Geologic and hydrologic settings for development of freshwater lenses in arid lands

Adam Milewski,1* Mohamed Sultan,2 Ahmad Al-Dousari3 and Eugene Yan4

1 Department of Geology, University of Georgia, 210 Field Street, 306 Geography-Geology Building, Athens, GA 30602, USA
2 Department of Geosciences, Western Michigan University, 1903 W. Michigan Avenue, 1187 Rood Hall, Kalamazoo, MI 49008, USA
3 Department of Geography, Kuwait University, Kuwait, Kuwait
4 Argonne National Laboratory, Argonne, IL, USA

Abstract:

Satellite observations were used to test the validity of previously identified favourable conditions for the formation of freshwater lenses, identify additional potential occurrences, and model modern potential recharge in the Raudhatain Watershed (3696) in northern Kuwait. Favourable conditions include infrequent yet intensive precipitation events, drainage depressions to collect the limited runoff, and presence of conditions (e.g. high infiltration capacity) that promote groundwater recharge and preservation (e.g. underlying saline aquifer) of infiltrating groundwater as freshwater lenses floating over saline aquifer water due to differences in density. Specifically, the following field and satellite-based observations were noted for the Raudhatain Watershed: (1) Over ~30 precipitation events were identified from the Tropical Rainfall Measuring Mission precipitation data (1998–2009); (2) slope is gentle (2 m/km), and the surface is largely (80%) covered by alluvial deposits with high infiltration capacities (up to 9 m/day); (3) no flows and long-term ponding were reported at the watershed outlet or detected from Landsat thematic mapper images; (4) infiltration is high based on increases in soil moisture content (from an advanced microwave scanning radiometer) and vegetation index following large precipitation events; and (5) freshwater lenses that overlie highly saline [total dissolved solids (TDS): >35 000] unconfined aquifers underlying the watershed are absent in the southern regions, where infiltrating fresh water mixes with the less saline groundwater (TDS: <10 000). Twenty potential locations (size: 1 to 75 km²) for freshwater lens development were identified in northern Kuwait, and continuous rainfall–runoff models (Soil Water and Assessment Tool) were applied to provide a first-order estimation of the average annual recharge in the watershed (127 × 10^6 m³) and freshwater lenses (8.17 × 10^6 m³). Results demonstrate the settings for enhanced opportunities for groundwater recharge, outline the amounts of and preservation conditions for the groundwater feeding the freshwater lenses, and highlight potential applications and locations of freshwater lenses in similar settings elsewhere in the Arabian Peninsula and beyond. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS SWAT; remote sensing; Kuwait; freshwater lens; arid; recharge

