Groundwater use and policy options for sustainable management in Southern Iraq

Ali A. Obeed Al-Azawia,b and Frank A. Wardc

aDepartment of Geosciences, University of Baghdad, Iraq; bDepartment of Agricultural Economics and Agricultural Business, New Mexico State University, Las Cruces, USA; cWater Science and Management Graduate Program, Department of Agricultural Economics and Agricultural Business, New Mexico State University, Las Cruces, USA

ABSTRACT
An important challenge facing the design of sustainable aquifer management plans is weak primary data on aquifer recharge and use patterns. Weak data limit the ability of policy makers to design efficient aquifer protection plans. The objectives of this article are (1) to estimate groundwater use patterns for an important food-producing region of southern Iraq, the Bahr Al-Najaf Basin; (2) to compare groundwater use patterns with the renewable groundwater supply; and (3) to describe a sustainable groundwater policy alternative to current use patterns. For this study, original data on groundwater pumping were secured for 2006–2011. The data show a pattern of unsustainable groundwater withdrawals. A policy intervention is described in which pumping permits could be assigned to groundwater users to promote sustainable use. Allowing or encouraging the permits to be transferable through trading to higher-valued uses could reduce the economic costs of protecting the aquifer while promoting its sustainable use.

Background
Climate variability and continued surface water shortages are raising the importance of groundwater as a strategic water source for growing populations and as a means of balancing the demands for future uses (Al-Azawi, 2009; Bouwer, 2002; Diamantopoulou & Voudouris, 2008; Loáiciga, 2004; MacDonald, Calow, MacDonald, Darling, & Dohartaigh, 2009; Martinez-Santos, Llamas, & Martinez-Alfaro, 2008; Seward, Xu, & Brendonck, 2006; Steward et al., 2013; Zhou, 2009). Long-term planning for the wise development and use of groundwater is urgently needed to ensure the sustainability of strategic aquifers. This need is highlighted today in the world’s arid regions.

Iraq is an under-studied region in the water resources management and policy literature. Yet, groundwater use there dates back centuries. Ancient mountain channels and hand-dug wells are the norm in many regions. Many hand-dug wells remain in use today. Villages are often located near surface springs and tap this water supply; hand-dug wells support...
domestic supplies. However, beginning in 1935, mechanical well drilling was introduced in Iraq and newer, deeper groundwater supplies were tapped (Al-Ansari, Ali, & Knutsson, 2014).

Most of Iraq’s groundwater aquifers are large-scale alluvial deposits located near the Tigris and Euphrates Rivers and consisting of Mesopotamian clastic and carbonate formations. These aquifers have weak potential for extensive domestic use because of poor water quality. These river aquifers typically contain reservoirs with large capacities. Annual recharge nationwide is estimated at 620 million cubic metres from rainfall percolation as well as surface water runoff. (Food & Agricultural Organization of the United Nations, 2016).

Sustainable aquifer management poses an especially urgent challenge in the southern part of the country. One important basin there, the Bahr Al-Najaf Basin, depends on groundwater to meet the bulk of its water use demand (Figure A1, supplementary material, available online at http://dx.doi.10.1080/07900627.2016.1213705). The basin is important for several reasons. It supplies a sizeable percentage of Iraq’s domestic food supply, though only a small percentage of the country’s farms are located there. The region also has a significant share of the nation’s groundwater pumping. Consequently, the design and implementation of policies promoting sustainable use will be important for the basin as well as for the nation.

In recent years, the Bahr Al-Najaf region has seen growing development and use of its water supplies. These developments have aimed to secure a reliable and sustainable income for the region’s population. Facing unreliable water flows and declining average surface levels, regional water users by necessity turned to increased pumping of groundwater to meet their needs. This activity became more pronounced over the six-year period of 2006–2011, which coincided with reduced surface supplies in the Euphrates River.

Previous investigations have been conducted in the region. A 2009 study of the Bahr Al-Najaf Basin found that groundwater use patterns exceeded the amount of groundwater recharge in the basin (Al-Azawi, 2009). The authors carried out preliminary hydrogeological studies in the Bahr Al-Najaf Basin. They examined the importance of groundwater resources in this basin. They recommended more extensive future work to determine the economic performance of continued increases in pumping in the basin, which is faced with the threat of ongoing episodes of drought. These authors were unable to break out historical groundwater use patterns such as in agriculture, industry, livestock ranching, and household domestic. This gap motivates the current investigation.

Iraq faces special problems connected to water and food security (Jaradat, 2003). Farmers in Iraq have been challenged for years by poor environmental conditions, with few affordable measures for adapting to salinity, climate, drought, pests, crop and livestock diseases, and input shortages, as well as related challenges of poor technology and institutions, and inadequate science-formulated policies (Jaradat, 2003).

A 2014 study concluded that in dry years about a third of the wheat needed for Iraqi domestic food security is imported in dry years (Schnittker, 2014). A related source of food insecurity is the widely publicized unstable domestic personal security conditions, made more difficult by ongoing sectarian violence. For example, in 2014 and 2015 militant groups controlled two important food-producing provinces in the region where the Tigris and Euphrates Rivers enter Iraq. Water in Iraq has been used as a military weapon (King, 2015). Low water availability, especially when made less reliable, undermines food security.

