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Long term (1960–2010) trends in groundwater contamination and salinization in the Ogallala aquifer in Texas

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SUMMARY

Although numerous studies have expounded on depletion of the Ogallala aquifer, very few researchers have studied groundwater quality therein which relates to the 'usability' of available groundwater resources. The objective of this study was to elucidate regional trends in groundwater quality and salinization in the Ogallala aquifer, underlying 49 counties and two Groundwater Management Areas (GMA 1 and 2) in Texas, on a decadal scale between 1960 and 2010. Contrasting groundwater quality distinguished GMA 1 (northern Ogallala) from GMA 2 (southern Ogallala), and shallow wells (depth <50 m) from deep (>50 m) wells. The GMA 2 was characterized by pronounced groundwater nitrate (NO_3^-) contamination accompanied by elevated levels of sulfate (SO_4^{2-}), chloride (Cl^-) and salinity (TDS), marked by an abundance of mixed cation SO_4–Cl and Na–Cl facies. In contrast, Ca–Mg–HCO_3 and Ca–HCO_3 facies prevailed in GMA 1 with substantially lower salinization, SO_4^{2-}, Cl^- and NO_3 contamination. In shallow wells, more abundant in GMA 2, about 80% and 32% of observations exceeded the United State Environmental Protection Agency's Secondary Maximum Contaminant Level (SMCL, 500 mg L^{-1}) for total dissolved solids (TDS) and MCL (44 mg L^{-1}) for NO_3, respectively in the 2000s (2000–2010), with progressive increases in both parameters since the 1960s (1960–1969). Majority (>60%) of the shallow observations since the 1980s (1980–1989) have exceeded the natural background of 11 mg L^{-1} of NO_3^- indicating anthropogenic sources, The NO_3^- contamination was more apparent in domestic wells indicating substantial human health risk. Groundwater salinization in this aquifer resulted from a combination of natural (e.g. upwelling of highly mineralized groundwater from the underlying formations, seepage from playas and saline plumes, and evaporative enrichment) and anthropogenic processes (irrigated agriculture and hydrocarbon exploration activities). Natural processes were largely aggravated by anthropogenic practices such as lowering of hydraulic heads in the Ogallala aquifer due to prolonged irrigational pumping, inducing cross-formational flow from underlying highly mineralized older formations (Edwards Trinity (High Plains)) which led to groundwater mixing between the formations and rise in salinity levels in the Ogallala aquifer over time.

1. Introduction

Rapidly diminishing fresh groundwater reserves has prompted numerous investigations in different parts of the world including the United States (US) to identify spatial patterns in groundwater quality and evaluate its potential consequences on environmental parameters and human health. The Ogallala aquifer, distributed across Wyoming, South Dakota, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas states in the US, is ranked first in the nation for total groundwater withdrawals, meeting about 23% of the nation's total groundwater needs and 30% of the nation's irrigation water needs (Rosenberg et al., 1999; Maupin and Barber, 2005). However, since the 1980s, there is an increasing concern over this aquifer depletion rate (USGS, 2001; Hernandez et al., 2010; Scanlon et al., 2010), which exceeds natural recharge (Rosenberg et al., 1999; Coliazzi et al., 2009). Estimates have revealed that about 30–50% of pre-development groundwater reserves from the Ogallala aquifer have already been mined, indicating an urgent need for strategic implementation of water

Abbreviations: CHP, Central High Plains; HP, High Plains; MCL, Maximum Contamination Level; SMCL, Secondary Maximum Contaminant Level; TWDB, Texas Water Development Board; SHP, Southern High Plains; TDS, total dissolved solids; USEPA, United States Environmental Protection Agency.

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conservation protocols to promote sustainable development (Nativ and Smith, 1987a; Segerra and Feng, 1994).

Besides future water availability, concerns about quality of groundwater resources in the Ogallala aquifer have been raised by several researchers. The United States Geological Survey (USGS) has conducted numerous water quality investigation studies across the High Plains (HP) aquifer spanning from Nebraska to New Mexico (Table 1) (Dennehy, 2000; McMahon, 2000; Litke, 2001; Becker et al., 2002; Gurdak and Qi, 2006; Stanton and Qi, 2006; McMahon et al., 2007, 2004; Gurdak et al., 2009). Most notable among these studies is that of Litke (2001). As a part of the National Water-Quality Assessment Program (NAWQA), Litke (2001) evaluated about 733 water quality parameters collected by 43 agencies from 29,041 sites across the HP aquifer between 1930 and 1998 and reported (1) substantial rises in nitrate and salinity over time, which were largely attributed to anthropogenic practices, (2) adverse impacts of sulfate and chloride on groundwater salinization processes, and (3) hydrochemical variability across the HP aquifer due to regional differences in physiographic, climatic, geologic, and human development patterns. However, Litke (2001) study had mainly focused on the entire geographic extent of the High Plains aquifer. Although the presence of poor water quality in the Texas part of the aquifer, commonly denoted as the Southern High Plains (SHP) aquifer in the USGS literature, was hinted upon, little information for this region was presented about detailed depth-stratified temporal trends and spatial variability about (1) individual water quality parameters such as sulfate (SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-), and total dissolved solids (TDS) with respect to different water use classes and (2) interrelationships between various water quality parameters. Implications of Litke's study, in relation to the findings of the present study, have been discussed in greater details in Section 3.1 (Spatial Variability of Groundwater Quality). In addition, very few studies are available in the relevant hydrogeologic literature of the HP aquifer which attempt to elucidate regional differences in major groundwater geochemical types (i.e. hydrochemical facies) between the northern and southern parts of the SHP.

