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Impact of agroecosystems on groundwater resources in the Central High Plains, USA

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A B S T R A C T

Agroecosystems impact water resources by consuming most fresh water through irrigation and by changing water partitioning at the land surface. The study assesses impacts of agroecosystems on groundwater resources in the Texas Central High Plains (37,000 km^2 area) by evaluating temporal variations in groundwater storage and quality. Percolation/recharge rates were estimated using groundwater Cl data and using unsaturated zone matric potential and water-extractable chloride and nitrate from 33 boreholes beneath different agroecosystems. Total groundwater storage decreased by 57 km^3 since the 1950s when irrigation began and individual well hydrographs had declines $\leq$1.3 m/yr. The renewable portion of groundwater is controlled by percolation/recharge, which is related to soil texture and land use. In fine–medium (f–m) grained soils, there is no recharge beneath natural ecosystems or rain-fed agroecosystems; however, recharge is focused beneath playas and drainages. In medium–coarse (m–c) grained soils, percolation/recharge is low (median 4.8 mm/yr) beneath natural ecosystems and is moderate (median 27 mm/yr) beneath rain-fed agroecosystems. Although irrigation increased percolation under all soil types (median 37 mm/yr), irrigation return flow has not recharged the aquifer in most areas because of deep water tables. Groundwater depletion (21 km^3 over 52 yr) is 10 times greater than recharge (11 mm/yr; 2.1 km^3) where water table declines are greatest ($\geq$30 m). Therefore, current irrigation practices are not sustainable and constitute mining of the aquifer, which is being managed as a nonrenewable resource.

1. Introduction

1.1. How do agroecosystems impact groundwater quantity?

Irrigated agroecosystems affect water demand by consuming ~90% of global fresh-water resources during the past century (Shiklomanov, 2000). Overabstraction of groundwater for irrigation has resulted in large groundwater level declines, particularly in the SW US, NW and W India, and the North China Plain (Siebert et al., 2005). By changing partitioning of water at the land surface among evapotranspiration (ET), runoff, and recharge, agroecosystems also alter the distribution of green water (soil moisture from precipitation) and blue water (surface water and groundwater). In contrast to irrigated agroecosystems, which deplete groundwater resources, conversion of natural ecosystems to rain-fed agroecosystems increases groundwater resources by enhancing percolation/recharge by up to two orders of magnitude in semiarid regions, such as southeast Australia (Allison et al., 1990) and SW Niger (West Africa) (Favreau et al., 2009). Percolation refers to deep drainage below the root zone that has not reached the water table to recharge the aquifer.

1.2. How do agroecosystems impact groundwater quality?

Vegetation plays a large role in controlling water quality because the process of ET is similar to desalinization in that it excludes salts, resulting in a buildup of salts in soils from bulk precipitation (precipitation + dry fallout), unless the salts are flushed through the soil profile by percolation/recharge. In many semiarid regions, large reservoirs of salts, including Cl, ClO_4, SO_4, F, and sometimes NO_3, have accumulated from bulk precipitation as a result of long-term drying under natural vegetation over millennia (Scanlon et al., 2009). Agroecosystems increase vulnerability of groundwater to contamination by increasing percolation/recharge rates mobilizing these salts and reducing time lags to reach the aquifer (McMahon et al., 2006). This mobilization of natural salt

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and nutrient inventories has been documented in the Murray Darling Basin in Australia and the Amargosa Desert and High Plains in the US (Stonestrom et al., 2003; McMahon et al., 2006; Scanlon et al., 2009). In addition to mobilizing these salts and nutrients that had accumulated over millennia in the soil profile through increased percolation/recharge, irrigation also adds salts to the system because irrigation water has much higher salt concentrations than precipitation. The impact of irrigation on water quality through salt loading depends strongly on the quality of the irrigation water. Irrigation can result in soil salinization and/or aquifer salinization over time.

1.3. What effect does soil texture have on percolation/recharge rates?

Field studies and a simple water balance model showed that recharge decreases by about an order of magnitude (30–3 mm/yr) with increasing clay content from 0 to 20% under cropland in the Murray Basin (Australia) for mean annual precipitation ranging from 310 to 380 mm (Kennett-Smith et al., 1994). A review of recharge studies in Australia showed that recharge rates within land use categories (annual vegetation and trees) varied across soil types (Petheram et al., 2000). Large variations in recharge in clayey soils were attributed to preferential flow. Modeling analyses of recharge in Texas, US, showed maximum recharge rates in sandy soils and large reductions in recharge with soil textural variability (Keese et al., 2005). More recent studies in the Nebraska Sand Hills and adjacent silt loam soils noted reductions in recharge and corresponding large increases in ET from sand to silt loam (Wang et al., 2009). These studies indicate that soil texture can play an important role in controlling recharge.

