Journal of Hydrology 519 (2014) 1084–1096

Contents lists available at ScienceDirect

Journal of Hydrology

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

Modelling vegetation water-use and groundwater recharge as affected by climate variability in an arid-zone *Acacia* savanna woodland

Chao Chen [a,b,c,*], Derek Eamus [a,b,d,e], James Cleverly [b,e], Nicolas Boulain [b], Peter Cook [a,f], Lu Zhang [g], Lei Cheng [g], Qiang Yu [b]

[a] *National Centre for Groundwater Research and Training (NCGRT), School of Environment, Flinders University, Adelaide, SA 5001, Australia*
[b] *Plant Biology and Climate Change Cluster, University of Technology Sydney, PO Box 123, Broadway, NSW 2007, Australia*
[c] *CSIRO Agriculture Flagship, PMB 5, PO Wembley, WA 6913, Australia*
[d] *NCGRT, University of Technology Sydney, Australia*
[e] *Australian Supersite Network, Terrestrial Ecosystem Research Network, University of Technology Sydney, Australia*
[f] *Water for a Healthy Country National Flagship, Commonwealth Scientific and Industrial Research Organisation, Division of Land and Water, Glen Osmond, Adelaide, SA 5064, Australia*
[g] *CSIRO Land and Water Flagship, Canberra, ACT 2601, Australia*

ARTICLE INFO

Article history:
Received 10 April 2014
Received in revised form 15 July 2014
Accepted 14 August 2014
Available online 21 August 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Ty Ferre, Associate Editor

Keywords:
Climate variability
Groundwater recharge
Savanna woodland
Vegetation water-use
WAVES

SUMMARY

For efficient and sustainable utilisation of limited groundwater resources, improved understanding of how vegetation water-use responds to climate variation and the corresponding controls on recharge is essential. This study investigated these responses using a modelling approach. The biophysically based model WAVES was calibrated and validated with more than two years of field experimental data conducted in Mulga (*Acacia aneura*) in arid central Australia. The validated model was then applied to simulate vegetation growth (as changes in overstory and understory leaf area index; LAI), vegetation water-use and groundwater recharge using observed climate data for the period 1981–2012. Due to large inter-annual climatic variability, especially precipitation, simulated annual mean LAI ranged from 0.12 to 0.35 for the overstory and 0.07 to 0.21 for the understory. These variations in simulated LAI resulted in vegetation water-use varying greatly from year-to-year, from 64 to 601 mm pa. Simulated vegetation water-use also showed distinct seasonal patterns. Vegetation dynamics affected by climate variability exerted significant controls on simulated annual recharge, which was greatly reduced to 0–48 mm compared to that (58–672 mm) only affected by climate. Understanding how climate variability and land use/land cover change interactively impact on groundwater recharge significantly improves groundwater resources management in arid and semi-arid regions.

1. Introduction

Groundwater is a valuable natural resource, which not only supports human activities, but also has a key role in sustaining the health of wide-spread groundwater dependent ecosystems (Eamus et al., 2006; Jha et al., 2007). Sustainable water resource management is a major challenge for water resource managers in arid and semi-arid regions (Fernandez et al., 2002), where excessive and unsympathetic groundwater abstraction can degrade ecosystem function (Clifton and Evans, 2001; Donohue et al., 2007). Vegetation dynamics in arid and semi-arid regions largely depend on soil water availability, which in turn, result in a number of complex hydrologic processes (Gee et al., 1994; Porporato et al., 2002; Scanlon et al., 2005; Garcia et al., 2011). Climate variations, which lead to changes in vegetation structure and/or its water-use, can have a major impact on recharge to groundwater because transpiration is a major component of catchment water balances, to which biological productivity is intimately coupled (Berry et al., 2005; Chen et al., 2010). Understanding the effects of climate variations on vegetation water-use and groundwater recharge is particularly important in arid and semi-arid regions, where limited water resource availability is a major factor constraining regional development. Similarly, climate change is a growing concern for water management globally, including Australia because of the potential for declines in water supplies.

Studies of these complex problems can be conducted in field conditions and much has been learnt about the relationship among

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* Corresponding author at: National Centre for Groundwater Research and Training (NCGRT), School of Environment, Flinders University, Adelaide, SA 5001, Australia. Tel.: +61 0295148405.

E-mail addresses: ccchenchao2009@163.com, chao.chen@csiro.au (C. Chen).

http://dx.doi.org/10.1016/j.jhydrol.2014.08.032

growth, photosynthesis and the water cycle (Farrington, 1989; Thorburn et al., 1993; Zhang and Schilling, 2006). However, field experiments are time consuming, relatively expensive and difficulties in up-scaling from limited numbers of observations are apparent (Singh et al., 2006). To overcome this, process-based models that link hydrology and plant ecophysiology have been developed that provide useful tools to investigate interactions amongst energy, water and momentum balances of the soil–vegetation-atmosphere system across multiple spatial and temporal scales (Baird et al., 2005; Guswa et al., 2002; Laio et al., 2001). Studies of modelling these coupled behaviours have been attempted previously (Zhang et al., 1999a; Gerten et al., 2004; Kucharik et al., 2000). For example, Barron et al. (2012) modelled the effects of climate on recharge across Australia and found that the role of climate drivers varied across soil and vegetation types, while Crosbie et al. (2011) reported that recharge in the Murray–Darling Basin would be increased despite a modelled decrease in rainfall, due to the effect of increased temperature stress on vegetation growth. Although these studies provide useful information for developing applicable water management practices, there is still a lack of systematic analysis of the effects of climate variability on vegetation water-use and consequential recharge in arid and semi-arid regions.

