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Evapotranspiration dynamics and effects on groundwater recharge and discharge at an arid waste disposal site

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ABSTRACT

Deserts have been used for waste disposal due to presumed low groundwater recharge. The US Department of Energy is evaluating groundwater flow and contaminant transport at a former uranium mill site near Tuba City, Arizona. They developed a groundwater flow model to determine how fast contaminants were moving towards a downgradient stream, Moenkopi Wash, used to irrigate crops. We used remote sensing algorithms and precipitation (PPT) data to estimate ET and the ET/PPT ratios within the 3513 ha groundwater model domain (GMD) from 2000 to 2012. ET and PPT were nearly balanced (125 mm yr^{-1} and 130 mm yr^{-1}, respectively). However, seasonal and interannual variability in ET and PPT were out of phase. Spatial variability in vegetation differentiated areas where ET was less than PPT (potential recharge areas) from those where ET exceeded PPT (potential discharge areas) within the GMD. ET estimates predicted that 0.2 million cubic meters per year of groundwater contributed to surface flows in Moenkopi Wash, supported by measurements of streamflow at the upstream and downstream boundaries of the GMD. Even small differences between ET and PPT can influence groundwater flow, hence land use practices that enhance discharge through ET can be part of an overall remediation strategy.

1. Introduction

Arid and semiarid environments have been considered well suited for long-term isolation of radioactive and other hazardous wastes due to presumed low groundwater recharge (e.g., Winograd, 1981; Reith and Thompson, 1992). Chloride profiles and soil water potentials even suggest a net upward water flux over the past 10,000–15,000 years in deserts of the southwestern United States (Scanlon et al., 2005). However, vegetation and soil properties can influence effects of climate on percolation and recharge. For example, using a combination of environmental indicators in central New Mexico, Sandvig and Phillips (2006) detected zero percolation past the root zone of creosote shrub communities in the last 20,000 years, but detected episodes of downward flux under juniper-grass communities (0.4 mm yr^{-1}) and ponderosa pine forests (2.3 mm yr^{-1}), and distinct differences in fluxes over short distances across ecotones. Direct measurements in lysimeters demonstrate the critical role of vegetation in controlling percolation in arid environments (Gee et al., 1994; Scanlon et al., 2005). Gee et al. (1994) compared percolation over many years in deep (3–18 m) lysimeters with and without vegetation at three arid sites with varying precipitation (PPT) amounts (100 mm yr^{-1} to 230 mm yr^{-1}) and soil types. Deep percolation, or groundwater recharge, ranged from 10% to >50% of PPT through bare sandy soils, whereas the presence of vegetation greatly reduced or eliminated recharge. Uniquely, lysimeters recorded zero recharge through silt loam soils both with and without plants. A literature survey indicated that as the ratio of potential evapotranspiration (ET_o) to PPT reaches 5 or above, the ratio of actual evapotranspiration (ET) to PPT often approaches 1.0, as any water not transpired by plants readily evaporates (Zhang et al., 2001). In arid and semiarid rangelands, >95% of PPT is removed as ET (Wilcox et al., 2003), and globally, transpiration accounts for 80%–90% of terrestrial evapotranspiration (Jasechko et al., 2013).

Effects of landscape-scale variability in vegetation and ET on groundwater recharge and discharge have implications for waste site evaluations and management. Under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA), the US Department of Energy (DOE) is responsible for characterizing and remediating

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groundwater at several former uranium ore processing sites in the western United States (DOE, 1996) where contamination levels exceed regulatory standards in 40 CFR 192. Groundwater contamination at these sites is attributable primarily to the large volumes of processing liquids that seeped from tailings impoundments during the years that mills operated (e.g., DOE, 2002, 2014). An understanding of effects of vegetation dynamics on the soil water balance (recharge and discharge) of contaminated aquifers may improve groundwater flow analyses and introduce options to hydraulically control and naturally attenuate groundwater contaminant plumes (Carroll et al., 2009; Breshlof et al., 2013; Looney et al., 2014). Disturbances such as heavy grazing and land clearing can result in lower-than-optimal ET rates for enhancing contaminant attenuation in groundwater (Glenn et al., 2008; Breshlof et al., 2013).

We estimated changes in landscape-scale ET for the groundwater model domain (GMD) (DOE, 2016) of an UMTRCA site near Tuba City, Arizona, where uranium, nitrate, and sulfate have migrated in shallow groundwater away from the site (DOE, 1998). A MODFLOW groundwater flow model (Harbaugh, 2005) was developed to estimate the volume of groundwater discharged annually to Moenkop Wash (DOE, 2015a, 2015b), a stream downgradient from the contamination plume that has been used to irrigate crops. The purpose was to estimate how long it would take for contaminants to reach the wash and to evaluate remediation strategies for contaminants in the plume. Mean precipitation is only 163 mm yr^{-1}, and rangeland vegetation has been historically overgrazed (Middleton and Thomas, 1997; Sheridan, 1981). Surrounding rangeland likely converted from shrub steppe and grassland to stabilized coppice dunes (Hodgkinson, 1983) and moving dunes (Draut et al., 2012a,b; Bogle et al., 2015). Our goals were to (1) determine the ET/PPT ratio for vegetation types within the GMD, (2) interpret the role of vegetation in determining the ratio, and (3) identify areas where improving vegetation health may enhance hydraulic control of groundwater movement. Our estimates of site ET were used as input to the groundwater model.

