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Estimation of spatial distribution of groundwater recharge from stream baseflow and groundwater chloride

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A B S T R A C T

In this study groundwater chloride concentration and baseflow are used to estimate the spatial variability of recharge. Total recharge over the entire watershed is estimated using the baseflow method, and then the spatial variability of recharge is approximated using groundwater chloride concentration. The efficacy of the method is demonstrated using data from a rural watershed in Alberta, Canada. By using the combination of two well established methods of estimating recharge, baseflow and chloride mass balance, there is no need to estimate wet and dry deposition rate of chloride. The presented method is tested by using a steady-state groundwater flow model. The groundwater model showed higher agreement between modeled vs observed heads when spatially variable recharge forced the upper boundary of the model (root mean square error reduced from 13.5 m to 8 m). In addition, we demonstrate a unique method for parameterizing hydraulic conductivity of a fluvial aquifer using a sand fraction transfer function. This new method reduces the dimensionality of the parameter estimation problem and provides a consistency check on the spatially varying recharge estimates.

1. Introduction

Understanding the rate, timing, and location of groundwater recharge is critical for groundwater contamination studies as well as groundwater supply (Healy and Scanlon, 2010). Areas of high recharge are often equated with areas of high aquifer vulnerability to contamination. In addition, the calculation of aquifer recharge is essential for the quantitative evaluation and modeling of groundwater resources (de Vries and Simmers, 2002).

Groundwater recharge cannot be measured directly; accordingly it is estimated by several different techniques. Selecting the proper technique is always difficult and factors including space and time scales, range, and reliability of recharge estimates are central in choosing the suitable technique (Scanlon et al., 2002). Moreover, recharge is highly dependent on climate and surface and sub-surface conditions. Therefore spatial variability of climate, surface and subsurface conditions must be considered to estimate recharge accurately (de Vries and Simmers, 2002). Its dependency on different factors makes the estimation of spatial variability of recharge highly uncertain, especially when the surface and subsurface conditions are heterogeneous.

Several studies have been conducted to estimate groundwater recharge and its spatial variability in different climatic conditions using variety of methods (Cook et al., 1989; Edmunds and Gaye, 1994; Scanlon and Goldsmith, 1997; Hartmann et al., 2012; Alcalá and Custodio, 2014). Cook et al. (1989) used the chloride profile and electromagnetic techniques to estimate rates and spatial variability of groundwater recharge. They found that recharge rates were approximately log-normally distributed, which were in agreement with previous results for infiltration rate and hydraulic conductivity. Wood and Sanford (1995) used a chloride mass balance (CMB) method to estimate recharge to in the southern High Plains Aquifer in Texas, U.S.A. by using 3000 measurements of chloride concentration in groundwater. They showed that CMB method can provide a time-integrated technique for evaluation of recharge flux to regional aquifers that is independent of physical parameters. Risser et al. (2008) compared four different methods of estimating recharge and two method of estimating baseflow (as a proxy for recharge) at two hydrologic research sites in Pennsylvania, USA. They showed that results from multiple estimates all provided reasonable estimates of groundwater recharge, but that they differed considerably.

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Groundwater models provide useful tools for groundwater resource management (Niazi et al., 2014). Recharge fluxes provide the surface boundary conditions of groundwater models. Due to the uncertainty associated with recharge estimates, the initial estimate of recharge is often adjusted during model calibration in order to match calculated heads and flow rates with measured heads and flow rates (Healy and Scanlon, 2010). Since model calibration is often plagued by nonuniqueness, reducing the uncertainty associated with recharge estimates reduces the degree of nonuniqueness in model calibration which, in turn, increases the reliability of calibrated groundwater models.

In some watersheds most of the recharge eventually discharges to streams in the form of baseflow. In these watersheds, the total baseflow of the river is a good estimate of the total recharge within the watershed (Mau and Winter, 1997; Healy and Scanlon, 2010). Consequently, baseflow methods can provide an integrated estimate of recharge over the entire watershed, but the spatial distribution of recharge across the watershed cannot be determined (Gaye and Edmunds, 1996; Halford and Mayer, 2000; Healy and Scanlon, 2010).

Chloride is a conservative environmental tracer, owing to its chemical stability and high solubility. As a result, the CMB method has been widely used in recharge studies (Eriksson and Khunakasem, 1969; Walker et al., 1991; Gaye and Edmunds, 1996; Wood, 1999; Marei et al., 2010; Naranjo et al., 2015). The CMB method needs an estimate of atmospheric deposition of chloride, which is not always available. Moreover, since the chloride concentration in atmospheric deposition is usually small in inland areas, its measurement uncertainty can lead to a large degree of uncertainty in the calculation of recharge.