These challenges prompted the present authors to investigate policy proposals to address food and water insecurity. Results published in 2010 suggested that a primary fact behind ongoing unreliable food security could be the absence of a water policy that enabled farmers
and water managers to better plan and achieve their crop production goals (Godfray et al., 2010). Iraqi lands are generally fertile and productive enough to secure adequate national grain and produce self-sufficiency, as long as there is water of the right timing, quality, quantity, and location.

Previous investigations internationally have a bearing on the motivation, conceptual framework, and conduct of this study. A 1999 investigation in China concluded that the long-term sustainability of the economically accessible groundwater resources of China’s Konan Basin was at risk. A comprehensive analysis of the groundwater system is essential prior to formulating plans for future groundwater development and management (Jha, Chikamori, Kamii, & Yamasaki, 1999). Despite the often unrealized potential of integrated water resources management (Biswas, 2004), such integrated analysis could provide a framework to inform the path forward for countries that suffer from related water, food, and health challenges. Despite the difficulties (Biswas, 2004), it is important for all multiple water uses to be coordinated and integrated into an overall water management plan (Bouwer, 2002).

Several studies have examined challenges surrounding sustainable aquifer management (Abderrahman, 2006). For aquifers, sustainable management can be defined as a programme that seeks to avoid irreversible damage to water resources while protecting the long-term capacity of the resource to sustain economically and environmentally valued services (Kinzelbach, Bauer, Siegfried, & Brunner, 2003).

The role of cooperation in the sustainable exploitation of a jointly used groundwater resource has been examined using a game-theoretic formulation (Loaiciga, 2004). Cooperative equilibrium can occur when each groundwater user is accountable for the impacts of their behaviour on costs borne by other users associated with the base user’s pumping, i.e. each user faces the marginal costs of their own actions. A celebrated investigation of 2005 was one of the first to distinguish ‘sustainability’ and ‘sustainable pumping’, two concepts often used interchangeably (Devlin & Sophocleous, 2005). The latter term refers to a pumping rate that can be sustained indefinitely without mining an aquifer, while the former term is broader and concerns such issues as ecology and water quality, in addition to sustainable pumping. To implement sustainable pumping, natural recharge rates must be known, to guide actual aquifer management plans (Devlin & Sophocleous, 2005), an important principle motivating this article.

A 2006 investigation presented the case for the use of ‘capture’ rather than ‘recharge’ as the guiding framework for sustainable groundwater development and use, with application to South Africa (Seward et al., 2006). Capture refers to the sum of all changes in discharge and recharge brought about by pumping. Analysis of the water balance equation shows the special circumstances that must apply for what has been termed “the water budget myth” (Devlin & Sophocleous, 2005) to reflect a properly hydrologically balanced aquifer analysis.

A 2007 investigation in Kuwait, a country adjacent to Iraq, found that the main natural source of water available in Kuwait is brackish groundwater (Al-Ruwaigh, 2007). That water is located in the Kuwait Group and the Dammam Aquifers. A 2007 investigation in China examined the sustainable development of groundwater resources in the North China Plain (Kendy et al., 2007). The authors found that this development would require an integrated plan that connects water resources, land use and climate changes, as well as social and economic factors. A 2008 investigation described an interdisciplinary framework of scenario design and modelling, providing a methodology to couple technical numerical modelling
approaches with key available data. The methodology was applied to the Mancha Occidental Aquifer in Spain (Martinez-Santos et al., 2008). In light of the historic conflicts in the area, the authors conducted modelling exercises that focused on vulnerability assessment. This assessment suggested that even low levels of recharge could be sustained over a period of 20–40 years.

A 2008 study focused on investigating hydrogeological characteristics and their related groundwater quality on Zakynthos, an island of 408 km² in the Ionian Sea. In their investigation, the authors conducted groundwater measurements, developed drilling data, and conducted pumping tests as well as chemical analyses of groundwater samples. Moreover, some recommendations were made to assist management in improving the sustainability of the groundwater resources of Zakynthos Island (Diamantopoulou & Voudouris, 2008).

A 2008 investigation described an effort to develop effective management strategies that ensure long-term, stable and flexible water supplies to meet growing municipal, agricultural and industrial water demand (Liu, Zheng, Zeng, & Lei, 2008). Another 2008 investigation focused on the village-level externalities that aggravate groundwater depletion. That work also examined potential policy options to enhance local collective action in water management (Shiferaw, Reddy, & Wani, 2008).

Where implemented by local communities, pro-poor policies can bring considerable sustainability benefits, while ensuring social justice in access to the resource. A 2009 study in the agriculturally productive region of Punjab, India, found that changes in cropping patterns have increased irrigation water requirements, in part because the irrigated area had increased from 71% to 95% of base levels. The study found that the number of tube wells increased from 0.192 million in 1970 to 1.165 million in 2005, a 35-year period. The excessive exploitation of groundwater created a declining water table situation (Aggarwal, Kaushal, Kaur, & Farmaha, 2009).

