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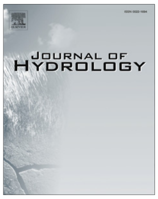

Estimates of net infiltration in arid basins and potential impacts on recharge and solute flux due to land use and vegetation change

Wendy Marie Robertson [a,*], John M. Sharp Jr. [b]

[a] Central Michigan University, Department of Earth and Atmospheric Sciences, Brooks Hall 314, Mt. Pleasant, MI 48858, United States
[b] The University of Texas at Austin, Department of Geological Sciences, 2275 Speedway Stop C9000, Austin, TX 78712-1722, United States

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SUMMARY

Human impacts on land use and vegetation in arid basins have, in some regions, altered infiltration, recharge, and groundwater chemistry. However, some modeling approaches currently used do not account for these effects. In the Trans-Pecos region of Texas the presence of modern water, increasing groundwater NO_3^- concentrations, and vadose zone cores flushed of naturally accumulated solutes belie the notion that basin groundwater is unaffected by overlying land use and vegetation change. Recharge to the Trans-Pecos basins is spatially and temporally variable, and due to human impacts it has likely changed since pre-western settlement time (circa 1850s). By using the INFIL 3.0.1 model, a spatially distributed model of net infiltration, the volume and spatial distribution of net infiltration was examined for two basins, Wild Horse/Michigan Flats and Lobo/Ryan Flats, with model simulations designed to examine the effects of irrigated agriculture and human impacts on vegetation. Model results indicate that recharge to the basins is not limited to mountain-front zones and discrete features (i.e., alluvial channels), rather, irrigation return flow contributes an estimated 6.3×10^7 m^3 (408 mm) of net infiltration over 40 yrs and net infiltration on the basin floors could contribute between 7% and 11.5% of annual basin recharge. Model results also indicate that net infiltration may be higher under current vegetation regimes than in pre-western settlement conditions; the removal of thick dense grasslands in INFIL model simulations enhanced net infiltration by 48% or more. Results from distributed models (like INFIL) improve upon scientific understanding of the links between vegetation regime and hydrological processes; this is important for the sustainable management of arid basin aquifers in Texas and elsewhere.

1. Introduction

The sustained availability of clean, potable water in arid regions across the globe is an issue of pressing concern due to population expansion and increased demand for resources; the question of how to manage limited groundwater resources has arisen in the Trans-Pecos region of West Texas, USA, where groundwater is used for irrigated agriculture, animal husbandry, and domestic water supply. Groundwater is the sole source of water for drinking, industry, and agriculture (Beach et al., 2004, 2008; Scanlon et al., 2006; Mahlknecht et al., 2008). Past water crises have hit the region hard and best management practices have been a topic of discussion for over three decades; one major uncertainty is quantifying recharge to basin aquifers. The models for water budgets and recharge used have been based upon a common conceptual model for groundwater recharge in arid basin aquifers, wherein the basins receive minimal modern recharge, there is no diffuse recharge on basin floors, and no recharge occurs from anthropogenic sources (i.e., irrigation return flow) (Maxey, 1968; Adar and Neuman, 1988; Darling et al., 1998; Uliana and Sharp, 2001; Van Broekhoven, 2002; Walvoord et al., 2002; Beach et al., 2004, 2008; Flint et al., 2004; Wilson and Guan, 2004; Pool and Dickinson, 2006; Uliana et al., 2007). This conceptual model describes a system where basin floor surface processes (i.e., alteration of vegetation density due to grazing practices and effects of intensive irrigated agriculture) are disconnected from the underlying groundwater due to thick vadose zones and annual evapo-transpirative (ET) demand exceeding annual precipitation. These assumptions are helpful for management policy but in these basins there is evidence of widespread modern recharge (Robertson and Sharp, 2012). Increased NO_3^- in the groundwater over time and the presence of CFCs indicate widespread recharge in the basins more recently (<70 yrs) than had been documented or modeled

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* Corresponding author. Cell: +1 512 350 6331.
E-mail address: rober2w@cmich.edu (W.M. Robertson).

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in previous studies, where the majority of recharge was assumed to have occurred during the last glacial maximum (10,000–20,000 yrs ago) based on age dating (^{14}C, ^{3}H) of groundwater (e.g., Darling et al., 1998; Uliana et al., 2007) and model simulations (e.g., Scanlon et al., 2001, 2006; Beach et al., 2004, 2008). Changes to the natural vegetation regime after western settlement including an increase in bare ground cover (Buffington and Herbel, 1965; Grover and Musick, 1990) have altered ET demand, surface runoff, and infiltration; irrigated agriculture (circa 1950s to present) has introduced additional water (through irrigation return flow) and labile N (through the application of synthetic and manure based fertilizers). These impacts to the physical properties of the surface of the basin floor are relevant for both groundwater quantity (amount of recharge) and groundwater quality (mobilization of solutes from the vadose zone). It is important to develop an approach to estimating recharge that can account for spatial variability in watershed properties and can reflect anthropogenic impacts such as changes to vegetation regime and intensive irrigation.

1.1. Site description

The basins of Wild Horse/Michigan Flats and Lobo/Ryan Flats are part of the Trans-Pecos basin aquifer system located in far west Texas (Fig. 1) (Sharp, 2001). Resulting from the Late Cretaceous Laramide Orogeny and subsequent Tertiary rifting, these basins are the eastern-most expression of the Basin and Range province (Barnes, 1979, 1983). The climate of the Trans-Pecos region is arid to semi-arid, with average annual precipitation ranging between 220 and 360 mm on the basin floors and between 500 and 750 mm in the adjacent mountainous areas (Beach et al., 2004, 2008). Some snowfall does occur in the region, particularly at higher elevations during the winter months, but the majority of the precipitation results from convective storm events that occur between June and October. The Trans-Pecos basin aquifer system consists of a series of unconfined basin aquifers underlain by Permian and Cretaceous aged bedrock (Beach et al., 2004, 2008). There is strong evidence for hydrologic connectivity between the basins (Sharp, 1989, 2001); regional flow of basin groundwater is from south to north in Lobo/Ryan Flats, entering Wild Horse/Michigan Flats through the southwest limb before turning east and entering the Apache Mountains (karstified limestone) (Sharp, 1989).