Mulga (*Acacia aneura* and related species) is a low-to-medium height (2–8 m) tree, dominating arid and semi-arid zones between approximately 20 °S and 31 °S in coastal Western Australia and throughout the continental interior. Mulga occupies almost 20% of the Australian continent and overlies many significant aquifers including the Great Artesian Basin. Covering such a large portion of continental Australia, vegetation water-use and recharge beneath the Mulga-dominated woodland are assumed to contribute significantly to regional water budgets (Eamus et al., 2013). Mulga is functionally a savanna as it consists of a discontinuous tree layer over a grassy understory with highly seasonal rainfall. This pattern is more pronounced in arid central Australia where rainfall variability is skewed towards very large event cycles (Berry et al., 2011; Morton et al., 2011). Some studies have shown that, in this water-limited environment Mulga plays an important role in controlling water fluxes, including runoff, infiltration and groundwater recharge (Perry, 1970; Dunkerley, 2002; Berg and Dunkerley et al., 2004). However to-date, no studies have quantified the responses of groundwater recharge to Mulga-dominated vegetation under variable climate in arid and semi-arid regions. Such knowledge of the magnitude of recharge is critical to the development of sustainable strategies to allocate limited groundwater.

The objective of this study was to produce a detailed mechanistic understanding of the dynamic links between vegetation water-use and climate, and their influence on groundwater recharge through application of a physiologically-based model of the soil–plant–atmosphere continuum. The primary purpose of this study was to test the hypothesis that recharge of groundwater is largely dependent on the rate of water-use of vegetation growing in an arid region of Australia. The aims of this study were to: (1) parameterise the WAVES model to allow simulation of plant growth and water balance components in the Ti-Tree Basin using field data; (2) quantify the responses of plant growth and vegetation water-use to climate variability and the corresponding effects on groundwater recharge.

2. Materials and methods

2.1. Study site

This study was performed in the Ti-Tree Basin, located 150 km north of Alice Springs, in the Northern Terrority of Australia (Fig. 1). The basin is approximately 5500 km^2, and comprises undulating sand plains with alluvial deposits along ephemeral drainage lines. Vegetation includes large areas of spinifex under sparse woodland of Corymbia opaca and low trees, including *Acacia coriaceae* and *Hakea macrocarpa*. The sand plains contain patches of Mulga (*A. aneura*) and the major rivers are lined with River Red Gums (*Eucalyptus camaldulensis var. obtusa*). Over most of the basin, the water table is between 20 and 50 m below the land surface. Due to low rainfall, groundwater is an important resource for stock, irrigation of small-scale horticultural cropping, and town and community supplies. Therefore recharge to the groundwater needs to be determined to ensure that the resource is properly managed.

The study site is located on the western margin of the Ti-Tree Basin (22.28S, 133.25E, a.s.l. 600 m) (Fig. 1). The climate is characterised as having hot summers and warm winters. Average annual rainfall at the nearest meteorological station (Territory Grape Farm Station) is approximately 333 mm, much lower than annual pan evaporation of 3109 mm. The ecosystem is a savanna woodland with an average canopy height of 6.5 m, which consists of a discontinuous tree layer over a grassy understory. The soil is characterised as a red kandosol (sand:silt:clay 74:11:15).

2.2. Data for model testing

2.2.1. Climate data

An eddy covariance (EC) tower was located on a flat plain between the Hanson and Woodforde Rivers, being a member of the OzFlux network (Cleverly, 2011). Potential fetch is 11 km to the east and 16 km to the south. EC data collection was initiated on 2 September 2010. Total solar radiation was measured 12.2 m above the ground with a CNR1 (Kipp & Zonen, Delft, The Netherlands). Air temperature and relative humidity were measured 11.6 m above the ground using an HMP45C (Vaisala, Helsinki, Finland). Precipitation was measured with a CS7000 (Hydrologic services, Warwick, NSW, Australia), centred in a 10 m × 15 m clearing at the top of a 2.5 m mast. Frequency of micrometeorological measurements was 10 Hz with a 30-min covariance interval.

2.2.2. Soil data

Soil samples were collected using a slide hammer (AMS Soil Core Sampler, Envco: The Environmental Collective, Auckland, New Zealand) to extract intact cores (38 mm diameter × 10 cm depth to a maximum depth of 1.4 m) for laboratory analysis. The experimental site had a fairly uniform soil profile and dry bulk density varied only slightly, ranging from 1.67 g cm^{-3} at the surface to 1.86 g cm^{-3} at 1.4 m depth. Consequently we assumed that the soil could be simulated as a single layer. A soil column of 4 m was chosen considering a relatively shallow rooting depth for Mulga, which was shown not to access soil water below 5 m, even in drought conditions (Hill and Hill, 2003; Anderson et al., 2008). Soil hydraulic characteristics required by the model (Table 1) were derived from the ASRIS v1 database (Johnston et al., 2003). Soil moisture was measured in two vertical arrays under Mulga and understory habitats using TDR probes (CS610, Campbell Scientific, Townsville, Australia). Insertions with the 45° angle were at 10, 60 and 100 cm representing average soil moisture across depths of 10–30, 60–80 and 100–120 cm, respectively. For model calibration (see below), soil water was averaged without weighting across Mulga trees and understory grasses.

2.2.3. LAI data

Although knowledge of leaf area index (LAI) is vital to any mechanistic understanding of the hydrological role of vegetation (Eamus et al., 2006), it is difficult to measure across large spatial scales and difficult to simulate due to spatial and temporal variability. To assess model performance, the simulated total LAI