1.4. What techniques can be used to assess impacts of agroecosystems on groundwater resources?

Groundwater level hydrographs can be used to quantify impacts of agroecosystems on groundwater depletion through irrigation pumpage and groundwater increase through recharge. Water table fluctuations have been used to quantify changes in recharge in response to land use changes in many regions (Sophocleous, 1991; Favreau et al., 2009). Soil profiles in the unsaturated zone provide records of long-term impacts of land use on subsurface water quantity and quality and link surface processes with aquifers. The Cl mass balance (CMB) approach or the Cl front displacement (CFD) approach has been used to quantify changes in percolation/recharge in different land use settings (Walker et al., 1991; Stonestrom et al., 2003; Scanlon et al., 2007). The CMB approach balances Cl input from bulk precipitation with Cl output in percolation/recharge and is used to estimate percolation/recharge. The CFD approach uses the Cl bulges that accumulated under natural ecosystems over millennia as a marker to track percolation. The Cl front marks the upper part of the Cl bulge. The presence of bomb pulse tritium has been used to distinguish prebomb (before 1950s) and postbomb tritium water and track unsaturated zone pore water movement related to irrigation return flow (McMahon et al., 2006). Modeling is also a useful tool to evaluate recharge related to agroecosystems and assess different controls on percolation/recharge, such as climate, soils, and crop rooting depths (Kennett-Smith et al., 1994; Keese et al., 2005).

The US High Plains (450,000 km^2 area), one of the largest agricultural areas in the US, provides an excellent study area to examine impacts of agroecosystems on water resources. This region constitutes one of the most intensively irrigated areas in the US, representing 30% of the nation's groundwater used for irrigation (Maupin and Barber, 2005). Groundwater depletion for irrigation from the High Plains or Ogallala aquifer is greatest in the Central High Plains (CHP) and in the north part of the Southern High Plains (SHP) with maximum groundwater level declines of ≥45 m since irrigation began in the 1950s (McGuire, 2009). Because of the importance of the High Plains for agricultural production and overabstraction of water from the High Plains aquifer, numerous studies have been conducted in this region. Regional recharge was estimated to be 11 mm/yr on the basis of the CMB approach applied to groundwater Cl data mostly in the north part of the SHP (Wood and Sanford, 1995). Recharge is attributed primarily to focused flow beneath ephemeral lakes or playas with rates of 60–120 mm/yr on the basis of unsaturated zone Cl and tritium data (Wood and Sanford, 1995; Scanlon and Goldsmith, 1997). Although there are ∼53,000 playas in the High Plains, they only occupy ∼0.4% of the land surface. Lack of percolation/recharge adjacent to playas under natural ecosystems in f–m g soils in the CHP is evidenced by bulge-shaped Cl profiles that have been accumulating Cl since Pleistocene times ∼10,000 yr ago; however, these studies are restricted to <1% of the area of the Texas CHP (Scanlon and Goldsmith, 1997). Conversion of natural ecosystems to rain-fed agroecosystems increased percolation/recharge rates in sandy soils in the SHP to a median value of 24 mm/yr (4.8–92 mm/yr) based on 19 unsaturated zone Cl profiles and groundwater level rises in the southeast part of the SHP (Scanlon et al., 2007). Irrigated agroecosystems generally resulted in moderate percolation/recharge rates in the SHP (18–97 mm/yr) similar to the range (4.8–92 mm/yr) under rain-fed agroecosystems (McMahon et al., 2006; Scanlon et al., in press). Limited profiling (two profiles) in irrigated areas in the CHP in Kansas resulted in recharge rates of 39 and 54 mm/yr (McMahon et al., 2006). At many of these sites, irrigation return flow has not reached the water table. However, previous groundwater models of the region simulated increased recharge under irrigated areas ranging from 24% of irrigation application in the 1940s and 1950s to 2% of irrigation application in the 1990s, assuming irrigation efficiency increased with transition from predominantly flood irrigation to sprinkler systems over time (Luckey and Becker, 1999; Dutton et al., 2001).

Although there have been numerous studies conducted in the High Plains, there is very little information on groundwater recharge throughout much of the CHP in Texas (Fig. 1). There is considerable interest in the renewability of groundwater resources in this region to support widespread irrigation practices. In addition, Mesa Water has purchased water rights for ∼600 km^2, and the Canadian River Municipal Water Authority (CRMWA) has rights for ∼1000 km^2 to supply the City of Amarillo. Mesa Water had plans to transport water from this region to large municipalities in Texas. The Canadian River is also a gaining river, and there is concern that overabstraction of groundwater would reduce baseflow discharge to the river and change it from a gaining to a losing river. There is also interest in enhancing recharge in the region to increase groundwater supply.

The objective of this study was to evaluate impacts of agroecosystems on water resources in the CHP, including effects on water quantity and quality and assessing water sustainability issues. Impacts of irrigation on groundwater quantity were evaluated using water level data from the 1950s to present and examining individual well hydrographs. Effects of agroecosystems on groundwater quality were assessed using groundwater total dissolved solids (TDS), Cl, and NO_3 data. Estimating recharge is also critical to determin the renewability of groundwater resources. Previous studies were limited to recharge estimation under natural ecosystems, including 9 playa and 13 adjacent interplaya sites, mostly in fine-grained (clay loam) soils (Scanlon and Goldsmith, 1997) and under rain-fed and irrigated agroecosystems at one site in clay loam soils (Fig. 1, Scanlon et al., 2008a,b, in press.). However, these studies covered <1% of the current study area. The current study expands on the previous work by including unsaturated zone matric potential and water extractable Cl and NO_3 under natural (14 profiles)