Many water balance studies reported for desert areas have been based on point measurements over relatively short time periods, using lysimeters (e.g., Gee et al., 1994) or soil sampling methods (e.g., Sandvig and Phillips, 2006), to infer groundwater flows over larger areas and longer time spans. ET is often the largest component of the water budget after PPT, but spatial and temporal heterogeneity in terrestrial vegetation creates high variability in ET (Frank and Inouye, 1994; Stephenson, 1998). Furthermore, plants might not use the same pool of water for transpiration that supports recharge (Evaristo et al., 2015), hence an independent estimate of ET is needed to complete the water budget. We used satellite imagery and meteorological data, as applied at a similar site near Monument Valley, Arizona (Glenn et al., 2008; Breshlof et al., 2013), to characterize the spatial and temporal variability of ET from 2000 through 2012 within a 3513 ha area at the Tuba City UMTRCA site.

2. Materials and methods

2.1. Study site relevant site history

The Tuba City climate is arid with mean winter low temperatures of −6 °C and summer highs of 34 °C (Western Regional Climate Center, 2012). Potential ET (ET_o) is about 1500 mm yr^{-1}, nine times mean PPT. The 3531 ha GMD included several gently sloping terraces separated by sandstone escarpments, at the southern edge of the Kaibito Plateau, descending from 1630 m above sea level, about 6 km north of U.S. Highway 160, to Moenkopi Wash at 1425 m above sea level.

The uranium ore processing mill operated at the site from 1956 through 1966 (DOE, 1998). About 725,000 tonnes of ore were processed first by acid leaching and then by alkaline leaching. Tailings were conveyed as a slurry into unlined piles covering about 10 ha, and some process water was diverted to three adjacent, unlined retention ponds covering another 10 ha. Contaminants in the piles and ponds included sulfate and nitrate derived from the leaching solutions, and uranium and other heavy metals derived from the ore. Tailings, ponds, and soil contaminated from windblown tailings were stabilized and covered in 1988. The engineered cover relies on a 100 cm thick compacted sandy clay layer to limit radon diffusion and rainwater percolation (DOE, 1989), and rock riprap to control erosion (NRC, 2015). Groundwater remediation began in 2002 (DOE, 2002) and now consists of 37 recovery wells extracting about 0.3 m^3 min^{-1} encompassing an area of about 40 ha (DOE, 2015a, 2015b). Contaminated water is treated by distillation and returned to the aquifer through an infiltration trench, with brine piped to an evaporation pond (DOE, 2015a, 2015b). After over 10 years of operation, the system extracted approximately a third of the estimated plume pore volume, but with no evident reduction in groundwater contaminant concentrations (DOE, 2015a, 2015b). Therefore, a detailed groundwater investigation with flow modeling was undertaken in 2014 with the goal of developing alternative remediation strategies (DOE, 2014, 2015a, 2015b).

2.2. Groundwater flow model

The Department of Energy (DOE) has developed conceptual and numerical models to understand groundwater flow at the Tuba City, Arizona, Disposal Site (DOE, 2014, 2015a, 2015b). Modeling objectives were to (1) simulate groundwater travel paths from the former mill to the primary discharge boundary approximately 2500 m downgradient of the mill site at Moenkopi Wash, (2) estimate groundwater travel times from the site to the Wash, and (3) evaluate capture of contaminated groundwater under multiple remediation scenarios.

To meet these objectives, the modeling process first involved extensive review and evaluation of site characterization data to form a conceptual model of the physical factors that describe the occurrence, movement, and quantity of water within the model domain (DOE, 1998, 2002, 2014, 2015a, 2015b, 2016). The conceptual model encompasses the local watershed within which all groundwater originates from precipitation. Groundwater discharge occurs as ET within the model domain and by aquifer discharge to surface flow in Moenkopi Wash. Overland flow was not considered important due to the lack of surface features indicating surface runoff. Contamination derived from mill operations (nitrate, sulfate, and uranium) extends downgradient approximately 450 m and is generally limited to the upper 30 m of the aquifer. Boundaries of the groundwater model domain (GMD) included an upgradient limit that was beyond the influence of site remedition activities, a downgradient limit that encompassed the aquifer discharge boundary along Moenkopi Wash, and a lateral extent wide enough to ensure that flow conditions are not influenced by site activities (Fig. 1). The GMD encompassed 3513 ha.

Numerical implementation of the conceptual model used MODFLOW (Harbaugh, 2005) to simulate groundwater flow in the porous Navajo Sandstone aquifer, and with the PEST program (Doherty, 2004) to calibrate the model (DOE, 2015a, 2015b). The model domain was centered on the mill tailings disposal cell. Model calibration was achieved by automated methods to match steady-state hydraulic heads measured during an extended period before active groundwater remediation began, and to transient hydraulic heads during a following period of active remediation. ET zones and estimates from this study were used to specify recharge and