Received 5 October 2012; Accepted 28 February 2013

INTRODUCTION

A common perception among hydrogeologists working on modelling the partitioning of precipitation in arid and semi-arid lands is that modern recharge is minimal (Bazuhair and Wood, 1996; Dettinger, 1989; Flint et al., 2000). In many of these arid areas, precipitation is localized over mountainous areas, where orographic barriers are known to affect the vertical distribution of precipitation in ways that render precipitation more pronounced over the highlands compared to that in the lowlands (Herschy and Fairbridge, 1999). Because many of these mountainous areas are largely composed of impervious or low-porosity rocks (e.g. crystalline basement rocks, massive limestone), they are less likely to develop reservoir qualities. Exceptions include massive units subjected to intense brittle deformation associated with tectonic activities including transcurrent faulting (Sultan et al., 1990; Sultan et al., 2008a) and rifting environments that improve such rocks’ reservoir qualities in areas of localized intense deformation (Sultan et al., 2011). The general steep topographic gradient of these areas is yet another impediment for groundwater recharge, where runoff in the valley networks within these mountains is moving at fast rates that reduce, by as much as 80%, the opportunities for groundwater infiltration and recharge of the alluvial aquifers flooring these valleys (Meyboom, 1966; Delin et al., 2000; Scanlon et al., 2002). In such steep mountainous areas, a large portion of precipitation could be lost as runoff towards neighbouring water bodies (e.g. seas, lakes, rivers). Because evaporation rates are high in many of these arid lands (Al-Ruwaih et al., 1998; Kwarteng et al., 2000), significant
losses to evaporation occur before infiltrating rain reaches critical depths (1 to 3 m; Nativ et al., 1997) where evaporation is no longer effective. Naturally, the higher the infiltration rates in these areas, the less the losses to evaporation and the greater the recharge. In this manuscript, we show that for the investigated watershed in northern Kuwait, the geologic and hydrologic settings are quite different from those experienced in many of the arid and semi-arid areas worldwide. The short duration and the high intensity of rainfall coupled with the flat topography and high infiltration capacities of outcrops in northern Kuwait enhance infiltration, reduce losses to evaporation, and increase recharge to the underlying unconfined aquifers (Kwarteng et al., 2000). The presence of saline and hypersaline groundwater on local and/or regional scales that typically salinize infiltrating fresh water upon mixing with saline groundwater is, in this case, contributing to the preservation of the infiltrating fresh water; the latter forms freshwater lenses floating on top of the highly saline [TDS > 35,000] groundwater. The importance of these lenses is pronounced given they serve as Kuwait’s only source of natural fresh water.

Using the Raudhatain Watershed (3696 km²) in northern Kuwait as our test site and knowing the locations of some of the freshwater lenses in the watershed and the settings that facilitate the formation of these lenses, we developed satellite-based observations to test the validity of pre-identified favourable condition for lens formation and to identify additional potential occurrences in Kuwait and in surrounding countries that are not being utilized today. We also estimated the partitioning of precipitation into runoff, recharge, and initial losses over the test site applying a physically based, semi-distributed, Soil Water and Assessment Tool (SWAT) model taking advantage of spatially distributed remote sensing and geographic information system (GIS) data sets. Findings have implications for groundwater assessment and utilization in Kuwait and in similar areas elsewhere worldwide.

SITE DESCRIPTION

Across Kuwait, and more so in the Raudhatain Watershed, the topography is generally very flat, with a gentle slope of 2 m for every 1 km. The elevations are the highest in the southwest (300 m a.m.s.l.) and decrease to sea levels towards the northeast (Gulf area). Low hills and shallow depressions are superimposed on the topographic gradient. The most prominent of these low hills are the Jal Az-Zor escarpment (average elevation: 122 m a.m.s.l.) and the Ahmadi Ridge (137 m a.m.s.l.) (Al-Ruwaih et al., 1998) (Figure 1). Examples of depressions include the Wadi Al-Batin, a valley that constitutes the western margin of Kuwait. Many additional near-flat areas of smaller spatial areal extent mark the local depressions and are mapped in Figure 1. These areas are surrounded by topographically higher areas, only a few metres higher than the depressions. These depressions are apparently Aeolian in origin because they are concentrated along the ‘sand wind corridor’, a term that describes the dominant current wind propagation direction from the NW to the SE (Al-Murad et al., 2010; Kwarteng et al., 2000) (Figure 1).

Figure 1. Location map of Kuwait showing the topography of the area (red areas: high; blue areas: low) derived from the global 30-m ASTER data. Raudhatain Watershed is outlined in red, while other watersheds are shown as grey polygons. Depressions of interest are shown as black polygons. The Sand Wind Corridor, where the predominant wind pattern is NW to SE, is outlined in purple.
The average annual precipitation in Kuwait is ~115 mm/year but can reach as high as 240 mm/year (Alhumoud et al., 2010). The rainy season extends from November to April (Kwarteng et al., 2000), with the highest precipitation occurring over the SE and NE portions of Kuwait. Figure 2 shows the average (1998–2009) annual precipitation over Kuwait extracted from the Tropical Rainfall Measuring Mission’s (TRMM) 3-hourly precipitation data (3B42.v6).