A 2009 investigation found that impacts of climate change in Africa may be undermining the sustainability of rural water supplies, the sole source of safe drinking water for rural populations (MacDonald et al., 2009). To help prepare for increased climate variability, it is essential to understand the balance between water availability, water access and water demand. In practice, this can mean investing in access to secure domestic water from alternative renewable sources, understanding and mapping renewable and non-renewable groundwater resources, and widening the scope of early-warning systems.

Work in 2009 addressed the issue of screening groundwater sources for integration into the public water supply system of the Algarve Region of Portugal (Stigter et al., 2009). From their work, a decision support system for an integrated water resources management scheme was developed. A more comprehensive analysis of sustainability was performed using transient as well as steady-state solutions for groundwater flow simulations. These simulations accounted for aquifer geometry, boundary conditions, recharge and discharge rates, pumping activity and seasonality.

Another 2009 investigation used a water balance framework to implement a plan for safe and sustainable yield (Zhou, 2009). Numerical simulation of a hypothetical case illustrated the natural groundwater balance and assessed effects of pumping and the dynamic formulation of capture. A 2012 work formulated a novel computable general equilibrium model (GTAP-W) to analyze the economy-wide impacts in several East Asian countries of more sustainable irrigation water use (Calzadilla, Rehdanz, & Tol, 2012). A 2014 study addressed participatory planning (Loehman, 2014). It combined revealed preference with economic
optimization to choose a desired future for sustaining groundwater. A 2014 study presented innovative methods which can be used to increase the production of virtual water for some strategic vegetable crops in parts of Tunisia, based on improved irrigation and better control of runoff and leaching (Lajili-Ghezal, Stambouli, Weslati, & Souissi, 2014).

Despite the noted and considerable achievements described above, important gaps remain in the search for sustainable groundwater and use patterns in southern Iraq. The aim of the present study is to fill some gaps not investigated by earlier scholarship. Bearing these gaps in mind, our objectives are to:

- Estimate the annual groundwater use for the important water-using economic sectors in the Bahr Al-Najaf Basin, Iraq.
- Compare those use patterns with the renewable groundwater supply.
- Describe sustainable policy alternatives to current aquifer management patterns.

**Methods of analysis**

**Study area**

Bahr Al-Najaf is west of Al-Najaf City and south of Baghdad, in the southern part of Iraq. It covers approximately 1200 km². In ancient times, it is believed, the area was covered with water, from which the term *bahr* (Arabic for ‘sea’) originated. The source of this surface water may have been springs and rainfall. Therefore, relics of water in some depressions can be seen (Figure A1, online supplemental material). Figure 1 shows that a series of drought years in 1995–2011 altered the recharge patterns in the basin (Iraqi Meteorological Organization, 2011). Most noticeable is a pattern of reduced rainfall, with consequent higher evaporation rates, exacerbated by high temperatures, all of which contributed to elevated groundwater depletion.

Water users in this region are dependent on groundwater pumping to support their livelihoods. For that reason, groundwater in the Bahr Al-Najaf Basin is the main water source.

![Figure 1. Historical yearly rainfall patterns (1980–2006), Bahr Al-Najaf Basin, Iraq.](image-url)
for all uses. Especially in 2007–2010, expanded water-using investments were made in this region for many uses. The most important new uses included factories, livestock ranches and crop irrigation. All raised groundwater use, with little attention given to recharge rates. Water planners and policy makers are most interested in maximizing the long-term economic development that can be secured while respecting the hydrologic constraints. Important constraints include the basin’s annual aquifer recharge as well as its total water-holding capacity. That is, its two important constraints are inflows and storage capacity. This is of course a classically studied issue in many of the arid developing regions of the world (Foster & Chilton, 2003). It is likely to receive growing attention in the face of emerging information on climate variability and change.

The main aquifer in the Bahr Al-Najaf Basin is in the Dammam Formation, composed mainly of limestone, dolomitic limestone, dolomite, and chalky limestone with marl beds (Jassim & Goff, 2006). Figure A2 in the online supplementary material shows that carbonate rocks in this aquifer are highly karstified and fractured, in areas of irregular limestone. Through erosion, the basin has developed fissures, sinkholes, underground streams, and caverns. Such conditions disturb the flow regime of groundwater and open places where groundwater appears as springs (General Commission for Groundwater, 2011), while also providing a supply source for underground reservoirs with high specific storage (Bredehoeft, 1967).

Generally, the basin’s groundwater flows from south-west to north-east, where there is a marked escarpment feature named Tar Al-Najaf (Al-Atai, 2006), as shown in Figures 2, 3, and A2 (in the online supplementary material). The subsurface flow from the central regional aquifer, located in Saudi Arabia (Al-Jawad & Khilail, 2001), is the main recharge source of the aquifer, in
addition to the smaller effects of rainfall on the formation outcrops outside the basin. The lengths of the groundwater flow paths range from a few metres to hundreds of kilometres. The region contains a deep groundwater flow system, with long flow paths between areas of recharge and discharge.

