wetlands on the Lachlan Valley and Darling River in New South Wales (Shaikh et al., 1998; Shaikh et al., 2001), Murrumbidgee River (Frazier et al., 2003), Koondrook Perricoota (Tuteja, 2007), Edwaard-Wakool floodplain (SKM, 2011), Macquarie Valley (MacDonald et al., 2011a), Gwydir Valley (MacDonald et al., 2011b). Whilst hydrodynamic modelling is suitable for floodplain inundation simulation at high spatio-temporal resolutions, the approach is costly and not time effective (Dutta et al., 2000; Dutta et al., 2007; Dutta, 2012). In recent years, new approaches have been incorporated in floodplain hydrodynamic modelling for large floodplains with reduced computational time (Neal et al., 2012). There is scope for further research before such models can be integrated with river-system models for applications in very large river basins.

The coupling of the previous approaches with water resources planning models remains challenging for multiple reasons: the runtime of hydrodynamic models prevent a coupled model to be run for long period of time (e.g. 100 years) and multiple climate scenarios to explore water resources availability. In Australia, several planning models have been used by water managers such as IQQM (Simons et al., 1996; Vaze et al., 2011), REALM (Perera et al., 2005) and BIGMOD-MSM (Close, 1996a,b). Recently, eWater CRC has developed a new river system model, "eWater Source" (Dutta et al., 2012a, 2013a; Welsh et al., 2013), which is expected to replace the old river system models. None of these river system models including Source are capable of explicitly modelling flood inundation. Instead, conceptual relationships, developed based on local knowledge and historical records and/or simulated outputs from hydrodynamic (HD) models, are used to define losses from river to floodplains (MacDonald et al., 2011a,b). In recent years, several attempts have been made to incorporate flood modelling capabilities within hydrological modelling framework (e.g.,Yamazaki et al., 2011, Sayama et al., 2012). These models are not designed for regulated river system and their spatial resolution and computational time are not suitable for estimating floodplain fluxes and stores at a river reach scale in regulated river systems.

The main aim of this research was to develop a simplified methodology for flood inundation simulation within river system modelling framework to enhance the flood inundation modelling capability of river system models and to produce floodplain fluxes and stores. Two conceptual storage-based approaches have been designed and integrated with two river system models developed for MDB. Approach 1 is a simple method suitable for data limited environment. Approach 2 is more comprehensive and suitable for areas with high resolution data such as LiDAR topography data. The computational time of the two approaches are relatively very small compared to any floodplain hydrodynamic models and thus, the river model with these two inundation modelling approaches can be implemented in a large river basin (e.g., MBD) for long-term simulation. This paper introduces the two approaches and presents the results of their applications in MDB. The results are compared with the observed data and the results from a 2D hydrodynamic model and flood maps derived from Landsat TM imagery for some of the recent flood events.

2. Methodology

The two approaches have been designed for two river system models developed by CSIRO, namely, the simplified MDB River Model (SMDBRM) and AWRA river model (AWRA-R). SMBDRM is a daily river system model of the entire MDB being developed by CSIRO and it incorporates various physical and management characteristics for water resources planning (Dutta et al., 2012b). AWRA-R is the river system component of the Australian Water Resources Assessment (AWRA) system developed jointly by CSIRO and the Bureau of Meteorology (BoM), Australia as part of the Water Information Research and Development Alliance (WIRADA) (Lerat et al., 2012; Vaze et al., 2013). Both are conceptual hydrological models designed using a node-link approach. This paper