The Kuwait landscape is covered by sedimentary rock units and unconsolidated sediments ranging in age from Middle Eocene to Recent. The Kuwait Group (Neogene–Quaternary) outcrops cover the overwhelming majority of the Kuwait landscape; the group is largely formed of unconsolidated sands and gravels and is subdivided into the Fars, Ghar, and Dibdibah Formations of Miocene and Pliocene ages. The latter formation is subdivided into an Upper and a Lower Dibdibah member. The overall infiltration rates in the Raudhatain Watershed are quite high because 70% of its area is covered by the Upper Dibdibah member (infiltration rate: 9 m/day) and the remaining 30% by the Lower Dibdibah member (infiltration rate: 5 m/day) and supports rapid infiltration of rainfall events (Grealish et al., 1998; Parsons, 1964). The Damam Formation, the oldest exposed rock unit in Kuwait, crops out in the central parts of Kuwait, but not within the Raudhatain Watershed. The Damam Formation and the Kuwait Group are the two most significant regional aquifers in Kuwait. The Kuwait Group aquifer [thickness: 150 m (SW) to 400 m (NE)] is underlain by the Damam Formation aquifer. The Kuwait Group is being recharged by infiltration from modern precipitation but is also receiving contributions by upward leakage from the underlying Damam Aquifer (Abusada, 1981). The latter suggestion is supported by the fact that the heads in the Damam Aquifer are generally higher by 3 to 20 m than those recorded for the Kuwait Aquifer. The Damam Formation is underlain by the evaporites of the Rus Formation, which separate it from the Umm Al-Radhuma Formation (Figures 3A and 3B). The two aquifers, Damam and Umm Al-Radhuma, are believed to be in hydraulic connectivity (Al-Ruwaih et al., 1998; Kwarteng et al., 2000; Fadlelmawla and Al-Otaibi, 2005).

The construction of continuous rainfall–runoff models is one of the methods that allow estimates to be made for the partitioning of precipitation into runoff, recharge, and evapotranspiration. The Raudhatain Watershed in northern Kuwait was selected as our test site for the following reasons: (1) The watershed is large, occupying 3764 km², which amounts to 22% of the total area of Kuwait, and thus, the watershed could potentially channel a large proportion of precipitation over Kuwait; (2) precipitation over the watershed is relatively large (average annual precipitation: 140 mm), as indicated from the analysis of the 3-hourly TRMM precipitation data for the period 1998–2009; (3) field measurements of infiltration rates, which are needed for modelling the partitioning (runoff, recharge, evapotranspiration) of precipitation, are available for the watershed; (4) the potential for recharge in this watershed is quite high as indicated by the surface rock compositions being largely formed of gravel, and sands with high transmissivities (295–3465 m²/day) and infiltration.

Figure 2. Average annual rainfall in Kuwait from 1998 to 2009 derived from TRMM data. The lowest annual precipitation (<100 mm) occurs in the SW, and the highest precipitation (>250 mm) falls in the E to NE. Also shown are the locations of rain gauges (purple circles).
rates (up to 9 m/day; Figure 3A) (Parsons, 1964; Kruseman and De Ridder, 1970; Grealish et al., 1998); (5) a large concentration of drainage depressions exists within this watershed; and (6) TDS values for the unconfined groundwater within the watershed are high (>35 000 ppm) allowing for the formation of freshwater lenses, as described in detail in the section on Identification of Freshwater Lenses.