Groundwater moves through aquifers from areas of recharge to areas of discharge (Harbaugh, Banta, Hill, & McDonald, 2000), normally at slow rates ranging from 1 to 1000 metres per year. Tens, hundreds or even thousands of years may elapse between initial recharge and eventual discharge to a spring, a stream or the sea (Bredehoeft & Alley, 2014). So, because of this slow groundwater movement, where renewable, this water needs to be managed over a long period of time in which the water extraction is made compatible with long-term recharge rates. Unsustainable use of groundwater will lead to reduced capacity to support economic use. Slow flow rates and long residence times are amongst the numerous distinctive features of this groundwater system which pose special challenges for farmers, water managers and national water planners.

**Fieldwork**

Fieldwork for this study was initiated to follow up on an earlier, preliminary study of the basin (Al-Azawi, 2009). In that study, investigators found that the use of groundwater for crop irrigation, livestock grazing, industrial, and domestic human use was unsustainable without special intervention by those responsible for protecting long-term beneficial water use in the basin.

For this study, detailed field survey work was initiated in the basin in 2011 to document changes in groundwater use patterns that had occurred over the previous five years. An
important mission of the fieldwork was to secure data on economic developments in the basin that had significantly contributed to growth in groundwater pumping. A water use survey was conducted of farms, factories and domestic users. The survey showed significantly higher use by all surveyed sectors in 2006–2011. The fieldwork was carried out with support from the General Commission for Groundwater and the Ministry of Water Resources in Iraq (General Commission for Groundwater, 2011).

Farm surveys were conducted by contacting farmers to discover cropping and water use patterns by season and year, cross-checked with well-pumping records (Directorate of Al-Najaf Agriculture, 2011). Similar surveys were also administered to factory owner/operators, cross-checked with data on actual pumping used for industry. For domestic users, the survey was administered in connection with household water use over the same period, including all household uses: drinking, bathing, cleaning, cooking, flushing, and outdoor landscape use where relevant.

**Groundwater use patterns**

*Irrigated crops*

The 21 villages scattered in the Bahr Al-Najaf Basin had a population of just over 5400 in 2008, growing to about 7400 in 2011 (Directorate of Al-Najaf Statistics, 2011). All these villages depend on agriculture and livestock grazing for their livelihood. Irrigated cropping takes place in two seasons, summer and winter. Over those two seasons, cropping patterns and water use vary widely (Directorate of Al-Najaf Agriculture, 2011). Table (1) shows the quantity of groundwater used by crop and season. That use was measured using Equation (1), as suggested by Al-Azawi (2009), with data on water use by crop type secured from the relevant Iraqi ministry (Iraq Ministry of Science & Technology Department of Soil & Crops, 2012). Crop water requirements were calculated for different crops the industry-standard FAO 56 method (Allen, Pereira, Raes, & Smith, 1998), of which an example is presented in Equations (1) and (2) below (Perry, 2007).

Total crop water consumption is estimated by:

\[ WCAg = ETc \times A \times TAP \]  \hspace{1cm} (1)

where
\[ WCAg = \text{water consumption in agriculture (m}^3/\text{y)} \]
\[ ETc = \text{water consumed by crop type (mm/y; Iraq Ministry of Science & Technology Department of Soil & Crops, 2012)} \]
\[ A = \text{constant coefficient, equal to a land area of one Iraqi donum, which is 2500 m}^2 (0.25 \text{ ha)} \]
\[ TAP = \text{total area under crop production (donum/y)} \]

Total crop evapo-transpiration (ET) is estimated by:

\[ ETc = ETo \times Kc \]  \hspace{1cm} (2)

Where
\[ ETc = \text{crop evapo-transpiration (mm)} \]
\[ ETo = \text{reference evapo-transpiration (mm)} \]
\[ Kc = \text{crop coefficient} \]
Table 1. Groundwater consumed by crop, season, and year, Bahr Al-Najaf Basin, Iraq.

<table>
<thead>
<tr>
<th>Season</th>
<th>Crop types</th>
<th>Cropland (donum)</th>
<th>Crop consumption of waters (ETc, mm depth/season)</th>
<th>Water consumption (m³/donum)</th>
<th>Total water consumption (million m³)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Maize 3,668</td>
<td>1,044</td>
<td>2,610</td>
<td>9.58</td>
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<tr>
<td></td>
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<td></td>
<td>Barley 5,078</td>
<td>586</td>
<td>1,465</td>
<td>7.44</td>
<td></td>
</tr>
<tr>
<td>Others 1,154</td>
<td>250</td>
<td>625</td>
<td>0.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total 18,338</td>
<td></td>
<td></td>
<td></td>
<td>32.0</td>
<td></td>
</tr>
</tbody>
</table>

Note: An Iraqi donum is a quarter of a hectare, or 2500 m².
Source: Directorate of Al-Najaf Agriculture (2011), Iraq.
The crop coefficient, \( K_c \), varies by crop, but can also vary with time, crop growth stage, soil type, and growth conditions. Details are explained in an industry standard (Allen et al., 1998), with qualifications and limitations expressed in other more recent contributions (Kumar & van Dam, 2013; Perry, 2007).

Application of equation (1), implemented with equation (2), produced the results shown in Table (1). The table shows estimated crop water use in the basin by season, crop and year.

