Journal of Hydrology 523 (2015) 515–530

Contents lists available at ScienceDirect

Journal of Hydrology

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

Quantifying climate and pumping contributions to aquifer depletion using a highly parameterised groundwater model: Uley South Basin (South Australia)

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ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 29 January 2015
Accepted 30 January 2015
Available online 9 February 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Climate variability
Pumping
Aquifer depletion
Highly parameterised model
Parameter estimation
Uncertainty analysis

SUMMARY

The relative contributions of climate and human stresses to aquifer depletion in real-world settings are rarely quantified, particularly where complex patterns of depletion arise from the spatial and temporal variability in aquifer stresses. These impacts can be assessed using calibration-constrained model predictions of disturbed (i.e., subject to human activity) and undisturbed (i.e., natural) conditions. Prior investigations that adopt this approach employ lumped-parameter or one-dimensional models. Here, we extend previous studies by using a highly parameterised, spatially distributed groundwater model to investigate the relative impacts of climate variability and pumping on aquifer depletion. The Uley South Basin (USB), South Australia, where there is conjecture surrounding the cause of declining groundwater levels, serves as a case study. The relative contributions of climate variability and pumping to USB depletion are shown to be highly variable in time and space. Temporal trends reflect variability in rainfall and pumping, as expected. Spatial trends are primarily dependent on the proximity to both the coastal boundary and pumping wells, and to the distribution of recharge and hydraulic properties. Results show that pumping impacts exceed those of climate between 1978 and 2012, and over the majority of the spatial extent of USB. The contribution of pumping to aquifer depletion is shown to be 2.9 and 1.4 times that of climate in terms of the time-averaged and maximum-in-time basin-scale water budget, respectively. Confidence in model predictions is enhanced by the outcomes of a linear predictive uncertainty analysis, which indicates that predictive uncertainty is lower than climatic and pumping impacts. This study demonstrates the application of a relatively simple analysis that can be used in combination with highly parameterised, spatially distributed groundwater models to differentiate causal factors of aquifer depletion.

1. Introduction

Understanding the relative contributions of climatic and human impacts on hydrological systems is essential for developing effective water resources management strategies. The majority of previous attempts to distinguish between climatic and human impacts on hydrological systems have focused on surface water processes, and in particular, stream flow responses (e.g., Ma et al., 2008; Lorenzo-Lacruz et al., 2010; Wang and Hejazi, 2011), as reviewed recently by Wang (2014). However, the complex nature of groundwater systems often precludes accurate assessment of the contributions of different causal factors to aquifer depletion, which is becoming an increasingly widespread issue (Wada et al., 2010; Werner et al., 2013). Such complexities occur in the form of spatial variability in hydraulic properties, intermittency in natural and human stresses, poorly constrained recharge, pumping and boundary condition controls, and difficulties in accurately determining surface water-groundwater interactions (e.g., Custodio, 2002; Skøien et al., 2003; Panda et al., 2007). As a result, quantification of the extent to which groundwater storage behaviour is impacted by various climate- and human-based controlling factors remains a challenge (van Loon and van Lanen, 2013).

The influence of climate variability and human activity on groundwater systems has previously been investigated using a range of approaches, including statistical- and concept-based time-series analysis (e.g., Shamsudduha et al., 2009; von Asmuth et al., 2008), artificial neural networks (e.g., Ghose et al., 2010), satellite-based gravity observations (e.g., Joodaki et al., 2014),

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http://dx.doi.org/10.1016/j.jhydrol.2015.01.081
0022-1694/

and numerical model applications (e.g., Heuvelmans et al., 2011). Numerical modelling approaches are increasingly applied in this context because they allow for: (1) the representation of system nonlinearities (e.g., watertable response to climate signals), and (2) generation of time series of state variables under natural conditions (e.g., groundwater levels not impacted by pumping) (van Loon and van Lanen, 2013). Model predictions of natural (i.e., in the absence of human activity) and human-influenced (or "disturbed") conditions are used to investigate climate and human effects in a relative manner. Differences between simulated natural and disturbed conditions are assumed to reflect the consequences of human activity, whereas climatic impacts are inferred directly from the variability caused by natural stresses (e.g., Ruud et al., 2004). This method requires the availability of: (1) well-constrained climate and anthropogenic stress data, and (2) historical field observations from both undisturbed and disturbed periods to provide confidence in the ability of the model, enhanced through calibration, to replicate hydrological system responses (e.g., Cong et al., 2009; Yan et al., 2013; van Loon and van Lanen, 2013).

Prior model-based investigations of the causal factors of groundwater decline employ either lumped-parameter or one-dimensional models. For example, van Loon and van Lanen (2013) applied a lumped-parameter rainfall-runoff model (HBV; Seibert, 2005) to the Upper-Guadiana catchment (Spain), and used an anomaly analysis to demonstrate that the influence of pumping on groundwater levels was, on average, four times higher than that of climate variability. Heuvelmans et al. (2011) used a one-dimensional unsaturated zone model (SWAP; Kroes et al., 2000) to investigate climatic and anthropogenic effects on phreatic groundwater level trends from 245 observation wells in a catchment in northern Belgium. They emphasised the importance of watertable depth and the time series duration in determining the controls on groundwater level trends.

