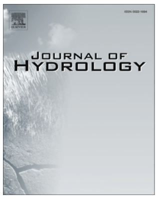
Journal of Hydrology 527 (2015) 844–857

Contents lists available at ScienceDirect

Journal of Hydrology

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



Estimation of groundwater recharge and drought severity with varying model complexity

Jana von Freyberg [a,b,c,*], Christian Moeck [b], Mario Schirmer [b,c]

[a] *Swiss Federal Institute of Technology Zürich, Department of Environmental Systems Science, 8092 Zurich, Switzerland*
[b] *Eawag – Swiss Federal Institute of Aquatic Science and Technology, Department of Water Resources and Drinking Water, 8600 Dübendorf, Switzerland*
[c] *University of Neuchâtel, Centre for Hydrogeology and Geothermics (CHYN), 2000 Neuchâtel, Switzerland*

ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 20 April 2015
Accepted 13 May 2015
Available online 19 May 2015

This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:
Groundwater recharge
Lysimeter
Model comparison
Drought
Soil water balance
Conceptual model

SUMMARY

A reliable quantification of groundwater recharge (GR) is essential for sustainable water resources management. This can be particularly relevant in regions where an increase in the duration and frequency of drought events is predicted due to future climate change. Although there exists a large variety of GR estimation methods, their results can differ considerably for an individual site due to the spatio-temporal scales and complexities they represent. Therefore, it is crucial to evaluate the potential range of GR estimates to allow for consistency and objective inter-comparison of modeling results among different sites. The current study systematically assesses the performance of six frequently used GR estimation methods, which differ in terms of their underlying conceptual framework and complexity. These methods utilize experimental data (lysimeter, river streamflow, groundwater-table variations) as well as soil–water-balance and physically-based modeling concepts. 13 years of hydro-climatic data were analyzed from the Swiss Rietholzbach research catchment for different temporal resolutions and extreme climatic conditions (i.e., dry periods). The major limitations and strengths of the six GR estimation methods were identified and summarized in a comprehensive overview, which will facilitate the selection of an adequate technique for the estimation of GR in future studies.

1. Introduction

Groundwater recharge (GR) is a driver of many hydrologic processes, which makes it an important variable in the water cycle (Bakker et al., 2013). Thus, for sustainable water resources management, a reliable quantification of GR is essential, particularly considering the effects of future climate change on water resources (e.g., Green et al., 2011; Middelkoop et al., 2001; van Roosmalen et al., 2009). A large number of methods exist, which aim to quantify GR from available hydro(geo-)logic and climatic measurements (Bakker et al., 2013). Frequently used physical techniques for GR estimation utilize direct measurements of lysimeters (e.g., Heppner et al., 2007; Risser et al., 2005; Xu and Chen, 2005), and temporal variations of river streamflow (e.g., Arnold and Allen, 1999; Combalicer et al., 2008; Nathan and McMahon, 1990; Rorabaugh, 1964) or the water table (e.g. Crosbie et al., 2005; Healy and Cook, 2002; Maréchal et al., 2006). Furthermore, unsaturated-zone modeling can be applied to estimate GR, such as analytic soil water balance models (e.g., Bond, 1998; Finch, 1998; Rodriguez-Iturbe et al., 1999) or numerical modeling using Richards' equation (e.g., Crosbie et al., 2011; Jyrkama and Sykes, 2007; Keese et al., 2005; Simunek and van Genuchten, 2008; van Roosmalen et al., 2009).

Typically, the uncertainty introduced by a specific GR estimation method cannot be evaluated objectively through representative measurements. Because GR estimation is furthermore very sensitive to the underlying climatic forcing functions and the parameters of the chosen method (Risser et al., 2005; Savenije, 2004; Scanlon et al., 2002), it is generally recommended to apply several techniques and to compare the GR estimates to each other (Nimmo, 2003; Healy and Cook, 2002). This, however, is not always practicable because of limited data availability. For example, many climate change impact studies apply solely one GR estimation method (e.g., Allen et al., 2010; Goderniaux et al., 2009; Ordens et al., 2014; van Roosmalen et al., 2009).