Industry
Industry in this basin typically pumps water from Quaternary and valley deposits, in addition to Tertiary deposits exposed on the surface. These developments have led to the establishment of many profitable factories, typically producing gravel, sand, bricks and gypsum. So an important economic and policy question centres on the economic value of the water used for these manufacturing purposes, compared to economic values displaced in future years as a consequence of groundwater depletion in the intervening period (Peterson & Ding, 2005). This is a classic example of the motivation to understand the economic theory of exhaustible resources (Hotelling, 1931; Solow, 1974).

From a statistical investigation carried out in 2011 (Directorate of Al-Najaf Statistics, 2011), Table 2 shows the numerous water-using factories in the basin. The factories in the study area are typically small commercial enterprises that use comparatively little water, mostly for employee drinking, flushing and minor cleaning. Each factory typically has only a single well. These factories were sampled. The average number of working days per well was 121.6 days per year, with an average discharge rate of 1296 m\(^3\)/day, about 15 L/s.

Average groundwater consumption is determined by applying the following equation (Al-Azawi, 2009), with results shown in Table 2. Water consumed by industry is:

\[
W_{CI} = N_f \times Q \times T
\]

where
- \( W_{CI} \) = water consumed by industry (m\(^3\)/y)
- \( N_f \) = number of factories
- \( Q \) = discharge of wells (m\(^3\)/day)
- \( T \) = total pumping time from production wells (days per year)

Livestock
Irrigated pasture supports domestic livestock grazing and crops for export, which are both important activities in the basin. The quality of groundwater is good, and it supports extensive production of irrigated livestock forage, as the basin is an important pastoral region in the country’s southern desert. Levels of water used per unit of livestock in the region have
not changed in a number of years, and are described elsewhere (Ismail & Matoley, 1982). Using our data source (Directorate of Al-Najaf Statistics, 2011), livestock water use is shown in Table (3) and in Figure A3 (in the online supplementary material). These results were determined by use of the following equation, from Al-Azawi (2009):

\[ W_{\text{Can}} = N_A \times D_C \times D_Y \]  

(4)

where

- \( W_{\text{Can}} \) = total livestock water use (\( m^3/y \))
- \( N_A \) = number of animals by type
- \( D_C \) = daily consumption (L/day)
- \( D_Y \) = days per year, 365

Results for 2006–2011 are shown in Table (3).

**Domestic**

Village residents in the basin use groundwater for their daily activities, despite its marginal chemical and biological properties (Al-Azawi, 2009) for human use. Table (4) presents estimated domestic groundwater use. The results express water use levels in combined urban and rural areas. Rural villagers typically use less water than their urban counterparts because of lower per capita incomes. According to previous work (Twort, Ratnayaka, & Brandt, 2000), groundwater consumption per capita for domestic uses by the villagers is approximately half of that in urban areas. Table (4) shows that the average groundwater consumed per person in villages in summer is about 87.5 L/day. Based on that fact, water use per person during the year is estimated as (Al-Azawi, 2009):

\[ W_{\text{CD}} = P \times q_{cp} \times D_Y \]  

(5)

Table 3. Average groundwater consumption by livestock, Bahr Al-Najaf Basin, Iraq, 2006–2011.

<table>
<thead>
<tr>
<th>Animal type</th>
<th>No. of animals</th>
<th>Average daily water consumption (litres per animal per day)</th>
<th>Annual water consumption (( m^3/y ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep</td>
<td>16,668</td>
<td>14</td>
<td>85,173</td>
</tr>
<tr>
<td>Cattle</td>
<td>1,426</td>
<td>50</td>
<td>26,025</td>
</tr>
<tr>
<td>Camels</td>
<td>600</td>
<td>45</td>
<td>9,855</td>
</tr>
<tr>
<td>Buffalo</td>
<td>915</td>
<td>50</td>
<td>16,698</td>
</tr>
<tr>
<td>Total</td>
<td>17,609</td>
<td>21.4</td>
<td>137,751</td>
</tr>
</tbody>
</table>


Table 4. Water use for human domestic consumption in urban areas (litres per day per capita)

<table>
<thead>
<tr>
<th>Use (litres per day per person)</th>
<th>Percentage of total</th>
<th>Population (thousands), 2006–11</th>
<th>Total use (( m^3/y ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilets</td>
<td>28</td>
<td>16</td>
<td>7,425</td>
</tr>
<tr>
<td>Food washing and cooking</td>
<td>14</td>
<td>8</td>
<td>37,942</td>
</tr>
<tr>
<td>House cleaning</td>
<td>13</td>
<td>8</td>
<td>35,232</td>
</tr>
<tr>
<td>Bathing</td>
<td>85</td>
<td>48</td>
<td>230,361</td>
</tr>
<tr>
<td>Clothes washing</td>
<td>35</td>
<td>20</td>
<td>94,854</td>
</tr>
<tr>
<td>Total</td>
<td>175</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Source: Directorate of Al-Najaf Statistics (2011), Iraq; Twort et al. (2000).