**METHODOLOGY**

Our methodology is twofold. Firstly, we developed and tested the validity of criteria to predict the locations of known freshwater lenses and then applied these criteria to locate previously unidentified fresh lenses in Kuwait and surrounding countries. GIS technologies were adopted to extract and analyse spatial relationships from co-registered relevant data sets, including satellite imagery (TRMM, Landsat thematic mapper (TM)), geological (e.g. soil types), topographical (e.g. slopes, distribution of depressions), hydrogeologic (infiltration rates, groundwater level), and geochemical (e.g. TDS in groundwater) data sets. Following the identification and verification of potential freshwater lenses, the average annual recharge to each of the identified lenses was estimated using the SWAT model.
Construction of a GIS to Host and Analyse Relevant Data Sets

The initial step in our methodology involved the generation of a database for data integration, analysis, and visualization, and to be used as inputs for the hydrologic model. An ArcInfo GIS–based interface for data manipulation and representation was generated to hold the data sets and to make them available via a web-based interface. The database incorporates all relevant co-registered digital mosaics with a unified projection [Universal Transverse Mercator, Zone 38 and 39] covering the entire Kuwait landscape: (1) geologic (scale: 1 : 1000000) and land use (scale: 1 : 1000000) maps derived from the Climatic Atlas of Kuwait (El-Baz and Al-Sarawi, 2000); (2) infiltration rates for various soil units (Parsons, 1964; Kwarteng et al., 2000); (3) advanced microwave scanning radiometer (AMSR-E) (spatial resolution: 0.25° × 0.25°) to extract soil moisture content taking advantage of the large differences in dielectric constants of wet and dry soils; (4) false colour mosaic of Landsat TM bands 2 (blue), 4 (green), and 7 (red) (spatial resolution: 28.5) created using processed individual reflectance TM bands; (5) digital elevation models (DEMs; spatial resolution: 30 m) generated from raw Level 1A advanced space-borne thermal emission and reflection radiometer (ASTER) scenes; (6) stream networks and watershed boundaries extracted from ASTER-derived DEMs; (7) 3-hourly, annual (1998–2006), and average annual (1998–2006) precipitation data extracted from the 3-hourly TRMM (3B42.v6 product; spatial resolution: 0.25° × 0.25°) data; (8) advanced very high resolution radiometer (AVHRR) data (spatial resolution: 1.1 km) to verify precipitation events through cloud detection; (9) meteorological data of air temperature and wind speed obtained from an online source, namely, the Directorate General for Civil Aviation in Kuwait (http://www.met.gov.kw:90); (10) well data including one or more of the following parameters: well location, well name, well type, solute chemistry, TDS, and depth to water table; and (11) spatial variations in total salinity for the unconfined aquifer(s) (Fadlelmawla and Al-Otaibi, 2005). Many of the utilized data sets were downloaded from public domain sites: TRMM 3B42.v6 products from NASA’s Distributed Active Archive System (DAAC) at http://daac.gsfc.nasa.gov, AVHRR products from the NOAA CLASS website at http://class.noaa.gov (CLASS, 1978), and AMSR-E from NASA’s DAAC.

Identification of Freshwater Lenses

The formation of freshwater lenses floating atop saline groundwater is common in many arid parts of the world. For example, such settings were reported from depressions and stream channels in Oman (Macumber, 1995) as well as the eastern Province of Saudi Arabia (Alsharhan et al., 2001). The weight of the rainwater that percolates into the ground depresses the salt water beneath it forming a profile that has the appearance of a lens, the Ghyben–Herzberg lens. Known freshwater lenses in northern Kuwait (e.g. Al-Raudhatain depression) range within 12–35 m in thickness and reside 24–45 m below the surface (Fadlelmawla et al., 2008).

Utilizing GIS techniques and digital mosaics, we identified settings conducive for the formation of freshwater lenses using a series of steps. We first identified the distribution of watersheds, followed by the depressions and wadi networks within the identified watersheds from the ASTER global 30-m DEM using ArcGIS watershed delineation/sinks package (Figure 2; black polygons). Knowing the locations of a few of these freshwater lenses and examining spatial relationships in relevant co-registered data sets described above, we identified the criteria that favour their formation. Each data set was given an equal weight, and values of each data set were extracted in areas of known freshwater lenses to develop the optimal criteria. Known freshwater lenses were found in areas that receive high rainfall (>100 mm/year; Figure 2) that occur over short time periods, have high infiltration rates (>5 m/day; Figure 4), and are floored by unconfined highly saline (>35 000 mg/l; Figure 3A) aquifers. Using these criteria, potential locations of previously unidentified lenses were traced. Over 100 areas ranging in size from 1 to 75 km² were found in Kuwait, of which 40 are located within the Raudhatain Watershed (Figure 1). Locations of previously identified and potential unidentified freshwater lenses were traced using the criteria and data sets developed in Kuwait (Figure 5).