The uncertainty inherent in a specific GR estimation method might also be relevant for drought risk assessment studies in hydrological systems where GR is closely linked to catchment storage and the streamflow regime (e.g., Beniston and Fox, 1996; Calanca, 2007; Jasper et al., 2004; Vanham et al., 2009).

---

* Corresponding author at: ETH Zurich, Department of Environmental Systems Science, Institute of Terrestrial Ecosystems, Universitätstrasse 16, 8092 Zurich, Switzerland.

E-mail address: jana.vonfreyberg@usys.ethz.ch (J. von Freyberg).

http://dx.doi.org/10.1016/j.jhydrol.2015.05.025
0022-1694/

Therefore, GR estimation methods should also be tested with respect to both mean and extreme climatic conditions to allow for an accurate assessment of the results. This could be achieved, for instance, by comparing different GR time series during very dry climatic conditions by means of drought characteristics (e.g., duration and severity; Mishra and Singh, 2010). Although there are several comparison studies focusing on GR (e.g., Allison et al., 1994 Flint et al., 2002; Gee and Hillel, 1988; Lerner et al., 1990; Scanlon et al., 2002; Simmers, 1998; Sophocleous, 1991; Sorensen et al., 2014; Xu and Chen, 2005), to date there is little research, which has systematically evaluated the accuracy and the validity of the applied GR estimation techniques during mean and extreme climatic conditions.

In addition, a comprehensive comparison of GR estimation methods can serve as a valuable learning tool that helps to identify first-order controls on GR recharge and to improve our mechanistic understanding of the relevant hydro(geo)logic processes (e.g., Beven, 2007; Dunn et al., 2008; Fenicia et al., 2014). As a reference for estimated GR, experimental data from large lysimeters (>2 m depth, >1–2 m^2 area) can be used. Despite certain limitations of lysimeters (Scanlon et al., 2002), they provide a method for direct measurements of the soil water balance that can also be representative for larger scales (Seneviratne et al., 2012; Young et al., 1996). Lysimeters with an outlet below the rooting depth of plants, are assumed to provide reliable estimates of the fraction of GR that will reach the water table without further loss (Heppner et al., 2007). To our knowledge, there exists only one study in which data from a large lysimeter were compared to GR estimates based on evapotranspiration models used in water balance equations (Xu and Chen, 2005). Since appropriate lysimeters are difficult to construct and require much maintenance, there are only a few comparison studies employing long-term lysimeter data, and they are often from smaller systems (e.g., Heppner et al., 2007; Risser et al., 2005).

In order to provide a comprehensive evaluation of widely established GR estimation methods, the main objectives of this study are: (i) to identify the major strengths and limitations of the methods at different time scales and climatic conditions by using measurements from a large lysimeter system and examining drought characteristics; and (ii) to learn from the differences of the applied GR estimation methods to identify first-order controls that drive GR.

Six GR estimation methods, which represent a variety of approaches and complexities (i.e., number of model parameters and type of input variables) as well as different spatial scales (i.e., plot to catchment scale), were tested in this study. These methods are: (a) large lysimeter measurements (seepage); (b) the streamflow-based automated recession-curve displacement method (RORA, Rutledge and Daniel, 1994); (c) the groundwater-table fluctuation method (WTF, Healy and Cook, 2002); soil water balance models with (d) one soil layer (SWB, Rodriguez-Iturbe et al., 1999) and (e) four soil layers (FINCH, Finch, 1998) and (f) a one-dimensional, Richard's equation model (HYDRUS, Simunek and van Genuchten, 2008). Daily time series of hydro-climatic data from the Swiss Rietholzbach research catchment were used. These data span a 13-year period (2000–2013) that cover a wide range of climatic conditions.