<table>
<thead>
<tr>
<th>Year</th>
<th>Useable renewable storage (million m$^3$)*</th>
<th>Total use (million m$^3$/y)</th>
<th>Excess demand from useable storage (million m$^3$/y)</th>
<th>Shortage as a percentage of renewable supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>41.4</td>
<td>44.8</td>
<td>3.4</td>
<td>7.6</td>
</tr>
<tr>
<td>2007</td>
<td>54.8</td>
<td>13.4</td>
<td></td>
<td>24.5</td>
</tr>
<tr>
<td>2008</td>
<td>56.3</td>
<td>14.9</td>
<td></td>
<td>26.5</td>
</tr>
<tr>
<td>2009</td>
<td>52.9</td>
<td>11.5</td>
<td></td>
<td>21.7</td>
</tr>
<tr>
<td>2010</td>
<td>68.7</td>
<td>27.3</td>
<td></td>
<td>39.7</td>
</tr>
<tr>
<td>2011</td>
<td>54.0</td>
<td>12.6</td>
<td></td>
<td>23.3</td>
</tr>
</tbody>
</table>

*Source: Al-Azawi (2009).

where

- $WCD = \text{water consumed in domestic uses in } (\text{m}^3/\text{y})$
- $P = \text{number of inhabitants in the area}$
- $q_{cp} = \text{daily water consumption per capita } (\text{m}^3/\text{day})$
- $DY = \text{days per year, 365}$

Equation (4) was used to estimate human domestic water consumption per year. Table (4) shows population levels in the basin from 2006 to 2011. This equation was used to estimated total water use based on population levels.

**Total use**

The above formulas were used to calculate total groundwater use in the basin. The total quantity of groundwater consumed for all purposes was determined according to the following equation, suggested by Al-Azawi (2009), with results shown in Table (5):

$$TCGw = WC_{Ag} + WC_l + WC_{An} + WCD$$

(6)

where

- $TCGw = \text{total consumption of groundwater } (\text{m}^3/\text{y})$

This equation tracks the four factors required to estimate the total consumption of groundwater; results, interpretations and policy implications are presented below.

**Results**

**Irrigated crops**

The results in Table (1) show that water consumption was lowest in 2006, then grew for later years. Water use in 2006 was lower than in 2007–2011 because of increasing agricultural investments in land in production, along with growth in associated wells to support that additional cultivation. An additional reason for the growth of land in production came from a number of farmers who received land grants in 2007 with the intent of raising agricultural productivity.

**Industry**

Table 2 shows water use by the 125 factories surveyed in the area. Most depend exclusively on groundwater for their industrial processes. The tabled percentages express rising water use with a rising number of factories in the basin. Factory growth entering the region showed
greater numbers in 2011 than in 2006, with a growth of about 10%. Sustaining industrial water use may require a policy promoting the transfer of water from agriculture to industry. Such transfers could be based on a flexible water rights system governing a rational and orderly transfer of water from agriculture to the higher-value industrial uses while protecting the regional aquifer (Cai, 2008; Rosegrant & Ringler, 2000). Such transfers could promote a Pareto-improvement outcome, in which all parties are made better off through flexible market trading that moves water from lower- to higher-value uses.

**Livestock**

Table (3) and Figure A3 (in the online supplementary material) show that cattle use more water than sheep by a factor of 10 to 3 per animal. The total water consumed by all livestock is an estimated 13,775 m$^3$/y. The increase in the number of animals in the basin occurred because of growing investments in ranching by overseas investors. This type of investment is one of the important sources of new economic value in this basin’s economy. Still, balanced economic growth cannot be sustained without protecting water supplies for long-term viability. This trade-off between current versus sustained economic development is a common problem in dry areas of the world that depend heavily on groundwater.

**Domestic**

Table 4 shows the level and distribution of water user for human domestic purposes. According to the results, the average amount of groundwater consumed per capita in the village areas during summer is 87.5 L/day. Total domestic water consumption in the study area is about 237,000 m$^3$/y.

**Total use**

In order to inform and guide policy interventions, it is important to find information on how much groundwater is used as well as how this use affects aquifer storage. Moreover, there is little to no recharge to the regional aquifer from the scant rainfall that occurs in this basin, so rainfall recharge effects are not considered here. A 2009 study established a groundwater balance for the study basin in which calculations were performed on inflows and outflows of groundwater from the basin, respectively. Sustained aquifer storage must ultimately be based on wise use of the renewable resource (Al-Azawi, 2009).

**Supply**

The basin’s supply comes from various sources of recharge. The total recharge that contributes to subsurface flow from the regional aquifer coming from west of the basin to the Iraqi–Saudi border area is an estimated 41.4 × 10$^6$ m$^3$/y (Al-Azawi, 2009). The discharge associated with normal and artesian wells in addition to the existing springs was 44.8 × 10$^6$ m$^3$/y in 2006 and 54.8 × 10$^6$ m$^3$/y in 2007, as estimated by Al-Azawi (2009). Results from Equation (6) and Table (5) clarify the relation between renewable storage and groundwater use in 2006–11. During 2006, groundwater consumption for various uses only slightly exceeded renewable recharge.
In 2007–2011, shortages were larger than in 2006. Hence, 7.6% of the groundwater consumption, $3.4 \times 10^6$ m$^3$/y, is drawn down from sustainable aquifer recharge. Through the year 2007, groundwater shortage increased by 24.5% compared to 2006, to $13.4 \times 10^6$ m$^3$/y. Table 5 shows similar shortages for the years 2008–2011. The lion's share of the increased use, as well as the increased shortages, is caused by the recent expansion of irrigated agriculture and water-using industry brought on by the growth of foreign investments.

