Hydrogeological and economical simulations: emergency water supply for Muscat

Slim Zekri\textsuperscript{a}, Ali Khamis Al-Maktoumi\textsuperscript{b}, Osman A. E. Abdalla\textsuperscript{c}, Jamila Akil\textsuperscript{d} and Yassine Charabi\textsuperscript{e}

\textsuperscript{a}Corresponding author. Department of Agricultural Economics and Rural Studies, College of Agricultural and Marine Sciences, Sultan Qaboos University, P.O. Box 34, Al-Khod 123, Muscat, Sultanate of Oman. E-mail: slim@squ.edu.om

\textsuperscript{b}Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences

\textsuperscript{c}Department of Earth Sciences, Sultan Qaboos University, P.O. Box 36, Al-Khod 123, Sultanate of Oman

\textsuperscript{d}Research Assistant at the Water Research Centre, Villa 6, P.O. Box 17, Postal Code 123, Sultan Qaboos University, Al Khoud, Sultanate of Oman

\textsuperscript{e}Department of Geography, College of Arts and Social Sciences, Sultan Qaboos University, P.O. Box 42, Al-Khod 123, Muscat, Sultanate of Oman

Abstract

Urban water in Gulf Cooperation Council countries is principally supplied from desalination plants. However, desalination could be interrupted by natural hazards such as cyclones or harmful algal blooms. Four scenarios have been considered to help public institutions in Muscat to establish a water strategy for emergency situations. The numerical simulations of groundwater pumping have shown that the aquifer can supply emergency water in a safe way without any apparent risk of seawater intrusion to the Al-Khod Aquifer. The results show that Muscat can be easily supplied by emergency groundwater for up to 10 consecutive days with volumes varying between 24 and 71 l/cap/day at a low cost of US$0.18 per m\textsuperscript{3}. Covering up to 66\% of the total regular demand during an emergency is technically feasible but would bring the cost up to US$1.49 per m\textsuperscript{3} for groundwater and a cost of US$38.6 per m\textsuperscript{3} for storage reservoirs made of concrete. The cost per m\textsuperscript{3} of using concrete reservoirs is close to the market price of bottled water. Finally, the Public Authority for Electricity and Water might think of decentralizing the water storage at house levels by requiring new houses to be equipped with reservoirs on the roofs.

Keywords: Cost estimation; Groundwater; Natural hazards; Numerical simulations; Water emergency

1. Introduction

Water scarcity is an ever-growing global challenge. According to the United Nations Water Development Report (UN, 2006) nearly half of the world’s population will be living in areas of high

© IWA Publishing 2014
water stress conditions in 2030. In the arid area of the Gulf Cooperation Council (GCC) countries the
rapid population growth and economic development are increasing the stress on the already limited
available water resources. The GCC region is characterized by extremely low rainfall, and thus there
is an absence of surface water resources. Until recently the region relied exclusively on groundwater
resources for all purposes. Since the amount of groundwater abstraction was far greater than the
amount of natural recharge, water levels in the aquifers have fallen rapidly and the groundwater quality
has been worsening due to increased salinity. Consequently, the unique alternative was, and still is, a
massive construction of desalination plants to provide domestic water supply. However, relying only
on desalination for satisfying urban water demand is uncertain in the short term because of the frequency
of environmental and technological disasters which put large desalination plants at risk. Consequently,
occasional or frequent failure of one or more desalination plants associated with natural or technological
events are likely to interrupt urban water supply.