First, all methods were compared on an annual and monthly basis by using field-based observations and literature data as initial model parameters. The same analyses were carried out after calibrating methods (b) to (f) against measured lysimeter seepage (calibrated models are marked with a "$*$"-sign). This allows for a more robust assessment of the performance and a meaningful comparison of the methods, despite the differences in the underlying modeling concepts. In the second part of this paper, drought characteristics were calculated from monthly GR time series and compared against historical events in order to systematically evaluate the performance of the different methods during very dry climatic conditions. These results are used to identify the main strengths and limitations of the six methods. From this, conclusions about flow processes and streamflow generation in the studied catchment are derived and recommendations for the effective estimation of GR at different spatio-temporal scales are provided at the end of this paper.

2. Materials and methods

2.1. Study site and observed data

The Rietholzbach research catchment is located in the pre-Alpine headwaters of the Thur river in north-east Switzerland (Fig. 1a). Its western sub-catchment (upper Rietholzbach, URHB, red line in Fig. 1b) covers an area of 0.94 km^2, from which around 72% is pastureland, 19% is forested, 4% is settlement and pavement and 5% is a wetland located in the central valley bottom. Elevations in the URHB range from 744 to 910 masl with a more flat topography in the valley bottom, which is underlain by Pleistocene glacial moraine deposits (Fig. 1b). The moraine deposits are a heterogeneous composition of unconsolidated conglomerates and Quaternary gravel pockets that form a shallow, unconfined aquifer with an average hydraulic conductivity of 2×10^{-3} m s^{-1} (Balderer, 1980). The bedrock is formed by the Upper Freshwater Molasse, which is composed of layers of consolidated conglomerates, sandstone, marl and freshwater limestone, with hydraulic conductivities between 1.5×10^{-6} m s^{-1} and 1.1×10^{-4} m s^{-1} (Balderer, 1983). Vertical groundwater flow between the two aquifers is assumed to be minor due to a confining low-permeability layer of clay and silt beneath the moraine deposits (von Freyberg et al., 2014). The soils in the valley bottom areas are mainly peaty soils and Gleysols, whereas on the hills and slopes Cambisols and Regosols are dominant (Germann, 1981).

All hydro-climatic variables (i.e., river streamflow, precipitation, groundwater-table depth) are measured at the experimental field site 'Büel' that is located near the URHB-catchment outlet (Fig. 1b). Further details about the instrumentation of the Büel site and data post-processing are provided in the Supplementary material (Table SI-1) and in Seneviratne et al. (2012). Data used in this study are from 1 January 2000 to 31 December 2012 and cover variable climatic conditions from very wet to very dry periods (Fig. SI-1). For instance, in 2003 an extreme summer heat wave occurred, which affected large parts of central Europe (Casty et al., 2005). Other years with less severe dry periods in the Swiss north-eastern pre-Alps were 2005, 2009 and 2011 (MeteoSwiss, 2009, 2011). Wet periods with several high-intensity precipitation events or a significant accumulation of snow occurred in 2001, 2002 and 2007 (Fig. SI-1a). During the 13-year period, average annual values of precipitation, actual evapotranspiration, river streamflow and lysimeter seepage were 1465 mm, 649 mm, 1188 mm and 1003 mm, respectively. The hydroclimatology of the catchment is representative for the eastern Swiss Plateau (Seneviratne et al., 2012).

2.2. Recharge estimation methods

2.2.1. Large lysimeter

The large weighting lysimeter (2.5 m deep, 2 m diameter) is located at the experimental field site 'Büel' near the URHB-catchment outlet (Fig. 1b and c). The lysimeter cylinder was filled with an undisturbed soil column from the same location in 1976. The system imitates the surrounding surface and subsurface properties, which allows for direct measurements of actual evapotranspiration and drainage through the unsaturated zone at