**Discussion: policy implications**

Renewable groundwater supplies are the major factor required for sustainable groundwater management programmes. Water from aquifers has certain advantages over surface water sources. Groundwater supplies are often better protected from pollution through the natural filtering of soils, reducing the need for expensive treatment. In addition, aquifer supplies are well positioned to meet the demand for reliable supplies (firm yield) for domestic and industrial uses, which suffer high costs when supplies are unpredictable. Both of these characteristics of aquifers make groundwater many times a more attractive and cheaper source of water than above-ground supplies (Doell & Fiedler, 2008; Tsur, 1990).

Sustainable groundwater management requires average use to be equal to or less than average renewable recharge (Sophocleous, 2005). Historically, the Bahr Al-Najaf Basin of Iraq has been one of the world’s most productive irrigation regions; crop production from irrigation has been an important source of livelihoods from ancient times (Jacobsen & Adams, 1958). In recent years, fluctuating surface water supplies in both the Tigris and Euphrates Rivers (Al-Ansari & Knutsson, 2011), has prompted a call for the nation’s aquifer waters to be managed carefully as a savings account to sustainably provide for the basin’s major uses: crop irrigation, livestock grazing, industrial, and domestic human use (Shomaker, Hagan, & Swartwout, 2003).

Sustainable use of surface and groundwater depends on the supply and demand of both sources of water over long periods of time. Planning for optimal timing, quantity, quality and location of water resources utilization is required to ensure the sustainability of present and future supplies for human livelihood. It remains an ongoing process.

**Towards a safe minimum standard**

Over the years 2006–2011, the scale of groundwater use in the Bahr Al-Najaf Basin continued to expand, with demand exceeding recharge for renewable storage and attendant depletion of the savings account of non-renewable storage. If these conditions persist, a time will come when the aquifer risks depletion beyond economic recovery, a threshold at which the “safe minimum standard” (Ciriacy-Wantrup, 1963) is compromised. To guard against this irreversible condition, several steps could be carried out in the policy realm, as described below.

**Transferable pumping permits**

Transferable pumping permits, sometimes described as tradable pumping permits, could be an efficient, equitable and sustainable groundwater policy option for containing pumping at sustainable levels. Issuing pumping permits and enforcing them can reduce stress on the aquifer. Still, such pumping restrictions alone can come at a high current economic cost. For
aquifer protection, the creation of transferable pumping permits, a water right that can be transferred, is likely to reduce the economic cost of limiting groundwater use in the study region. The transferability of these permits has the potential to significantly reduce the economic losses that would otherwise be suffered in the study area in the face of simple restrictions on current pumping.

One attractive feature of transferable permits is their flexible capacity to embrace growth in demand from future high-valued uses. New industrial water users could simply purchase pumping rights from existing permit holders under a voluntary market trading arrangement. Under such a voluntary arrangement, we would expect the sellers to be the lowest-valued existing pumpers, typically irrigators of forage crops.

Under a market transferable permit system, the equilibrium market price would compensate for the economic value of that existing pumping reduced by the transfer. While we have not yet estimated the economic gains from transferability of pumping permits, a 2004 study in North Carolina, USA, is suggestive (Kirsch & Characklis, 2004). It found that regionalization and groundwater permit trading can reduce economic losses from reduced use by the permit seller by up to 35%. A more recent study identified the long-term aquifer protection value and short-term economic benefits of enacting a policy to issue pumping permits while also permitting them to be tradeable. Such a programme would reduce the current economic costs of shortages while also protecting sustainable use of the aquifer (Latinopoulos & Sartzetakis, 2015).

According to our analysis, the sustainable average pumping level is $41.4 \times 10^6 \text{ m}^3/\text{y}$. When combined with the market transferability of such permits, use of these permits for pumping sustainable levels of groundwater discharge could gravitate to their highest-value use pattern. Such use patterns would permit overall reductions in pumping to be sustainable while minimizing the annual economic cost suffered from use reductions. Transferable resource use permits have been investigated for some time as a measure to minimize the economic costs associated with protecting sustainable use of other exhaustible resources, such high seas fisheries (Branch, 2009; Branch et al., 2006; Chu, 2009; Grafton et al., 2006; Hilborn, Punt, & Orensanz, 2004).

To implement any sustainable pumping policy in the study region, the amount of abstracted groundwater discharged from the aquifer needs to be better monitored by installing and maintaining sturdy and reliable well meters. Meters could be installed for domestic uses and industrial developments, as well as irrigation. Meters can take the place of periodic surveys, a common way to identify changes in water use.

The design of policies for sustainable groundwater use and aquifer protection is a long-term enterprise. In the face of long time horizons, combined with wide spatial coverage, numerous uncertainties can be expected in plans to protect sustainable groundwater use. Uncertainty should be handled by its explicit formulation in policy design. Transparency in the policy formulation process and widespread public approval are key elements in carrying out sustainable groundwater management on the ground. An honest understanding and analysis of public perceptions is a major factor to define, understand, and guide sustainable aquifer use (Benvenisti, 2003).