In the following, a method for estimating the spatial distribution of recharge is presented that uses a combination of the baseflow (BF) method and the CMB method. The efficacy of the method is demonstrated using data from a rural watershed in Alberta, Canada. Hereafter this approach is referred to as the BF-CMB. In the BF-CMB method, total recharge over the entire watershed is estimated using the baseflow method, and then the spatial variability of recharge is approximated using groundwater chloride concentration. It will be shown that the proposed method does not need an estimation of the atmospheric deposition rate of chloride as long as the groundwater contribution to baseflow is estimated with a high degree of confidence.

In addition, we demonstrate a unique method for parameterizing hydraulic conductivity of a heterogeneous sandstone-mudstone aquifer using a transfer function based on the fraction of sandstone. This new method reduces the dimensionality of the parameter estimation problem and provides a consistency check on the spatially varying recharge estimates.

2. Concept of baseflow-chloride mass balance (BF-CMB) method

With the BF-CMB, the first step is to delineate the watershed boundary and estimate the integrated recharge over the entire watershed by analyzing the stream hydrograph and estimate the portion of stream flow that is directly contributed by groundwater discharge using a method that is appropriate for the particular watershed and aquifer. This type of method is commonly referred to in the literature as the baseflow method (Healy and Scanlon, 2010).

The next step is to generate a grid for the watershed. For the sake of simplicity, this study uses square grid cells having uniform size of 400 m by 400 m. To use the chloride method, we assume that the water sample from a well is sourced from local recharge within the grid cell. The validity of this assumption will be discussed later. The average annual groundwater recharge flux (R_C, m y^{-1}) for each grid cell of the watershed is calculated from the CMB by

$$R_C = \frac{M_{Cl}}{Cl_{GW} \times A} \tag{1}$$

$$M_{Cl} = Cl_p \times P \times A + M_{ClI} - M_{ClO} \tag{2}$$

where M_{Cl} (kg y^{-1}) is the average annual mass of chloride entering the grid cell, A (m^2) is the area of a grid cell, Cl_{GW} (kg m^{-3}) is the chloride concentration in groundwater, Cl_P (kg m^{-3}) is the chloride concentration of precipitation plus the contribution of atmospheric deposition of chloride expressed as concentration in precipitation, P (m y^{-1}) is average annual precipitation over the grid cell, M_{ClI} (kg y^{-1}) is the average annual mass of chloride that enters the grid cell, and originates from sources other than precipitation such as road salt or dissolution of halite, and M_{CLO} (kg y^{-1}) is the average annual mass of chloride that leaves the grid cell via runoff.

If we equate the total amount of recharge, R_{BF} (m y^{-1}) estimated using the baseflow method to the average recharge estimated by the chloride method, then

$$R_{BF} = \frac{\sum_{k=1}^{n} R_c^k}{n} = \frac{\sum_{k=1}^{n} \frac{M_{Cl}^k}{Cl_{GW}^k \times A}}{n} \tag{3}$$

where n is the total number of grid cells in the watershed.

In the absence of detailed knowledge of the spatial variability of all terms in Eq. (2), we need to make an assumption that M_{Cl} is constant for all grid cells in the watershed. This assumption is reasonable when the watershed is far from sources of salts (e.g., ocean) and has a relatively small size and low topographic relief, resulting in relatively uniform atmospheric deposition rates over the watershed. Additionally, M_{ClO} and M_{ClI} should be constant for all of grid cells. The validity of this assumption for the study area is assessed in subsequent sections. When these assumptions are acceptable, Eq. (3) can be written as

$$\frac{R_{BF} \times n}{\sum_{k=1}^{n} \frac{1}{Cl_{GW}^k}} = \frac{M_{Cl}}{A}. \tag{4}$$

Subsequently, recharge in each grid cells is calculated by substituting Eq. (4) into Eq. (1):

$$R_k = \frac{R_{BF} \times n}{Cl_{GW}^k \times \sum_{k=1}^{n} \frac{1}{Cl_{GW}^k}}. \tag{5}$$

Eq. (5) enables us to estimate recharge rate in each grid cell and does not require the estimation of chloride deposition rate or average precipitation. As with the CMB method (Wood, 1999), the validity of the underlying assumptions of the BF-CMB method should be carefully assessed before applying it. In order to implement this method we need to estimate the value of chloride concentration in the groundwater for each grid cell. The spatial distribution of chloride can be estimated by using geostatistical models.

In order to apply the BF-CMB method, we need to exclude the grid cells that are not within the boundary of the WNC watershed. This was done in ArcGIS by using the "Extract by Mask" tool. Subsequently, Eq. (4) was applied to the chloride map to produce a recharge map. A Python script in ArcGIS was used to calculate spatially varying recharge by applying Eq. (4) to each grid cell using its kriged chloride concentration. Since the recharge grid is the same as the kriged chloride grid, no upscaling or averaging of the chloride grid is required.

3. Study area

The study area is the West Nose Creek (WNC) watershed (Fig. 1) which is defined by the stream gauging station (SGS) located 14 km above the confluence of WNC with Nose Creek. The gauging station