Construction and Calibration of Continuous Rainfall–Runoff Models

We adopted a catchment-based, continuous, hydrologic model (1998–2009) to quantify the spatial and temporal distribution of surface runoff and potential groundwater recharge. A rainfall–runoff model was constructed using SWAT, developed by the Blackland Research Center (Arnold et al., 1998; Arnold and Fohrer, 2005). The use of the ArcSWAT (SWAT, 2009) interface allowed the import of co-registered data sets from the generated ArcGIS data sets into the constructed model. Examples of imported model inputs include digital elevation, land use, soils, meteorological data sets (precipitation, air temperature, relative humidity, wind speed, solar radiation), soil parameters, model parameters, and calibration data sets. The adopted modelling approach involved the collection and pre-processing of relevant remote sensing data, identifying and verifying the validity of the identified precipitation events using several remote sensing techniques, and construction and calibration of a catchment-
Figure 4. An example of the systematic approach used for identifying and verifying rainfall and recharge events. (a) Daily rainfall image (21 December 2007) acquired from TRMM. (b) AVHRR image showing clouds (white areas) on 21 December 2007. (d) Soil moisture image extracted from AMSR-E before the rainfall event (19 December 2007) showing little soil moisture. (e) Soil moisture image extracted from AMSR-E after the rainfall event (21 December 2007) showing increased soil moisture. (c) Landsat TM image (27 December 2007) indicating no significant ponding (black areas). (f) Normalized difference vegetation index image derived from Landsat TM on 27 December 2007 identifying areas of vegetation (green). Also shown are the stream networks extracted from ASTER (blue lines).

Figure 5. Locations of freshwater lenses in the Arabian Peninsula draped over a Landsat image. Red polygons represent areas of known locations of freshwater lenses, whereas purple polygons represent areas of postulated locations (Brook et al., 2006; Mukhopadhyay et al., 1996; Young et al., 2004). Also shown is the distribution of the Hormoz salt formation in the subsurface (modified from Sultan et al., 2008b).
based, continuous hydrologic model to quantify the spatial and temporal distribution of surface runoff and potential groundwater recharge.

**Model Construction.** Watersheds were divided into sub-basins, and sub-basins were further subdivided into hydrologic response units (HRUs), with each HRU possessing unique land use and soil type attributes. Initial losses and direct overland flows in HRUs were estimated using the US Department of Agriculture Soil Conservation Service’s method (SCS, 1972). The method is suited for humid, semi-arid, and arid conditions (SCS, 1985) and has been successfully applied to several ephemeral watersheds in arid environments, which resemble Kuwait in hydrogeologic characteristics (e.g. climate, topography, and land use) (Milewski et al., 2009a; Osterkamp et al., 1994). The SWAT theory manual provides details on the equations and concepts incorporated in SWAT to partition the hydrologic cycle (Neitsch et al., 2005); here we provide a brief description utilized in this investigation.