The unsaturated zone within the basins is typically thick (depths to water range from 10 to 225 m (Beach et al., 2004)). The soils within the basin are predominantly loams, sandy clay loams, clay alluvium, loamy alluvium, and sandy loams; all are classified as moderately well-drained to well-drained (see Appendix Table 2 for soil descriptions) (Soil Survey Staff, 2012). Soil horizons are thin (typically less than 1.5 m (Soil Survey Staff, 2012)) and are underlain by unconsolidated basin fill consisting of alluvial and wind-blown deposits (Barnes, 1979, 1983) with some volcaniclastic sediments present at depth in southern section of Ryan Flats (Beach et al., 2004). Thickness of unconsolidated basin sediments ranges from a few meters near the mountain front zone to several hundred meters thick in the middle of the basins (Barnes, 1979, 1983).

Within the Trans-Pecos basins, there is evidence for long-term (10,000–20,000 yr) accumulation of solute (including NO_3^- and Cl^-) in the vadose zone beneath the roots of natural vegetation (Scanlon, 1991; Scanlon et al., 2003; Walvoord et al., 2003). This accumulation occurred as a result of a drying climate in the Holocene and high ET demand by native vegetation (Walvoord et al., 2003). The build-up is likely spatially variable and, in some areas such as beneath irrigated fields and in ephemeral channels, vulnerable to flushing (Scanlon, 1991; Robertson et al., 2012, in preparation; Robertson, 2014).

The current vegetation regime at low elevations is mixed scrubland/grassland with blue stem grass, grama grass, agave lechuguilla, and creosote as the major vegetation types; at higher elevations, juniper is dominant. Juniper woodlands have the thickest vegetation density (~35%); vegetation on the basin floor is typically much thinner (~20–25% for scrubland and 10–15% for grassland), with bare soil and rock as the dominant cover (McMahon et al., 1984; Schmidt, 1995; Beach et al., 2008). Prior to western settlement (pre 1850s), the basins were covered in thick, dense grasslands (Humphrey, 1958) with sparse shrubs and succulents. Extensive grazing in the Trans-Pecos occurred in the 1880s (sheep and cattle) and continued through the 1940s, resulting in a shift from grassland/savannah to scrubland, a marked decrease to the rangeland productivity, an increase in bare ground cover, and an increase in woody vegetation species on the basin floors (Humphrey, 1958; Johnston, 1963); the effects of over-grazing combined with fire suppression practices and climatic shifts in the desert Southwest have resulted in regional loss of grasslands and woody vegetation encroachment on the basin floors (e.g., Archer, 1994; Van Auken, 2000).

Between the early 1950s and 2010 the region experienced another series of major land use changes. The production of inexpensive synthetic fertilizers after World War II caused a boom in development of land for intensive irrigated agriculture. Yield from the basin aquifer system ranged from $2.5 \times 10^7 - 4.2 \times 10^7$ m^3/yr in the 1950s and 1960s; extraction peaked in the 1970s to early 1980s at $6.2 \times 10^7 - 6.8 \times 10^7$ m^3/yr (Beach et al., 2004). During peak production, approximately 20% of the land was used for irrigated agriculture; pecans, cotton, and alfalfa were the primary crops. Toward the late 1970s through the early 1980s irrigated agriculture had caused a drop of up to 25 m in the basin water table levels. It became economically unviable to produce irrigation water from some wells and many farmers went bankrupt, sold their land, or switched to raising cattle. In 2010, only 5–7% of the land was being used for irrigated agriculture; the remainder was used for grazing or left fallow, allowing native and invasive species to re-colonize. From peak water demands, current extraction has decreased; an estimated 3.8×10^7 m^3/yr of water is withdrawn from the basins each year, down to the range of extraction rates of the early 1960s (Beach et al., 2004). In most of the measured wells (8 of 12 monitored wells), water table levels have not yet fully recovered to pre-irrigation withdrawal levels; they remain 3–19 m lower than their measured level in 1950 (Beach et al., 2004).

1.2. Previous studies

Several estimates of recharge have been calculated for Wild Horse/Michigan Flats and Lobo/Ryan Flats (Gates, 1980; Nielson and Sharp, 1985; Mayer, 1995; Mayer and Sharp, 1998; Finch and Armour, 2001; Beach et al., 2004). With the exception of the 1% rule (i.e., 1% of precipitation in the catchment results in recharge (Gates, 1980)), which does not use any watershed parameter beyond precipitation to estimate recharge, the studies assumed that recharge to the basin aquifers occurs as the result of mountain front and mountain block recharge. These models also assume that on the basin floors, diffuse recharge does not occur because the average annual ET demand is much greater than average annual precipitation, and anthropogenic impacts on the basin floor surface (i.e., irrigated agriculture and alteration of the vegetation regime) do not affect infiltration or recharge. It is common in studies of arid (and some semi-arid) systems to assume that when annual (or monthly) ET demand exceeds precipitation, negligible recharge occurs (e.g., Maxey, 1968; Adar and Neuman, 1988; Flint et al., 2004; Seyfried et al., 2005). Recharge in the previous models, when spatially distributed, was limited on the basin floors