Physics and Chemistry of the Earth 53–54 (2012) 10–18

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

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

Numerical modeling groundwater recharge and its implication in water cycles of two interdunal valleys in the Sand Hills of Nebraska

Xi Chen [a,*], Yuanyang Huang [a], Minhua Ling [a], Qi Hu [b], Bo Liu [a]

[a] State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[b] School of Natural Resources, University of Nebraska – Lincoln, Lincoln, NE 68583-0987, USA

ARTICLE INFO

Article history:
Available online 14 September 2011

Keywords:
Nebraska Sand Hills
Groundwater recharge
Groundwater model
Water cycle

ABSTRACT

The topography and geomorphology of the sand dunes and interdunal valleys in the Nebraska Sand Hills play important roles in regional water cycle by influencing groundwater recharge and evapotranspiration (ET). In this study, groundwater recharge, associated with precipitation and ET as well as soil hydraulics, and its spatial variations owing to the topography of dunes and valleys are examined. A method is developed to describe the recharge as a function of the storage capacity of dunes of various heights. After the method is tested using observations from a network of wells in the Sand Hills, it is used in the MODFLOW model to simulate and describe recharge effects on groundwater table depth at two different dune-valley sites. Analysis of modeled groundwater budget shows that the groundwater table depth in the interdunal valleys is critically influenced by vertical groundwater flows from surrounding dunes. At the site of higher dunes there are steadier and larger vertical groundwater flows in the dunes from their previous storage of precipitation. These vertical flows change to be horizontal converging groundwater flows and create upwelling in the interdunal valleys, where larger ET loss at the surface further enhances groundwater upwelling. Such interdunal valley is the major concentration area of the surface water and groundwater flow in the Sand Hills. At the site of shallow dunes and a broad interdunal valley the supply of groundwater from the dunes is trivial and inadequate to support upwelling of groundwater in the valley. The groundwater flows downward in the valley, and the valley surface is dry. Weak ET loss at the surface has a smaller effect on the groundwater storage than the precipitation recharge, making such area a source for groundwater.

1. Introduction

The Nebraska Sand Hills is the largest and currently stable sand dune area in the Western Hemisphere (58,000 km^2). The stability of the dunes affects the dune-valley morphology, the landcover, and ecosystems of the Sand Hills, further influencing the water recharge of the High Plains Aquifer which extends across eight states in the US central Great Plains. Processes determining the stability of the dunes include the short- and long-term climate variations and ecological and hydrological feedbacks to climate change. Paleo-records have shown destabilized and mobilized dunes in the region during the megadroughts in the Medieval Warm Period (MWP) (approximately 800–1300 AD) (e.g., Cook et al., 2004, 2007; Herweijer et al., 2007; Meko et al., 2001; Sridhar et al., 2006), and re-stabilization of the Sand Hills after MWP (more discussions can be found at http://sandhills-biocomplexity.unl.edu).

Among the possible processes that may have helped stabilize the Sand Hills is the high groundwater table, which maintains the lakes and wetlands and supports wet meadows in interdunal valleys and the grass cover on dunes and highlands (Bleed, 1998; Gosselin et al., 1999, 2006; Gosselin and Khisty, 2001). The wet meadows are dominated by graminoids, in contrast to the grasses in the uplands, and contribute about 50% of the annual primary production of the entire Sand Hills. Because these grass covers in both the dunes and interdunal valleys help restrain the mobility of the sand dunes, understanding the groundwater variations and recharge and their influence on the grass cover will also shed light on stability of the Sand Hills.

Recharge of the groundwater is achieved by precipitation, while the recharge rate is further modified by topography, vegetation, and soil type. In contrast to humid climate regions, where recharge is generally occurring in topographic highs and discharge in topographic lows, in arid alluvial-valley regions recharge usually occurs in topographic lows, such as channels of ephemeral streams. Vegetation cover in these low-lying land areas plays an important role in determining the recharge rate. Recharge is usually much greater in nonvegetated areas than in vegetated areas (Gee et al., 1994), and is greater in areas of annual crops and grasses than in areas of trees and shrubs (Prych, 1998). Soil texture and permeability

* Corresponding author.
E-mail address: xichen@hhu.edu.cn (X. Chen).

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doi:10.1016/j.pce.2011.08.022

affect recharge rate because coarse-grain soils generally result in higher recharge rates than fine-grain soils do. Cook et al. (1992) found a negative correlation between clay content in the top 2 m soil layer and the recharge rate. In the Nebraska Sand Hills, high permeability of sandy soils in sand dunes allows fast precipitation recharge into the aquifer. Meanwhile, the average 200 m thick aquifer provides a large groundwater storage capacity. In summary, topography and geology in the Sand Hills play essential roles in groundwater recharge and variation (Gosselin et al., 1999).

Estimating groundwater recharge is a challenging task because of difficulties in field measurement and complex mechanisms involved in water exchange between saturated and unsaturated zones. These difficulties also influence the accuracy of groundwater models and water budget analysis. Over the years, many methods have been developed to evaluate recharge rates using available meteorological data and soil hydraulic-parameter data. Techniques for estimating recharge rate in unsaturated-zone are applied mostly in semiarid and arid regions where the unsaturated zone is generally thick. These techniques are described in detail in Gee and Hillel (1988), Hendrickx and Walker (1997), Scanlon and Goldsmith (1997), and Zhang (1998).