Initial losses are largely dictated by the curve numbers (CN); the latter is a function of the antecedent moisture condition, the land use, the hydrologic condition, and the hydrologic soil type (SCS, 1985). Evaporation on bare soils was subject to transmission losses, a partitioning from the latter to the deep aquifer was assumed to be negligible (Scanlon, 1994). A simplified top soil profile was employed in the model, with soil properties dictated by the assigned land use and soil type. In our case, the ‘Southwestern US Arid Range’ provided the SWAT database was the selected land use type across the entire study area, which most closely resembled the mapped unit (El-Baz and Al-Sarawi, 2000). The majority of parameters relating to soil and land use properties were extracted from existing databases or given average default values based on standard reference values (Gheith and Sultan, 2002; Milewski et al., 2009a; Neitsch et al., 2005). Channel flows were estimated using the Muskingum routing method (McCarthy, 1938), whereby the Manning’s coefficient for uniform flow in a channel was used to calculate the rate and velocity of flow in a reach segment for a given time step. Channel flows were subject to transmission losses, a partitioning that depends on the channel geometry, upstream flow volume, duration of flow, bed material size, sediment load, and temperature (Neitsch et al., 2005). The saturated hydraulic conductivities of soils were estimated from the field data. The groundwater recharge to the shallow aquifer is based on the percolation at the bottom of the soil profile at the end of each time step and the transmission losses. Simulations were performed at daily time steps, the smallest time steps allowed by SWAT using cumulative 3-hourly TRMM data over periods of 24 h and applying monthly average values for temperature, wind speed, relative humidity, and solar radiation as daily estimates.

Because false positives were reported in TRMM data sets (e.g. Bauer et al., 2002; Turk et al., 2003), TRMM-based precipitation events were verified using procedures described in Milewski et al. (2009b). A precipitation event was verified if substantial cloud coverage and change in soil moisture were associated with the investigated event; other events that did not meet these criteria were omitted and were given a value of zero. The selected events were verified using a module (cloud detection module) that tests for the presence of clouds and another one (soil moisture module) that tests for changes in soil moisture for precipitation events, both incorporated in the remote sensing data extraction module (RESDEM) (Milewski et al., 2009b). Only events exceeding a threshold value of 5 mm were considered; in arid environments, smaller events are not expected to contribute to recharge given the high evaporation rates in these areas (Milewski et al., 2009b). Figure 4 demonstrates the overall approach for the selection and verification of one of these precipitation events. Using RESDEM, we first identified the days during which precipitation exceeded a threshold value of 5 mm. One of these events occurred on 21 December 2007 (Figure 4a). Identified precipitation events were then verified by examining the presence of clouds on AVHRR scenes acquired on the same day (Figure 4b), and by an increase in soil moisture content when comparisons are made between soil moisture content images (AMSR-E) acquired before (Figure 4d) and after a precipitation event (Figure 4e). TRMM corrected values compared well with rain gauges in the study area (~0.80 RMSE).

**Model Calibration.** Over the investigated period, the examined watersheds have witnessed a few but extensive precipitation events. Over ~30 events were reported, ten of which exceeded 15 mm/day. One would expect that, at least for the largest events, there would be flow at the watershed outlets. To the best of our knowledge, there was no flow reported at the outlet of the two watersheds throughout the investigated period, consistent with earlier studies (e.g. Mukhopadhyay et al., 1996). This observation could be in part related to the general flat topography of the area that would facilitate recharge and/or ponding of water in the lowlands or flat areas. A number of these areas where ponding is to be expected are shown on Figure 1. The figure shows the depression areas (black polygons) draped over the ASTER data from which they were extracted using the TOPAZ routine (Garbrecht and Martz, 1995). Three major depressions and or flat areas were observed in the Raudhatain, Umm-Al-Ahish, and Abdali areas in the Raudhatain Watershed (Figure 1).
To test whether water accumulated following large precipitation events within these depressions and lowlands, we examined Landsat TM images acquired shortly after (1 to 14 days) each of the major (>15 mm) precipitation events throughout the examined periods. Figure 4c shows a Landsat image acquired on 27 December 2007, 6 days after one of these major events. Only in the NE corner, the area where large-scale oil spills were reported, do we observe water ponding. In these areas, we suspect the spills formed impervious layers and led to water ponding. These satellite-based observations are consistent with our field observations, where small (<50 m wide) ponds, locally named barkhas, were observed at the lowlands following large precipitation events (Figure 4c).

