Journal of Hydrology 552 (2017) 258–266

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Soil moisture data as a constraint for groundwater recharge estimation

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ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 25 May 2017
Accepted 23 June 2017
Available online 29 June 2017
This manuscript was handled by C. Corradini, Editor-in-Chief, with the assistance of Rao S. Govindaraju, Associate Editor

Keywords:
Conditioning
Groundwater recharge
Soil moisture content
Soil texture
Vertical percolation

ABSTRACT

Estimating groundwater recharge rates is important for water resource management studies. Modeling approaches to forecast groundwater recharge typically require observed historic data to assist calibration. It is generally not possible to observe groundwater recharge rates directly. Therefore, in the past, much effort has been invested to record soil moisture content (SMC) data, which can be used in a water balance calculation to estimate groundwater recharge. In this context, SMC data is measured at different depths and then typically integrated with respect to depth to obtain a single set of aggregated SMC values, which are used as an estimate of the total water stored within a given soil profile. This article seeks to investigate the value of such aggregated SMC data for conditioning groundwater recharge models in this respect. A simple modeling approach is adopted, which utilizes an emulation of Richards' equation in conjunction with a soil texture pedotransfer function. The only unknown parameters are soil texture. Monte Carlo simulation is performed for four different SMC monitoring sites. The model is used to estimate both aggregated SMC and groundwater recharge. The impact of conditioning the model to the aggregated SMC data is then explored in terms of its ability to reduce the uncertainty associated with recharge estimation. Whilst uncertainty in soil texture can lead to significant uncertainty in groundwater recharge estimation, it is found that aggregated SMC is virtually insensitive to soil texture.

1. Introduction

An essential aspect of water resource planning often involves the estimation of groundwater recharge rates, here defined as the rate at which water arrives at the water table of an aquifer following precipitation, interception, snow melt, evapotranspiration and percolation through the unsaturated zone. In many cases, water loss during percolation through the unsaturated zone below the reach of plant roots can be assumed negligible. Consequently, vertical percolation beneath the reach of plant roots and groundwater recharge are often treated as being the same (Quinn et al., 2012; Sorensen et al., 2014). Hereafter, vertical percolation is referred to as a proxy for groundwater recharge. Vertical percolation rates (VPR) can be estimated using a multitude of different models, all of which require historic data of some form to enable appropriate model parameter calibration.

Ideally, such models should be calibrated to observed groundwater recharge rates. However, groundwater recharge data is difficult to observe directly. Some studies have sought to derive recharge data by separating out base flow from river discharge rate records (Rutledge, 2007). The problem here is that base flow separation methods are, in themselves, *ad hoc* and unconstrained, unless combined with some form of tracer based mass balance study (Lott and Stewart, 2016). Another method is to assume a specific yield for an unconfined aquifer and to infer recharge rates from water table changes (Healy and Cook, 2002). The problem with this latter approach is that there is often significant uncertainty about the time-varying characteristics of specific yield (Healy and Cook, 2002; Mathias and Butler, 2006) and significant care is required to properly take into account the effects of lateral groundwater flow rates (Healy and Cook, 2002; Cuthbert et al., 2016).

Arguably, the most direct method of observing recharge rates is to measure VPR from an in situ lysimeter (von Freyberg et al., 2015). The issue here is that such facilities are very expensive to manage and very few facilities exist around the world.

Another related approach is to continuously monitor moisture content within a soil profile over a long period of time (Ireson et al., 2006). Providing that precipitation (net of interception) and actual evapotranspiration (AE) are also monitored, soil moisture content (SMC) data can be used to develop a VPR measurement by water balance. However, a problem is that AE is not often measured. Instead, an estimate of potential

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http://dx.doi.org/10.1016/j.jhydrol.2017.06.040

evapotranspiration (PE) is generally obtained using weather station data (incoming radiation, temperature, humidity, wind speed etc.) in conjunction with an appropriate physics model (e.g. Allen et al., 1998). Under such conditions, a direct estimate of VPR is not possible by water balance, as the quantity of AE is unknown. Consequently, VPR must instead be estimated by simulating soil-plant-water processes using an appropriate model, which is conditioned to the observed SMC data.

Interestingly, previous modeling studies have focused on the ability of models to estimate SMC data as opposed to the value of SMC data as a conditioner for estimating VPR (Ragab et al., 1997; Sorensen et al., 2014). In a recent study, Sorensen et al. (2014) presented SMC data from four instrumented sites from southern England. They then compared estimated SMC data from four different uncalibrated recharge estimation methods. The authors conclude that, whilst each of four models provided a "generally good agreement" between simulated and observed SMC, there were large discrepancies between the different VPR estimates, leading to concerns over the value of SMC data for conditioning groundwater recharge modeling in the future.

In the current study, the four aforementioned instrumented sites presented by Sorensen et al. (2014) are revisited to quantify the extent to which observed SMC data can be used to reduce uncertainty associated with groundwater recharge in the context of a single model structure. In particular, the model structure used includes a recently developed soil moisture accounting procedure (SMAP) designed by Mathias et al. (2015), which is described later on in this article. Unknown input parameters associated with this SMAP only include information about the soil texture of the site (i.e., % clay, % silt and % sand).

