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Spatio-temporal analysis of potential aquifer recharge: Application to the Basin of Mexico

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Summary Regional estimates of aquifer recharge are needed in data-scarce regions such as the Basin of Mexico, where nearly 20 million people are located and where the Basin's aquifer system represents the main water source. In order to develop the spatio-temporal estimates of aquifer recharge and to analyze to what extent urban growth has affected aquifer recharge, this work presents a daily soil water balance which uses different vegetation and soil types as well as the effect of topography on climatological variables and evapotranspiration. The soil water balance was applied on a daily time step in the Basin of Mexico for the period 1975–1986, obtaining an annually-lumped potential recharge flow of 10.9–23.8 m^3/s (35.9–78.1 mm) in the entire Basin, while the monthly values for the year with the largest lumped recharge value (1981 = 78.1 mm) range from 1 m^3/s (0.3 mm) in December to 87.9 m^3/s (23.7 mm) in June. As aquifer recharge in the Basin mainly occurs by subsurface flow from its enclosing mountains as Mountain Block Recharge, urban growth has had a minimal impact on aquifer recharge, although it has diminished recharge in the alluvial plain.

Introduction

The analysis of the spatial and temporal variability of potential aquifer recharge is needed in order to improve the understanding of regional and local groundwater flow systems as well as to prevent pollution of aquifers. The variability of recharge events is important in both arid and semi-arid areas where from a long-term analysis, evapotranspiration greatly exceeds rainfall but where short, high intensity rainfall events largely exceed evapotranspiration,

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thus making more water available for recharge. Recharge can be classified based on its spatial occurrence: diffuse recharge is derived from precipitation or irrigation on large areas, while focused (localized) recharge occurs at topographic depressions such as streams and lakes (Scanlon et al., 2002). Aquifer recharge was classified by Lerner et al. (1990) as actual recharge, which is the water that reaches the water table and potential recharge, which is the water that might be available for recharge but which due to specific situations (e.g. high water table) is transformed into run-off. Different methods can be used to analyze aquifer recharge such as direct measurement, water balance methods, Darcian approaches, tracer techniques and empirical methods developed for particular case studies (Lerner et al., 1990).

Regional estimates of aquifer recharge need to consider both its spatial and temporal variability as this will improve its estimation (Lerner et al., 1990). In addition, a regional hydrogeological conceptual model needs to be developed before attempting to estimate recharge, as it can occur as subsurface flow, from streams located above the water table (i.e. loosing streams), or as in a common situation in alluvial basins defined as Mountain Block Recharge (MBR), which is used to define the flow that enters an aquifer through the mountains by which it is limited. Studies that have developed estimates of MBR can be classified depending on whether they focus on the mountain block or on the basin (Wilson and Guan, 2004). Basin-centered methods include the calibration of groundwater flow models which limit the modeling domain to porous media or to the application of Darcy's law along the mountain block, while mountain block approach methods include isotope methods, empirical relations between MBR and precipitation or by lumped water balances (Wilson and Guan, 2004). A large number of studies have attempted to estimate MBR, mainly in the Western United States: Wasiolek (1995) developed both seasonal and annual estimates of MBR through a simple water balance in five different watersheds to estimate seasonal and annual MBR to the Tesuque aquifer system in Santa Fe, New Mexico while Maurer et al. (1996) determined subsurface flow to Eagle Valley in Nevada using Darcy's law and the chloride balance method, Wilson and Guan (2004) describe seven studies that estimated MBR in New Mexico, Utah, Colorado, Texas and Arizona.

A good overview of methods to estimate regional aquifer recharge is given by de Vries and Simmers (2002), while an inter-comparison study of recharge estimates using different methods is given by Flint et al. (2002) who compared the outcome of water balance techniques, Darcy's law in the unsaturated zone, chloride mass balance, atmospheric radionuclides and empirical approaches in the Yucca mountain in Nevada. The recharge values obtained with each method were different, and ranged from 0 to 300 mm/yr, and according to these authors no single method adequately characterizes recharge. The difficulty of estimating aquifer recharge has been mentioned by several authors such as Sophocleous (1995) who states that it is one of the most difficult and uncertain factors to measure and that there is no established practical methodology to satisfactorily regionalize recharge estimates. The main factors that control recharge are climate, soils, vegetation/land use and topography (Fayer et al., 1996; Keese et al., 2005). The role that vegetation plays on aquifer recharge varies according to different authors: Keese et al. (2005) mention that its presence diminishes recharge, while others (Berndtsson and Larson, 1987) mention that it increases infiltration. Keese et al. (2005) studied 13 regions in Texas with different climate, vegetation and soil types. They found that vegetation reduces aquifer recharge as areas covered with trees have lower recharge values than those areas covered by grass due to the tree's deeper roots; for their study areas, mean annual precipitation explained 80% of the variation in recharge. The fact that vegetation diminishes recharge is explained by Finch (1998): when root depth increases, aquifer recharge decreases as larger soil moisture deficits develop and need to be replenished before the soil reaches field capacity, which is when the soil will start to drain. However, the plants' water demand should also be considered here as a pine does not require the same amount of water as an arid shrub.

Despite the existing difficulties and uncertainties, regional estimates of aquifer recharge are needed even when data are scarce, as is the case for the Basin of Mexico, home to nearly 20 million people and to whom the Basin's aquifer system is the main water supply source. Unfortunately existing data in the region do not suffice to develop a detailed infiltration model and existing data are limited to the Basin's southern area, where the Mexico City Metropolitan Zone (MCMZ) is located. In addition, estimates of the spatial distribution of recharge in the study area are needed in order to analyze the impact of urban growth both on its quantity and quality. Accordingly, a methodology to estimate potential aquifer recharge in the Basin (which mainly occurs as MBR) was developed, which can also be applied to other areas. This methodology estimates potential aquifer recharge through a simple soil water balance which considers different vegetation types, soil units and the effect of topography on climatological variables such as rainfall and temperature, as described in the following sections.

Development of a simple daily soil water balance

The daily soil water balance developed for this study, considers the evolution of a depletion depth caused by a water deficit when plant water requirements are not met. This simple bucket model uses daily evapotranspiration which is computed according to the FAO-56 methodology (Allen et al., 1998) and the Near Surface Soil Storage (NSSS) term introduced by Rushton et al. (2006), which partitions water that enters the soil water balance into a component that remains in the upper soil (NSSS) and another component that diminishes soil depletion through the use of a fractional storage coefficient (F_{st}). The daily soil water balance is expressed as

$$D_i = \text{if } (ET_{act} \leqslant SM_i, D_{i-1} - SM_i(1 - F_{st}), D_{i-1} + ET_{act_i} - SM_i), \quad (1)$$

where D_i represents depletion (e.g. water deficit with respect to the soil's field capacity), SM_i soil moisture and ET_{act_i} actual evapotranspiration on day i in mm. Before applying this equation, rainfall (R) is partitioned into runoff and water that enters the soil water balance under the assumption that all excess rainfall is transformed into