The field and satellite-based observations cited above, namely, the general absence of runoff at the outlets of the watersheds and the general absence of long-term and large water accumulations following any of the precipitation events, suggest that infiltration is quite high in the examined areas and is widespread across large segments of the examined areas. In other words, infiltration and recharge are not largely restricted to the valley networks, as is the case with many of the arid parts of the world (Dettinger, 1989; Bazuhair and Wood, 1996; Flint et al., 2000; Milewski et al., 2009a). In such environments, soils with high infiltration capacities such as alluvial deposits are largely restricted to the valley floors, whereas the remaining areas within the watershed are largely formed of more impervious soil and rock types. Additional support for the suggestion that infiltration is not restricted to the valley network comes from an examination of normalized difference vegetation index and soil moisture images. The increases in soil moisture content and vegetation index that are expected following a precipitation event (Milewski et al., 2009b) are not restricted to the valley network; instead, they are observed across the entire watershed (Figure 4f). In addition, the satellite-based observations cited above are supported by the reported soil types in the area and by the infiltration tests conducted there. The study area as described above is largely covered by the Upper Dibdibah Formation consisting largely of gravels and sands with very high infiltration rates (3–9 m/day; Parsons, 1964; Grealish et al., 1998; Kwarteng et al., 2000).

We used the satellite- and field-based observations cited above to calibrate the model: Model parameters related to flow (e.g. SURLAG, CH_K, CN) and infiltration (e.g. SOL_AWC, CN, CH_K, SOL_Z) were adjusted to eliminate runoff at the wadi outlet and water accumulations in depressions. This was accomplished by reducing the flow parameters (e.g. CH_N, ALPHA_BF; SURLAG) and increasing (e.g. SOL_AWC; CN; CH_K) the infiltration parameters.

RESULTS AND DISCUSSION

A total of ~100 drainage depressions were identified, ranging in size from 1 to 75 km² for the entire country of Kuwait, totalling 607 km² (3% of the total area). Depressions were categorized as either primary or secondary depressions, where primary depressions are those most likely to form freshwater lenses and secondary depressions are less likely to form lenses. The majority of the primary depressions are found in the northern area, in the Raudhatain Watershed, which receive a high amount of precipitation (~160 mm/year; Figure 2) and have the highest infiltration rates (9 m/day; Figure 3A) and the most saline groundwater (Figure 3A). In the Raudhatain Watershed, 40 drainage depressions were identified for potential development of freshwater lenses (three of which are known locations), covering an area of 242 km² (Figure 1). Secondary depressions are found in central and southern Kuwait. In these areas, precipitation is moderate (~120 mm/year; Figure 2), infiltration rates are moderate (~5 m/day; Figure 3A), and the salinity of the groundwater is low to moderate (<10 000 TDS; Figure 3A).

First-order estimates for the amount of recharge feeding the identified lenses within the Raudhatain Watershed were obtained by constructing a hydrologic model (SWAT) and calibrating it using field- and satellite-based observations. The calibrated model was used to predict the annual recharge to the Raudhatain drainage depressions (Table I). The average annual precipitation, runoff, initial losses, and recharge was estimated for the Raudhatain Watershed at 5.24 × 10⁸ m³, 1.34 × 10⁷ m³ [3% of total precipitation (TP)], 3.84 × 10⁸ m³ (73% of TP), and 1.27 × 10⁸ m³ (24% of TP), respectively. Given that the identified depressions cover an area of 242 km², amounting to approximately 7% of the Raudhatain Watershed, we estimate the average annual recharge for the period 1998–2009 within the drainage depression at 8.17 × 10⁶ m³ and the total recharge at 9.80 × 10⁷ m³.