Groundwater recharge can also be evaluated using unsaturated zone model (Simunek et al., 1998; Hsieh et al. 2000; Chen et al., 2008) and groundwater models (Sanford, 2002; Lowry, 2008). Because there are not available observation data of recharge rate in the large field, the recharge rates estimated using unsaturated zone model are rather uncertain. Because recharge rate and hydraulic conductivity are often highly correlated, groundwater model inversion using only hydraulic-head data is limited to estimating the ratio of recharge rate to hydraulic conductivity. The estimated recharge may not be unique because the same distribution of hydraulic heads can be produced with a range of recharge rates, as long as the ratio of recharge to hydraulic conductivity remains the same. Recent studies have coupled unsaturated model and groundwater model, such as UZF-MODFLOW (Niswonger et al., 2006), to estimate groundwater recharge. This method needs extensive observation data, however, such as soil moisture content in addition to groundwater table, for reliable evaluation of groundwater recharge. Such data are often absent in large watersheds.

One simple method for estimation of groundwater recharge is to directly develop a relationship between the recharge and precipitation in terms of influences of depth to groundwater and lithology. This relationship is usually developed in an annual scale based on statistical data of precipitation, depth to groundwater table and streamflow discharge, e.g. the annual recharge is linear proportion to annual precipitation. For a short term groundwater modeling, however, the recharge processes along with precipitation changes are very important to capture dynamic variations of groundwater flow influenced by climate and topography.

In this study, we develop a multiple regression analysis between monthly recharge and monthly precipitation series in the Sand Hills through examining the recharge processes associated with climatic and topographic variations. This regression analysis captures the regulations on recharge by the unsaturated zone thickness (sand dunes) of the Sand Hills topography. The method is evaluated by groundwater modeling and further used for investigating geomorphic influences on hydrological cycle in the Sand Hills region.

2. Study sites and observation data

Two interdunal valleys at the University of Nebraska's Gudmundsen Sand Hills Research Laboratory (GSRL) are selected for this study (Fig. 1). These valleys are located in the central Sand Hills and represent two of the major types of interdunal environments: dry and short-grass valleys, and sub-irrigated wet meadows. The latter, or "wet valley" (hereafter "West Valley"), is a groundwater discharge area. Groundwater converges in these wet valley areas with sustained "upwelling." In contrast, groundwater flow beneath the dry and short-grass valley, or "dry valley" (hereafter "East Vellay"), is from west–southwest to east–northeast, passing the valley towards the south branch of the Middle Loup River (Fig. 1). When vertical gradients exist in the dry valley, they are downward. The dry valley is interpreted to be a "recharge" and "flow-through" valley (Gosselin et al., 1999).

2.1. West Valley

The dunes flanking the West Valley are higher (68 m above the valley floor) and have steeper slopes than the dunes surrounding the East Valley. The floor of the West Valley is a broad, flat sub-irrigated wet meadow, and densely covered with predominantly emergent wetland grasses and alfalfa used for hay production. To minimize the impact of high water levels on the harvesting of hay, a drainage ditch trending east to west was installed in the 1930s. Both the valley and the ditch extend westward for about 5 km. Although the ditch was constructed, its flow pattern is similar to other natural streams in the region. Groundwater flows toward the center of the valley from both the north and the south and emerges at the surface. Available data suggest that groundwater flows laterally beneath the dunes south of the West Valley (Gosselin et al., 1999). There is a groundwater mound under the large dune north of the West Valley, which serves as a groundwater divide between the West Valley and the Middle Loup River to the north.

2.2. East Valley

The dunes in the fringe of the East Valley are broad, with irregular surfaces, gently sloping toward the valley, and have a maximum relief of about 43 m above the valley floor. Vegetation on the dunal uplands consists of sparse bunchgrasses, small cacti, yucca, and other plants of desert-species. The floor of the East Valley is hummocky, with a gently rolling surface. A few small, shallow ponds are present in local depressions. Otherwise, the valley floor is dry. Very thin sandy soil is present at the valley surface. Vegetation density varies considerably over the valley floor but is generally moderate, with much of the total surface area covered by bare sand and silt. Groundwater flows from the west–southwest toward the east–northeast, and there are variably horizontal and vertically downward gradients (Gosselin et al., 1999).

2.3. Observational data

Precipitation and evapotranspiration (ET) data are obtained from a weather station in GSRL, operated by the US High Plains Regional Climate Center. The average annual precipitation from 1995 to 1999 at the station is 472 mm. Over 80% of it occurred during April–September, and less than 5% came in the winter months (Gosselin et al., 2006). The seasonal pattern of potential ET (PET) is similar to the annual rainfall distribution, but PET reaches its maximum in July, 1 month after the precipitation peak (see Fig. 3a in Gosselin et al., 2006).

Groundwater fluctuations are related to spatial and temporal variations in ET and precipitation, especially in the West Valley (Gosselin et al., 1999). A monitoring network of wells was established in West and East Valleys in 1994. The locations of these wells are marked in Fig. 1. Data from this network also are used in this study. The average depth to groundwater table during 1995–1999 was about 1.0 m for the observation wells 1–5 in the West Valley, varying from 0.5 m in the cold season from November to March to 1.5 m in the warm season from April to October. Large fluctuations up to 50 m were observed in wells 12 and 13 in the