Oman is characterized by a low groundwater recharge rate. Currently, 94% of Muscat’s urban water is
supplied from seawater desalination plants. This is due to the increasing shortage of groundwater, the
economic expansion in the city and the growing population. The present population of Muscat is
around 775,875 inhabitants (MNE, 2011). The full dependence on seawater desalination plants for sup-plying water is risky, especially in areas vulnerable to frequent and intense cyclones and harmful algal
blooms (HABs). Webster et al. (2005) examined the number of tropical cyclones, and their intensity and
duration over the past 35 years and indicated a large increase in the number and proportion of cyclones
reaching categories 4 and 5, especially in the North Pacific, Indian and Southwest Pacific Oceans. Thus,
storms and tropical cyclones that hit Muscat, such as Gonu 2007 and Phet 2010, are likely to occur more
frequently and will affect neighbouring terrestrial areas, especially coastal areas (Fritz et al., 2010; Al-
Shaqsi, 2011). In addition and according to the Public Authority for Electricity and Water (PAEW, 2012),
the HABs phenomenon that affects seawater, commonly called red tides, have frequently
menaced the Omani coasts since 2008. The problem is observed worldwide and several recent publications
have mentioned that HABs cause significant problems mainly to reverse osmosis desalination
that result in increased chemical consumption, rapid membrane fouling rates and, in extreme cases,
plant shut down (Caron et al., 2010), depending on the concentration of the algae in the seawater as
well on the algal species involved (WRFAWT, 2010). In the United Arab Emirates, the HABs forced
five seawater desalination plants to shut down during October 2008 due to clogging of intake filters
and fears of an irreversible fouling of the reverse osmosis membranes (Berktay, 2011).

In Oman’s northern coastal area, the red tides lasted about four months from 2008 to 2009 and in 2010
HABs were very concentrated which led to the obstruction of the desalination plant’s filters and mem-
branes. Worse, in 2011, the HABs forced one of Muscat’s desalination plants to shut down for three to
four days due to the obstruction of cartridge pre-filters and membranes causing an interruption of the desa-
linated water supply to several districts. Moreover, the HABs liberate organic compounds that alter the
taste and odour of drinking water, which is not expected to be removed during the desalination process.
The phenomenon of HABs is one of the major causes of seawater desalination plant shut down in Muscat.
The HABs event is not easily predictable and its frequency has increased during the last decade. HABs are
such a serious matter that in 2012 the International Atomic Energy Agency (IAEA) started providing tech-
nical support to Oman to face its menace by tracking the isotopes of water (Muscat Daily, 2011).

Dooge (2004) pointed out that in areas frequently affected by an environmental risk hazard, five
phases of disaster should be considered: anticipating, warning, impact, relief and rehabilitation.
Muscat is frequently affected by a risk hazard, so it can be positioned easily in the warning phase.
Vrba & Verhagen (2006) suggested considering a catastrophic event rather as a warning that should stimulate the public and the authorities to establish water solutions for emergency situations.

Facing emergency water supply in Muscat has only been addressed by considering the building of concrete reservoirs according to the PAEW plan. Unlike most cities in the GCC, where desalination plants are located hundreds of kilometres from the cities serviced (Missimer et al., 2012), Muscat is a coastal city where urban water is provided by two desalination plants one of which is located in the middle of the city while the second is located only 50 km from the city. The distribution system provides uninterrupted water supply 24/7. Several distribution system ground storage facilities, with two days’ capacity, are dispersed in the city with the aim of matching the supply to the demand variations and short water treatment system failures. Aquifer storage and recovery (ASR) and other managed aquifer recharge (MAR) technologies are increasingly being used to face long- and short-term water emergencies (Maliva & Missimer, 2010; Ghaffour et al., 2013). ASR and MAR are probably the most cost-effective technologies to allow strategic water storages (Missimer et al., 2012; Zekri et al., 2013).

This paper presents the options for facing short-term water emergency situations in the capital city (Muscat) of Oman, including pumping groundwater from the Al-Khod Aquifer. The interdisciplinary nature of this research requires both hydrogeological and economic analysis. First, a hydrogeological investigation is carried out to determine the aquifer’s capacity to respond to demand during an emergency while ensuring the protection of the aquifer from seawater intrusion. Thus, the adequate pumping rate and localization of the wellfield are undertaken. This is followed by an economic evaluation and a comparison of the options to face the emergency situation through building concrete reservoirs or a better management of the aquifer and the expansion of the number of wells.

2. Methodology

From a methodological point of view, the hydrogeological part is based both on an analytical approach and a numerical approach. The analytical approach helps to assess the effect of intensive pumping from the aquifer during an emergency period. This effect is mainly related to the drawdown of the water table. The drawdown caused by pumping wells will be estimated using the water table fluctuation (WTF) method which is based on the principle that the decline/rise in the groundwater level is proportional to the volume of water being discharged/recharged (Sharda et al., 2006). The volume of groundwater discharge \( V_{gw} \) can be calculated by:

\[
V_{gw} = S \Delta WT A
\]  

where \( S \) is the storativity, which is the specific yield for an unconfined aquifer, \( \Delta WT \) is the change in water table depth and \( A \) is the downstream area of the dam.