Texas is the second largest consumer of water resources of the Ogallala aquifer after Nebraska (Allen et al., 2005; Maupin and Barber, 2005; Coliazzi et al., 2009), mainly to support irrigated agricultural practices, which consume over 90% of groundwater withdrawn from the aquifer (Coliazzi et al., 2009; TWDB, 2012). Projected groundwater depletion of the Ogallala aquifer in Texas is expected to reduce groundwater supplies of the state by about 30% by 2060 (TWDB, 2012). There are increasing concerns over degradation of groundwater quality in the Ogallala aquifer in Texas. Although the USGS has conducted numerous studies in different parts of the High Plains aquifer (Stanton and Fahlquist (2006): Texas and Nebraska; Fahlquist (2003): Texas and New Mexico; McMahon et al. (2004): Hale and Castro Counties in Texas) (Table 1), detailed long-term hydrochemical investigations focusing on the SHP region are relatively scarce. In addition, these studies were constrained to either smaller geographic area within Texas (e.g. Fahlquist (2003) study focused entirely on the southern parts of the SHP without providing any information about the northern parts of the SHP) or covered larger geographic area, but "averaged" out the finer heterogeneities in water quality within Texas (e.g. Stanton and Fahlquist, 2006). These studies also lacked long-term comparative assessment of water quality and the trends therein.

With surging dependence on the groundwater resources of the Ogallala aquifer in Texas, following questions arise: (i) Is there a distinguishable spatio-temporal pattern in water quality across the Ogallala aquifer? (ii) Is there any discernible relationships between distribution of NO_3^- and other species? (iii) What type of hydrochemical assemblages (major chemical groundwater types) lead to groundwater salinization, (iv) Are there regional differences (spatial pattern) between the hydrochemical assemblages? (v) Can major factors affecting groundwater quality be broadly outlined at regional scale? These questions become more pertinent as majority of past studies lack either the spatial (both horizontal and vertical) or a long-term aspects (e.g. changes in water quality since the inception of irrigated agricultural practices in the 1950s) of hydrochemistry. Moreover, most of these studies have focused on individual parameters such as NO_3^- (Hudak, 2000a,b; Scanlon et al., 2008; Bronson et al., 2009; Enwright and Hudak, 2009; Chaudhuri et al., 2012) SO_4^{2-} (Malapati et al., 2011), sodium (Na^+), water hardness (Hudak, 2001), and Cl^- (Scanlon et al., 2010). Thus a comprehensive effort to summarize multiple water quality parameters to offer a holistic appraisal of vertical

Table 1
Groundwater quality investigation in the High Plains aquifer as conducted by the USGS ("*n*" represents sample size).

USGS Study	Study Area	Time Period	Salient Findings
Stanton and Fahlquist (2006)	Texas and Nebraska ($n = 59$)	2003–2004	• Median dissolved solids contents (814 mg L^{-1}) exceeded the SMCL in Texas • Dissolved solids were positively correlated with nitrate and chloride levels
Fahlquist (2003)	Texas and New Mexico ($n = 48$)	2001	• >60%, 14%, 22%, and 12% of wells exceeded the dissolved solids, chloride, sulfate, and nitrate environmental thresholds, respectively • Anthropogenic influences on nitrate contents • Poor groundwater quality in Texas
McMahon et al. (2004)	Texas (Castro and Hale Counties) ($n = 8$)	2002	• High levels of sodium, chloride, sulfate, and bicarbonate • Recent groundwater recharge at shallow depths • Groundwater chemistry is largely dominated by anthropogenic processes (agriculture) • Potential mixing with underlying Cretaceous formations due to irrigational pumping
McMahon et al. (2007)	Entire aquifer	1999–2004	• High levels of median chloride (165 mg L^{-1}), sulfate (160 mg L^{-1}) and dissolved solids (814 mg L^{-1}) in Texas • High variability in groundwater composition in Texas as marked by presence of mixed cation hydrochemical facies
Gurdak et al. (2009)	Entire aquifer	1999–2004	• Conversion of rangeland to irrigated land has affected groundwater quality • Solute transport follows slow (fine-grained soils) and fast paths (beneath topographic depressions such as playa lakes) • Groundwater quality substantially differs between shallow and deep groundwater • Mixing between different formations adversely affected groundwater quality
Gurdak and Qi (2006)	Entire aquifer ($n = 336$)	Post-1950 (recently recharged water)	• High probability of nitrate contamination in the Texas part of the aquifer • High nitrate levels more frequent at shallow depths with less clay contents • Adverse impacts of agricultural activities (irrigation) on nitrate contamination