Environmental Modelling & Software 26 (2011) 1554–1567

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

A conceptual framework for incorporating surface–groundwater interactions into a river operation–planning model

David W. Rassam*

Hydrological Modeller,[1] CSIRO Land and Water and eWater CRC, Ecosciences Precinct, 41 Boggo Rd, Dutton Park, QLD 4102, Australia

ARTICLE INFO

Article history:
Received 18 May 2011
Received in revised form
28 July 2011
Accepted 28 July 2011
Available online 24 August 2011

Keywords:
Groundwater–surface water interaction
River operation–planning model
River low flow
Groundwater extraction
River depletion
Analytical solutions
River–aquifer exchange flux
Conjunctive management

ABSTRACT

Groundwater discharge constitutes a significant proportion of the total flow volume in most rivers. The exchange flux between surface and groundwater greatly impacts the surface as well as the groundwater balance with serious implications on ecosystem health especially during low flow conditions. There is a move towards conjunctive river–aquifer management with the integration of surface–groundwater exchange fluxes into surface and groundwater models to manage water as a single resource. Groundwater–Surface water (GW–SW) exchange fluxes are seldom integrated into river operation and planning models. The time lags associated with the impacts of groundwater processes on nearby rivers can greatly compromise the forecasting capacity of river models especially during low flow conditions.

This paper presents a conceptual framework for integrating GW–SW exchange fluxes into the new generation river operation–planning model 'Source Integrated Modelling System'. The proposed GW–SW Link Module adopts a simple pragmatic approach for estimating the exchange fluxes between a river reach and the underlying aquifer using explicit analytical solutions. This flux becomes an inflow/outflow to that river reach and forms part of the routing and calibration processes. The exchange flux comprises four components: (1) natural exchange flux resulting from river stage fluctuations during low flow conditions, within bank and overbank fluctuations; (2) flux due to groundwater extraction; (3) flux due to changes in aquifer recharge; and (4) flux due to changes in evapotranspiration. The sum of those components during every time step dictates whether the river loses water to or gains water from the aquifer.

The proposed analytical solutions were found to provide flux predictions that agree favourably with those derived from a numerical groundwater model. Recognising that the simplifying assumptions that underpin the explicit analytical solution are likely to be violated in the natural world, a suite of criteria was recommended for their use under many violating conditions related to boundary conditions, head gradients, and aquifer heterogeneity. Low flow indices were adopted to demonstrate the critical role of GW–SW exchange flux when predicting river low flows. Explicit accounting of GW–SW interactions into river operation and planning models greatly enhances their forecasting capacity during low flow conditions.

1. Introduction

1.1. *Significance of surface–groundwater interactions*

Groundwater discharge from shallow aquifers into catchment surface waters represents the major part of the total flow volume in most rivers (Wittenberg, 2003). The magnitude and direction of the exchange flux between surface and groundwater is mainly determined by the hydraulic gradient between a river and the underlying aquifer. It can greatly impact the surface water and groundwater balance with serious implications on ecosystem health especially during low flow conditions. Krause et al. (2007) reported that although groundwater contributions from a river stretch in the northeast German lowlands represent only 1% of the annual total discharge within the river, its impact is much higher during low flow conditions in summer where 30% of the river runoff which is generated in the catchment is originated by groundwater discharge from the riparian zone along this river. During extreme low flow conditions, the groundwater–surface water(GW–SW) exchange fluxes are crucial in determining the hydro-chemical conditions and resulting ecological stress during

---

* Tel.: +61 7 3833 5586, +61 400 877 676 (mob); fax: +61 7 3833 5501.
E-mail address: David.rassam@csiro.au.

[1] Mail to: GPO Box 2583, Brisbane, QLD 4001, Australia.

1364-8152/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsoft.2011.07.019

a time which may coincide with the main vegetation growth period (Krause et al., 2007).

The critical issues of water resource availability and ecological sustainability have highlighted the need to integrate surface–-groundwater interactions in both groundwater and surface water models thus leading to a conjunctive approach that manages water as a single resource. Recent initiatives by the Australian government such as the Murray-Darling Basin Sustainable Yields Project (MDBSY; see http://www.csiro.au/partnerships/MDBSY.html) have explicitly required the incorporation of groundwater fluxes when estimating surface water resources in the basin. In Kansas in the USA, aquifer management regulations now include baseflow when evaluating a groundwater permit application (Sophocleous, 2000). It is now recognised that in order to maintain healthy rivers and wetlands, only a small fraction of aquifer recharge can be exploited. As such, there is a move towards conjunctive river–aquifer management by amending safe yield regulation to include baseflow, which is represented as a groundwater withdrawal that has already been appropriated (Sophocleous, 2010).

