Journal of Hydrology 517 (2014) 901–912

Contents lists available at ScienceDirect

Journal of Hydrology

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

Groundwater fluxes in a shallow seasonal wetland pond: The effect of bathymetric uncertainty on predicted water and solute balances

Mark A. Trigg[a,b,*], Peter G. Cook[b], Philip Brunner[c]

[a] *Hydrology Group, School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK*
[b] *National Centre for Groundwater Research and Training (NCGRT), School of the Environment, Flinders University, GPO Box 2100, Adelaide, SA 5001, Australia*
[c] *Institut de Géologie et d'hydrogéologie, Université de Neuchâtel, Rue Emile-Argand 11, CH-2009 Neuchâtel, Switzerland*

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form 7 February 2014
Accepted 13 June 2014
Available online 27 June 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Todd C. Rasmussen, Associate Editor

Keywords:
Wetland ponds
Bathymetry
Uncertainty
PEST
Solute balance
Bézier curve

SUMMARY

The successful management of groundwater dependent shallow seasonal wetlands requires a sound understanding of groundwater fluxes. However, such fluxes are hard to quantify. Water volume and solute mass balance models can be used in order to derive an estimate of groundwater fluxes within such systems. This approach is particularly attractive, as it can be undertaken using measurable environmental variables, such as; rainfall, evaporation, pond level and salinity. Groundwater fluxes estimated from such an approach are subject to uncertainty in the measured variables as well as in the process representation and in parameters within the model. However, the shallow nature of seasonal wetland ponds means water volume and surface area can change rapidly and non-linearly with depth, requiring an accurate representation of the wetland pond bathymetry. Unfortunately, detailed bathymetry is rarely available and simplifying assumptions regarding the bathymetry have to be made. However, the implications of these assumptions are typically not quantified. We systematically quantify the uncertainty implications for eight different representations of wetland bathymetry for a shallow seasonal wetland pond in South Australia. The predictive uncertainty estimation methods provided in the Model-Independent Parameter Estimation and Uncertainty Analysis software (PEST) are used to quantify the effect of bathymetric uncertainty on the modelled fluxes. We demonstrate that bathymetry can be successfully represented within the model in a simple parametric form using a cubic Bézier curve, allowing an assessment of bathymetric uncertainty due to measurement error and survey detail on the derived groundwater fluxes compared with the fixed bathymetry models. Findings show that different bathymetry conceptualisations can result in very different mass balance components and hence process conceptualisations, despite equally good fits to observed data, potentially leading to poor management decisions for the wetlands. Model predictive uncertainty increases with the crudity of the bathymetry representation, however, approximations that capture the general shape of the wetland pond such as a power law or Bézier curve show only a small increase in prediction uncertainty compared to the full dGPS surveyed bathymetry, implying these may be sufficient for most modelling purposes.

1. Introduction

The importance of wetlands to biodiversity is now widely recognized (Murray et al., 2003) and there is growing recognition of the importance of groundwater to many of these systems. Indeed, the management and policy requirements for the protection of groundwater dependent ecosystems (GDEs) globally are an important issue. However, with a few notable exceptions, the groundwater requirements of these ecosystems are not well understood (MacKay, 2006). Numerical models, of which water and solute balance models are examples, have become an indispensable decision tool in groundwater management (Sophocleous, 2000). Modelling of GDE and groundwater interactions allows the development and testing of our conceptual understanding of how these systems function and is perhaps a key research area that would benefit management by allowing the projection of GDE response to different magnitudes, rates and season of groundwater drawdown, as well as different climatic scenarios (Eamus and Froend, 2006).

Water balance methods are often not sufficiently accurate to estimate groundwater inflow, and hence environmental tracer methods have been used in combination with water balance

---

* Corresponding author at: Hydrology Group, School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK. Tel.: +44 (0)117 928 8290; fax: +44 (0)117 928 7878.

E-mail address: mark.trigg@bristol.ac.uk (M.A. Trigg).

http://dx.doi.org/10.1016/j.jhydrol.2014.06.020

Nomenclature

A	wetland surface area (m^2)
c_g	groundwater inflow EC (mS/cm)
c	mean EC in wetland (mS/cm)
c_P	mean precipitation EC (mS/cm)
c_Q	mean EC of pond outflow (mS/cm)
c_s	mean surface water EC (mS/cm)
c_0	initial salt mass (kg)
d	wetland depth at deepest point (m)
d_0	max. wetland depth (m)
E	evaporation from pond (m/day)
I_g	groundwater inflow (m^3/day)
I_s	surface water inflow (m^3/day)
P	precipitation falling on wetland (m/day)
$P_{0,1,2,3}$	Bézier control points coordinates (r, d)
Q	surface & groundwater outflow (m^3/day)
r	bathymetry radius (m)
r_0	max. bathymetry radius at d_0 (m)
t	time (days)
t_g	groundwater period parameter (days)
V	pond volume (m^3)
α_P	precipitation factor
α_E	evaporation factor
α_g	groundwater input factor (m^2)
α_Q	groundwater output factor (m^2/day)