<table>
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<th>Area (km²)</th>
<th>Precipitation (m³)</th>
<th>Runoff (m³)</th>
<th>Initial losses (m³)</th>
<th>Recharge (m³)</th>
<th>Total recharge (m³)</th>
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<td>3.84E+08</td>
<td>1.27E+08</td>
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<td></td>
<td>8.17E+06</td>
<td></td>
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<td></td>
<td></td>
<td>1.48E+08</td>
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</table>

Table I. SWAT model results from 1998 to 2009
consistent with earlier findings (Al-Sulaimi et al., 1988). These should be considered as minimum recharge estimates given that they are solely related to contributions from initial losses and that recharge from transmission losses from local runoff in stream channels was ignored because of the limited size of its recharge area underneath the stream channel compared to its area of depression. It may have a limited function to support the development of region-wide freshwater lenses in the depression area. Using the same procedures, we estimated the average annual recharge within the secondary depressions at $1.23 \times 10^7$ m$^3$. As indicated earlier, it is less likely for the infiltrating water in the secondary depressions to form freshwater lenses. The settings conducive for the development of freshwater lenses in Kuwait that we described earlier, namely, the presence of depressions, regional saline unconfined aquifer, intense precipitation, and high infiltration rates, are not unique to Kuwait and are common in many of the surrounding areas.

In the Arabian Peninsula, the Empty Quarter aquifer system’s stratigraphic units (age: Cambrian to Quaternary) that are exposed in the foothills of the Red Sea Hills provide opportunities for groundwater recharge from rain precipitating over the Red Sea Hills. Groundwater flows from west to east, reaching depths of up to 7 km near the Gulf; waters become highly salinized (TDS: $>90,000$ ppm) due to interaction with aquifer rock units (e.g. Appelo, 1994; Chapelle and Knobel, 1983) and/or dissolution of thick (2 km) Hormoz evaporite series. Leakage from the deep-seated saline aquifers and structural discontinuities near the Gulf provide passages for ascending groundwater from depth. Along the eastern and the SE margins of the Empty Quarter, extensive sabkhas form in the lowlands where groundwater is to be found at near-surface levels or as shallow unconfined saline aquifers at topographically higher areas. Moreover, the Dammam Formation, which underlies Kuwait, is present throughout the Arabian Peninsula (Edgell, 1997; Alsharhan et al., 2001; Mukhopadhyay et al., 1996). Many of the reported freshwater lenses in these areas are to be found, as is the case with Kuwait, floating on the highly saline leakages from the Empty Quarter aquifer system and now residing in shallow unconfined aquifers (Alsharhan et al., 2001). Two of these freshwater lenses, (1) an unnamed freshwater lens that was found during field excursions (Sultan et al., 2008b), hereafter referred to as EQ1, and (2) the Liwa lens in United Arab Emirates (Rizk and AlSharhan, 2003), are located in areas where highly saline groundwater (TDS: $>50,000$ ppm) is present and were identified using the aforementioned criteria and methodologies, as shown in Figure 5. Similar locations were identified in Qatar, Bahrain, and Eastern Saudi Arabia (Alsharhan et al., 2001). Figure 5 shows the distribution of reported (red areas) and potential locations (purple areas) identified in this study. ASTER DEM images indicated that lenses are found in natural depressions, stream channels, and dune fields, where infiltration is expected to be quite high and precipitation is sporadic but intense. Inspection of TRMM data for these areas has shown that over the past 10 years, there have been more than 20 events, each of which exceeded 20 mm.

SUMMARY AND CONCLUSION

Fresh water is an important resource across the globe and especially vital in arid environments such as the Middle East. Unfortunately, fresh water is often limited in such areas; however, the development of freshwater lenses provides opportunities for increased use by human consumption and agriculture if utilized sustainably. This manuscript provides and validates criteria necessary for the formation of freshwater lens in Kuwait and surrounding areas. A hydrologic model demonstrated the potential recharge to these areas and provides a more complete understanding of the total available water resources. Implications for identifying areas of freshwater lenses and using remote sensing as a tool to verify these locations for other arid environments both in the Middle East and elsewhere are clear.

ACKNOWLEDGMENTS

We would like to thank the involvement of the Kuwait Institute for Scientific Research (KISR). We also acknowledge and send our thanks to Dr. Mohamed Ahmed for his insight and work in the paper and project.

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