1.2. Processes contributing to the groundwater–surface water exchange flux

A number of processes contribute to the exchange flux between surface and groundwater; most importantly they include: groundwater extraction, aquifer recharge (including diffuse recharge, recharge from irrigation return, and recharge from overbank flow), bank storage, and evapotranspiration. Aquifer recharge represents a gain to the GW system (which may enhance discharge to the river), while groundwater extraction and evapotranspiration represent a loss to the GW system (which may deplete the river). Bank storage is a dynamic phenomenon whereby a river recharges the aquifer during a flood event and then water discharges back to the river after the flood wave recedes. The net result of those processes at any point is space and time can either lead to a gaining or a losing river. Some or all of those processes might contribute to the exchange flux with the extent of the contribution varying significantly in space and time depending on the hydrogeological configuration as well as human and/or environmental drivers.

Drought conditions that result in limiting a surface water resource can place enormous stress on a groundwater resource via increased groundwater extraction. Groundwater extraction, which initially depletes the aquifer, eventually depletes nearby rivers by either reducing aquifer discharge to rivers or by inducing river recharge to aquifers. Long-term sustained extraction can lead to significant reductions in river flow; Mair and Fares (2010) investigated river flow in the Makaha Valley (O'ahu, Hawai'i) and reported reductions in river flow of up to 36% since 1971 as a direct result of groundwater extraction. River depletion can lead to increased intermittency of river flow, which has adverse ecological impacts. Stream fed aquifer recharge may be a naturally occurring phenomenon but it is enhanced by the increased downward gradients that are developed due to extensive groundwater abstraction. Andersen and Acworth (2009) analysed the annual flow difference between two gauging stations on the Namoi River in eastern Australia, which indicated that losses from the Namoi River are significantly larger than the combined surface water diversion and groundwater abstraction. Large overbank events, although not very frequent, can lead to significant aquifer recharge. Evapotranspiration is a significant discharge mechanism for groundwater in shallow aquifers (Rassam et al., 2002; Cook and Rassam, 2002), in closed hydrologic basins (Abdalla, 2008), and along riparian buffers. Bank storage can significantly reduce storm-inflow peaks and contributes partially to baseflow, the natural groundwater discharge to a river (Hantush et al., 2002). Exchange fluxes during bank storage can significantly affect water and nitrogen budgets in perennial, as well ephemeral streams with perched water tables (Rassam et al., 2008a).

The temporal and spatial scales at which these processes contribute to the exchange flux vary significantly. For example, river depletion resulting from groundwater extraction is delayed by time lags that range from days to hundreds of years; the extent of the extraction activity may vary along a river reach thus leading to gaining and losing sub-reaches. Because of the intensive spatial and temporal variabilities there is a need for dynamic modelling of their impacts on river flow.

1.3. Rationale for current work

Near-river–aquifer systems are complex due to the difficulties in estimating flows into and out of the aquifer, the complicated nature of the GW–SW interaction processes, and the uncertainty of aquifer properties (Sophocleous, 2010). Because of this complexity, computer models are used to model groundwater systems and estimate the exchange flux between surface water and groundwater. Many of the large river systems around the world are highly regulated they provide resources for a range of water needs such as irrigation, urban use, and the environment. River operation–planning models are becoming increasingly complex due to the rapid growth in urban and agricultural sectors, environmental requirements, over allocation, and changes to land use and climate change. The interaction between the surface and groundwater systems as represented by the GW–SW exchange flux is seldom integrated within river operation-management models (Valerio et al., 2010). Traditionally, the interaction between surface and groundwater is implicitly accounted for during the routing calibration of river management models. The slow time-variant nature of the groundwater processes leads to unrealised impacts that are outside the calibration period of the river model, which compromises the forecasting capacity when used outside its calibration period. Fully coupled models such as MODHMS (Hydrogeologic Inc., 1996) and GSFLOW (Markstrom et al., 2008) have the capacity to simultaneously simulate the flow of surface water, groundwater, and their interaction. However, they do not take into account the complex operational aspects of river management.

The most commonly used approach to account for GW–SW exchange in river operation and planning models is linking them to groundwater models such as MODFLOW (McDonald and Harbaugh, 1988). This can be achieved either via a dynamic link where the models are run simultaneously (Valerio et al., 2010), or via an external link whereby fluxes estimated by the groundwater model are imported as known inputs into the river model. The latter approach has been adopted by the MDBSY project in Australia. Due to the very strict time constraints that prevented dynamic coupling of the surface and groundwater models, the GW–SW interactions were evaluated from groundwater models using a new 'dynamic equilibrium' approach. A number of shortcomings were identified in this approach (Rassam et al., 2008b). Lessons learnt from the MDBSY project have emphasized the need and demonstrated the lack of tools that can pragmatically model the GW–SW interactions on a large scale.

The world-wide increasing demand for water has led to the adoption of integrated water resource management approaches. It is recognised now that water management strategies must be multi-disciplinary evaluating not only the technical and scientific dimensions of a water system, but also the economic, political, legislative and organizational aspects, which are equally important (Molina et al., 2010). In addition, this approach should be accompanied by stakeholder's participation (Martínez-Santos et al., 2010).