The drawdown caused by the well’s discharge is given by:

\[
\Delta WT = V_{gw} / S A
\]  

For the numerical approach, a 3D groundwater model that represents the aquifer system in the Al-Khod area was designed to investigate the response of the aquifer to different abstraction rates using MODFLOW Processing Pro code (Chiang & Kinzelbach, 1993; Harbaugh et al., 2000). Figure 1
presents a schematic drawing that illustrates the finite difference mesh of the model’s aerial view. The main goal of the transient simulations is to test that the aquifer capacity can deliver the required volume of water during an emergency situation and make sure that the aquifer will not be irreversibly damaged (for example by groundwater quality deterioration due to seawater intrusion).

In reality, the aquifer receives input flow through the upstream boundary, which varies significantly with time and is difficult to quantify. For the steady-state simulation, a constant head boundary is assigned at the upstream boundary, which is located about 3 km on the upstream side of the Al-Khod dam, whereas no flow boundary is imposed for the transient simulations. A constant head boundary is assigned for the sea boundary downstream of the dam. The coastal line is located more than 7 km from the stress area where the pumping wells are installed. During the simulation process, the drawdown caused by the pumping wells did not reach the constant head boundary, which rules out the influence of the boundary conditions. The inactive zone (in the upper stream part of the study area) represents the crystalline ophiolitic rocks along the margins of the wadi which make the no-flow boundaries parallel to where groundwater generally flows. The flow domain is discretized with 20 × 50 m resolution level with finer mesh in the vicinity of the wellfield (10 × 25 m) (541 columns by 196 rows – 106,036 cells). The cell refinement was carried out for the stress area where pumping wells are located farther from the boundary conditions. The aquifer was simulated for three years with 46 stress periods. At the beginning, the model was run for steady-state flow and the computed head distribution was used as an initial head for the transient state model that simulates the impact of the different abstraction rates. Although the aquifer was recharged with a good amount of water in the area downstream of the dam, for the purpose of this study, a zero recharge was assigned during the simulation period of three years. An evapotranspiration rate of 2,000 mm/year with a 15 m extinction depth of the water table was assigned to the active zone of the simulated zone. Other hydraulic parameters are presented in Table 1.

The economic approach is based on estimating the cost of groundwater pumping compared to the cost of storing desalinated water in concrete reservoirs. The cost consists of summing the capital and variable
costs linked to the provision of groundwater up to the ground. Only the costs of increasing the groundwater supply to meet demand when there is an emergency are considered. Water distribution costs are not taken into consideration, as the existing wells are already connected to the pipeline network. We assume that the distribution cost will not affect the unit cost if we increase the water production when there is an emergency. Accordingly, we consider the following costs:

- Energy cost required to lift the groundwater.
- Annual capital costs allowances of pumps and wells drilling. The latter cost includes the cost of mobilizing the equipment; the cost of foot drilling, casing, and screening; the cost of other material involved; and the cost of pumping tests on wells whenever new wells are proposed.
- Operation and maintenance costs.
- Groundwater disinfection cost.

The energy cost of pumping water is a function of the yield, the depth to water, and the pump’s efficiency (Job, 2004). We assume an efficiency of 70% for all the pumps. The total energy cost for pumping groundwater up all the wells is computed as follows:

$$\sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \frac{E_i \times R}{F}$$

(3)

where $i$ is well index, $C_i$ is cost of pumping groundwater (US$), $E_i$ is energy required to lift water (kg m), $R$ is energy cost of pumping (US$/kWh), $F$ is pumps’ efficiency (considered to be 70%).