Policies to promote water conservation in agriculture have a role to play. Agriculture is the largest source of aquifer pumping in many of the dry parts of the world (Siebert et al., 2010). Water-conserving technologies such as drip or sprinkler irrigation systems are possibilities, rather than continuing with flood irrigation, the oldest irrigation system in Iraq. Such
water-conservation measures would likely be a behavioural response to programmes promoting transferable pumping permits. Similar conclusions were reached in a celebrated 1994 study in California’s Central Valley (Provencher & Burt, 1994). Of course, debates remain about the real size of the water savings from converting from flood to drip irrigation (Ward & Pulido-Velazquez, 2008). Moreover, not all crops currently grown in the study basin are likely to achieve economic viability by shifting to drip irrigation. That viability depends on the size of the public subsidy needed to promote the use of water-conserving irrigation technologies (Ward, 2014). Two recent studies on water-conserving impacts of drip irrigation could inform important policy debates on future conservation policy choices for the study region (Kumar, Turral, Sharma, Amarasinghe, & Singh, 2008; Kumar & van Dam, 2013). The water savings from drip irrigation, if measurable, could be significant in situations like this one, due to the unique climate.

Water conservation in irrigated agriculture can contribute to sustainable use in the study region. It can also release water for other uses, which often produce more economic value than earned by irrigated agriculture. It could also allow expanded irrigation into new areas, as well as reduction of salinity in return flows, contributing to improved water quality. In addition, well-managed withdrawals of groundwater based on sustainable pumping rates lower than natural recharge can contribute to long-term sustainable aquifer use (Sophocleous, 2002, 2005). More sustainable groundwater use patterns can be achieved in part by economically budgeting groundwater for water-conserving crops where economically viable (Shiferaw et al., 2008). Another challenge requiring attention comes from the need to manage the common pool (Madani & Dinar, 2012) characteristics of groundwater, as well as environmental externalities (Esteban & Albiac, 2011). Water users sharing the commons who disregard these externalities can lead to excessive extraction and may irreversibly damage aquifers.

**Role of stakeholders**

Stakeholder-led initiatives have a recent history of success in coming to grips with unsustainable groundwater pumping. A good example comes from a 2009 experiment conducted in a region of Mexico that had suffered unsustainable pumping. Despite well-laid plans for sustainable groundwater use, these plans needed continued updating and adjustment in the face of climate variability and change. The authors of the 2009 study compared two experimental approaches for promoting stakeholder self-regulation of groundwater extractions: (1) locally autonomous aquifer organizations with powers to regulate groundwater extractions, and (2) aquifer organizations with advisory powers only. As a result of competition between the state and federal levels, the advisory-only boards faced numerous challenges in successfully achieving the desired reductions in groundwater extraction (Wester, Hoogesteger, & Vincent, 2009).

In the study basin in Iraq, the aquifer is large, soil and climate are productive, pumping depths are shallow, and recharge levels are low. In a region such as this, the risk of overexploitation presents a classic challenge for public policy makers, water managers and individual farmers. This challenge has been observed for many years to be an ongoing issue in several parts of the Middle East (Gleick, 1994). In this ‘perfect storm’, it is common for water tables to fall and continue to do so until they stabilize at a much lower level.
Stakeholder meetings could be organized to inform the benefits of judicious use of water to avoid long-term water shortages, using the methods described in more detail elsewhere (Stave, 2003; Voinov & Bousquet, 2010). Industrial water users could also be informed of the importance of recycling wastewater for reuse in certain industrial process steps instead of the current levels of high water use without reuse. Stakeholders typically take interest in such interactions because sustainable water programmes contribute to the economic security of everyone in the community. For the success of any sustainable project, influential stakeholders must be convinced, an approach that can be enhanced through the use of innovative modelling approaches such as systems dynamics (Alley, Healy, LaBaugh, & Reilly, 2002; Winz, Brierley, & Trowsdale, 2009).

Conclusions

Groundwater tables fall when discharge exceeds recharge. Still, the level and extent of recharge is often uncertain and hard to measure. Aquifer overexploitation can sometimes be reversed. Remarkably, short-term unsustainable pumping combined with longer-term attention to the problem can be a step towards sustainable development (Custodio, 2002). In our view, sustainable adjustments to an aquifer’s water balance can occur in the Bahr Al-Najaf Basin in Iraq.

A celebrated resource economist of the 1950s coined the term ‘safe minimum standard’ to avoid passing the threshold of irreversible damage (Ciriacy-Wantrup, 1963). This study has attempted to increase the extent of reliable aquifer knowledge of the Bahr Al-Najaf Basin in Iraq to support and inform debates over sustainable aquifer planning. More work is planned for the future. We intend to conduct research to formulate economic/hydrologic optimization models of the behaviour of the regional aquifer and its water users. Sustainable groundwater use in this Iraqi basin should be established by management institutions in concert with regional stakeholders, while taking into account hydrologic, environmental and political constraints. Multidisciplinary studies supported by reliable data and integrated water resources modelling are desired ends in this basin and have started, but full integration of the disciplines must await future research.

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Disclosure statement

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