The outline of this article is as follows. An explanation is provided concerning the data, models and conditioning strategies to be applied. The aforementioned SMAP is used to estimate VPR at the four instrumented sites in southern England. Probability of non-exceedance (PNE) confidence limits are acquired using four successive methodologies. For comparison, PNE confidence limits are first acquired assuming any soil texture is equally likely to be applicable at each of the four sites. PNE confidence limits are then refined by conditioning the SMAP to the observed SMC data from each site. For further comparison, an additional set of PNE confidence limits is acquired by restricting soil texture to be within a polygon on a soil texture ternary diagram associated with the soil texture classification for that site as designated by the UK soil observatory (UKSO). The results are compared and contrasted so as to draw wider conclusions with regards to the value of observed SMC data when seeking to estimate VPR for groundwater recharge studies in the future.

2. Data and methodology

2.1. Data

The data used for this study include daily net rainfall (i.e., rainfall minus canopy interception losses) and PE data in conjunction with observed SMC from the four instrumented sites previously discussed by Sorensen et al. (2014). The four sites include Warren Farm, Highfield Farm, Beche Park Wood and Grimsbury Wood, all of which are located in Berkshire, UK.

Daily net rainfall and AE data were obtained by Sorensen et al. (2014) using JULES (Best et al., 2011) driven by nearby meteorological observations. A default JULES parameterisation was used for grassland sites with woodland vegetation parameters defined using observations by Herbst et al. (2008).

Routine SMC data were obtained at each site as follows (Sorensen et al., 2014). Point measurements of SMC were obtained using neutron probes at 17 intervals at depths of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.3, 2.6, 2.9, 3.2 m, respectively. The results were then aggregated together, by depth weighting, to obtain a depth of water contained within the top 3 m of the soil profile.

Soil texture maps from the UK soil observatory (UKSO, 2016) were used to provide soil texture data describing the surface cover of the four sites.

The UKSO map covers Great Britain and integrates geology and soil characteristics at a scale of 1:50 000, with a 1 km resolution version available for regional overviews. The simplified soil texture classifications are derived from measured soil textures (% clay, % silt and % sand) taken from archive samples held by the British Geological Survey. The map uses terms that refer to: sandy soils, silty soils, clayey soils and loamy soils with additional indicators for the presence of chalk fragments (chalky) and peat (peaty). For reference, soil texture ternary diagrams illustrating the various available UKSO soil texture classifications are presented in Fig. 1.

2.2. Geology and soil cover of the field sites

Location maps of the four field sites, Warren Farm, Highfield Farm, Beche Park Wood and Grimsbury Wood, have previously been presented by Sorensen et al. (2014). The four locations cover a range of different superficial geology, soil type and land use. Warren Farm and Highfield Farm are grassland sites. Beche Park Wood and Grimsbury Wood are deciduous woodland sites. All four sites are underlain by chalk geology, with water tables located at greater than 10 m depth. The Chalk in this area is overlain by superficial clay-with-flints formation or Paleogene deposits comprising of clays, interbedded sands and silty clays with the exception of Warren Farm which is chalk outcrop (Sorensen et al., 2014).

Soil logs indicate the following (Sorensen et al., 2014): Warren Farm consists of a thin 0.2 m soil, including flints, overlying weathered chalk which grades into consolidated chalk between 1 and 3 m depth. Highfield Farm consists of a very heterogeneous fine loam to around 0.4–0.5 m, above clay with various degrees of interbedded gravel. Beche Park Wood consists of around 0.3 m of gravely clay, over clay-with-flints containing occasional sand filled fissures. Grimsbury Wood is predominantly silty clay overlain by 0.3 m of loam.

The soil texture for the four sites according to UKSO is as follows: Warren Farm is described as a "chalky silty loam". Highfield Farm is described as "loam to sand". Beche Park Wood is described as "clay to clayey loam". Grimsbury Wood is described as "clay to silt".

The UKSO map provides quite reasonable soil texture descriptions for Beche Park Wood and Grimsbury Wood. However,the UKSO map soil texture descriptions do not compare well with the field descriptions for Warren Farm and Highfield Farm, previously provided by Sorensen et al. (2014). Indeed there are many problems associated with determining soil texture for soils associated with chalk (Kerry et al., 2009). Nevertheless, the UKSO soil textures will be considered further as an alternative conditioner for groundwater recharge estimation.

2.3. Vertical percolation rate (VPR) modeling

The soil moisture accounting procedure (SMAP) previously proposed by Mathias et al. (2015) was used to simulate VPR at the four sites. The model requires daily net rainfall, PE data and soil texture data to provide estimates of aggregated SMC and VPR.

The SMAP has been specifically designed to emulate Richards' equation in conjunction with the plant roots stress function of Feddes et al. (1976) and the pedotransfer function stored within the ROSETTA database (Schaap et al., 2001). The associated conceptual model comprises a 3 m thick homogenous soil column