methods to constrain the interactions between wetlands or lakes and groundwater. ^{2}H and ^{18}O have been applied widely to calculate groundwater inflow and outflow (Krabbenhoft et al., 1990; Hunt et al., 1996; Yehdegho et al., 1997; Gurrieri and Furniss, 2004) or surface water evaporation (Gibson et al., 1996; Yehdegho et al., 1997). Ion chemistry (including sodium, chloride and calcium) have also been used, both independently (Hayashi et al., 1998; Ferone and Devito, 2004; Heagle et al., 2007, 2013; Kizuka et al., 2011), and in combination with isotopic tracers (LaBaugh et al., 1997). Similarly, Corbett et al. (1997) and Schmidt et al. (2009) used point samplings in time of radon to estimate groundwater inflow. For highly transient systems, however, time series of tracer data are required to capture the dynamic nature of the water balance. In these systems, electrical conductivity has been used (e.g. Quinn et al., 2010) as it can be measured easily and remotely using sensors and data loggers. More recently, time-series of radon has also been used to analyse the transient dynamics of wetlands (Dimova and Burnett, 2011) and river bank infiltration (Gilfedder et al., 2013) over periods of several days.

All of the above mentioned tracers are interpreted by calculating a water and solute mass balance of the surface water body. These mass balances can be either applied in a steady-state or in a transient mode. Steady-state mass balance approaches do not require a detailed description of the bathymetry. However, in many cases steady-state approaches are not an appropriate description of the system and transient approaches need to be used. Observation data usually available to capture system dynamics are the changes in water depth and solute concentration over time. However, depth in itself is not sufficient to calculate in and outgoing water fluxes, and changes in water volumes over time are required. Similarly, water volumes are also required to calculate the changes in solute mass over time. However, volumes cannot be directly measured. The surface water area is also important because it controls evaporation losses and gas exchange processes. To link observations of depth to volume and surface area, the bathymetry of the system is required.

Despite the obvious importance of bathymetry, most solute and water balance studies provide scant information on how bathymetry was determined and the accuracy of the resulting depth–volume–area relationship e.g. Gurrieri and Furniss (2004), Dimova and Burnett (2011). In the absence of a detailed measured bathymetry, other studies assume a simple mathematical form for the bathymetry, which is parameterized with a small number of measurements of depth and area and/or volume, e.g. Castaneda and Angel Garcia-Vera (2008) and Hayashi and van der Kamp (2000). Minke et al. (2010) explore in some detail the basic bathymetric error in using these relationships compared to a detailed survey, but do not quantify the implications for water and solute mass balance model results. Although uncertainty analyses on water and solute mass balances have been carried out in some cases (Gibson et al., 1996; Choi and Harvey, 2000), few studies consider how uncertainties in bathymetry may impact on estimated water balance components. The only study that we are aware of that specifically considers uncertainties introduced by errors in bathymetry is (McJannet et al., 2012), although in this case variations in lake volume were relatively small, and so uncertainty due to bathymetry was small relative to other model parameters. This might not be the case for shallower wetlands, where changes in pond area can be more pronounced, and hence the depth–volume relationship can become very non-linear.

In this paper, we use a solute and water balance approach to reconstruct the water balance of a shallow, groundwater dependent wetland pond over a period of six years. The solute and water balance is based on a time series of daily water depth and electrical conductivity measurements, and on measurements of wetland pond bathymetry obtained using dGPS and LiDAR survey. In particular, we examine how uncertainty in bathymetry affects the calculated water balance components by running the model with a range of bathymetry approximations.

2. Water and solute balances

The surface water balance for a pond can be expressed as:

$$\frac{dV}{dt} = I_s + I_g + PA - Q - EA \tag{1}$$

where V is the pond volume [L^3], I_s is the surface water inflow rate [$L^3\,T^{-1}$], I_g is the groundwater inflow rate [$L^3\,T^{-1}$], Q is the combined surface water and groundwater outflow rate [$L^3\,T^{-1}$], P is the precipitation rate [$L\,T^{-1}$], E is the evaporation rate from the water surface [$L\,T^{-1}$], A is the surface water area [L^2] and t is time [T]. V and A are typically inferred through water depth using equations describing the bathymetry.

The mass balance for a conservative solute can be written as:

$$\frac{dcV}{dt} = I_s c_s + I_g c_g + PAc_P - Qc_Q \tag{2}$$

where c is the mean concentration of tracer within the pond [$M\,L^{-3}$], c_s, c_g and c_P are the mean concentrations in surface water inflow, groundwater inflow and precipitation, respectively, and c_Q is the mean outflow concentration. For isotopes and noble gases additional terms are required e.g. Krabbenhoft et al. (1990) and Cook et al. (2008).