Simple groundwater models (e.g., lumped-parameter models) provide rapid insight for management decision making by avoiding the large computational times and data requirements associated with more complex models (Refsgaard, 1997). However, field-scale groundwater problems require consideration of the spatial and temporal variability in groundwater levels, fluxes, aquifer properties and boundary conditions that invariably occur. Spatially distributed, physically based groundwater models provide a basis for representing many commonly encountered field-scale complexities (Cuthbert, 2014). Given recent advances in computing power, these models, and highly parameterised versions thereof, have been applied in regional groundwater contexts (e.g., Fienen et al., 2010; Dausman et al., 2010a). Highly parameterised models allow for: (1) enhanced extraction of information from observation data, and (2) comprehensive evaluation of predictive uncertainty (Hunt et al., 2007). However, these have not been adopted in previous efforts to distinguish between climate- and human-induced groundwater impacts.

The primary objective of this study is to extend previous model-based strategies for distinguishing between climatic and human impacts by using a highly parameterised, calibration-constrained groundwater model within a regional setting. A critical and systematic evaluation of the model is undertaken to offer new insights into the performance of such models for assessing causal factors of hydrological impacts. The analysis is applied to the investigation of the Uley South Basin (USB), southern Eyre Peninsula (South Australia). The sustainability of this resource is of concern given significant water level decline between 1970 and 2005 (Werner et al., 2011). Groundwater hydrographs have since stabilised at low levels relative to historical conditions. The causes of groundwater trends are the subject of ongoing debate, as indicated by a recent parliamentary inquiry (NRC, 2013) into Eyre Peninsula water management, which reports that "the cause of the decline of water quantity and quality in the limestone basins cannot be clearly attributed to either natural causes or over-extraction". Moreover, the USB provides an ideal setting for the application of a highly parameterised, spatially distributed groundwater model given the availability of relatively widespread and long-term water-level monitoring data, comprehensive model- and field-based recharge estimates obtained through a concurrent study (Ordens, 2014), relatively well-constrained groundwater extraction information, and a lack of persistent surface water systems and catchment runoff more generally (Werner et al., 2011).

2. Study area

USB is a topographically enclosed surface drainage basin of 129 km^2 bounded by coastal cliffs of up to 140 m AHD (Australian Height Datum, approximately mean sea level) and inland reliefs of between 30 and 180 m AHD (Fig. 1). The region has a temperate climate characterised by winter-dominant rainfall (May–October), and hot, dry summer months (November–April) (Harrington et al., 2006). Average annual rainfall and pan evaporation rates are 560 and 1547 mm/y, respectively (Bureau of Meteorology, 2010). The land surface is composed predominantly of exposed calcrete or skeletal soils of sandy and clayey loam (Evans, 1997). Solution features (e.g., sinkholes) are widespread across USB, and serve as a mechanism for rapid groundwater recharge (Ordens et al., 2012). USB's vegetation consists primarily of Mallee scrub, drooping she-oak and significant areas of sparse grassland (Ordens et al., 2012).

Groundwater in USB occurs predominantly within an unconfined Quaternary sand and limestone aquifer (QL) (Evans, 1997). The QL is underlain by a discontinuous Tertiary clay aquitard (TC) and a semi-confined Tertiary aquifer comprising silty and clayey sand (TS) (Harrington et al., 2006). These sediments overlay an Archaean metamorphic basement (Harrington et al., 2006).

The USB constitutes the primary freshwater supply for urban, agricultural and industrial activity in the Eyre Peninsula (Harrington et al., 2006). Groundwater pumping began in 1976 (Barnett, 1978), and occurs solely from the QL aquifer. The production well field expanded from 8 to 17 wells (Fig. 1) in 2000 (Clarke et al., 2003). Traditionally, USB groundwater management has been undertaken in accordance with a flux-based approach (Werner et al., 2011), whereby recharge estimates have been used to allocate extraction volumes (EPNRM, 2006). Specifically, 60% of the estimated recharge volume is reserved for groundwater-dependent ecosystems; the remainder is deemed available for extraction (DFW, 2012).

The hydrostratigraphic model for USB, illustrated in Fig. 2, is based on drill logs (DEWNR, 2013), cliff-face observations (Bestland, 2010) and downhole and airborne geophysical surveys (Fitzpatrick et al., 2009). Of particular significance is the airborne electromagnetic data (Fitzpatrick et al., 2009), which suggest the presence of a north–south trending basement ridge, which divides the USB from aquifers to the west.

The USB boundary is defined following previous approaches as the area of saturated QL material (e.g., Harrington et al., 2006; DFW, 2012). The extent of the TS aquifer is considerably greater than the region of saturated QL material, and hence we represent the continuation of the TS aquifer using boundary conditions.

Groundwater level data (DEWNR, 2013) from 101 observation wells provide the basis for interpreting the hydrology of the system. The majority (approximately two-thirds) of groundwater level observations pertain to the QL aquifer, although a considerable portion of observation wells are assumed to monitor both aquifers, particularly prior to the improvement in construction of