The energy, $E_i$, required to lift water from well $i$ is expressed in kg m and can be calculated as the product of the groundwater weight, $W_i$ (in kg) times the well’s depth, $D_i$ (in m), that is by using Equation (4):

$$E_i = W_i \times D_i$$

(4)

Or equivalently, by expressing $W_i$ in terms of the running hours, $T$, (in h) and pumping rate, $P_i$ (in m$^3$/mn) as:

$$E_i = P_i \times 1000 \times 60 \times T \times D_i$$

(5)
Finally, by using $E_i$ as derived above and the typical kg.m versus kWh conversion (as reported for example in (Job, 2004)), Equation (3) becomes:

$$\sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \frac{0.3766161 \times P_i \times 1000 \times 60 \times T \times D_i \times R}{138,254.933 \times F} \quad (6)$$

The annual allowance cost for the pumps and wells is calculated using Equation (7) based on an interest rate of 5% and a lifespan of 20 years.

$$\text{Annual capital cost} = \frac{C \times r \times (r + 1)^t}{(r + 1)^t - 1} \quad (7)$$

where, $C$ is capital cost, $R$ is interest rate, $T$ is lifespan.

The annual operation and maintenance costs are assumed to be 50% of the annual energy cost. Finally, the unit cost of pumping groundwater is computed by dividing the total costs by the volume of groundwater produced.

3. Hydrogeological aspects of the Al-Khod Wellfield

The Al-Khod Wellfield is the largest aquifer of Muscat and the only used source of groundwater in the city. During the period 2008–2011, an average of 6.83 Mm$^3$ of groundwater was pumped annually from the reservoir (PAEW, 2012, personal communication). The Al-Khod Wellfield is supported by a recharge dam that was built in 1985 with the double purpose of accelerating the recharge of the aquifer and protecting the urban area from floods. The recharge dam is designed to retain the surface runoff generated by precipitation. Given the high evapotranspiration and accumulation of sediments in the bottom of the dam, the collected fresh water is released downstream gradually in the next few days after the rainfall event to artificially recharge the aquifer (Bajjali, 2005). The cost of the dam was US$15.08 million (at constant 1985 US$) with a maximum storage capacity of 11 Mm$^3$ (MWR, 1998). It is estimated that 75 to 80 percent of the total captured volume recharges the groundwater (Al-Ajmi & Abdel Rahman, 2001). Thus the annual recharge from the dam to the aquifer is estimated at 2.59 Mm$^3$ with an average cost of the water of US$0.47 per m$^3$ (Al-Ajmi & Abdel Rahman, 2001). The recharge to the aquifer varies considerably according to the rainfall intensity. Recently Abdalla & Al-Rawahi (2013) estimated that during the decade 1997–2006 at least 64 Mm$^3$ reached the aquifer as recharge induced by the dam.

The Al-Khod Fan captures rainfall over a 1,635 km$^2$ area extending from the Al-Jabal Al-Akhdar plateau towards the coast (Figure 2). The Samail Catchment forms a gorge at the Old Al-Khod town and then spreads to form the main fan. The geology of the fan is composed of upper Quaternary alluvium gravels that constitute the main aquifer and is underlain by an impermeable ophiolitic sequence that marks a no-flow boundary. The aquifer is formed in predominantly alluvial sediments of different ages and compositions (mostly sand and gravel). The study area is mainly characterized by quaternary surficial deposits. Tertiary sedimentary cover exists at the narrow upstream part of the study area. The ophiolites (seeb formation is exposed on both sides of the wadi samail in the upstream boundary of the
study area. According to Abdalla & Al-Rawahi (2013) and references cited therein, the study area lithology can be grouped into three different successive alluviums: (1) the upper gravel unit: predominately composed of large-sized gravels including boulders, (2) the middle unit: discontinuous clayey gravel that is found in the form of lenses between the upper and lower gravel units, and (3) the lower unit: cemented gravel that is more compacted and conglomeratic. The aquifer is simulated in this study as one unconfined layer where the thickness gradually increases from the upstream to the coast of the sea. The thickness of the aquifer in the upstream end is set to be 50 m and linearly increases to 100 m at the sea coast (Abdalla & Al-Rawahi, 2013).

Groundwater flow generally mimics the surface water that flows from the upper to lower stream side towards the coast with a variable hydraulic gradient. Such a gradient is higher at the upper stream side where it accounts for about 0.01 and is reduced towards the sea. The gradient is strongly affected by the topographic variation as the upper stream area has a comparatively high elevation compared to the plain coastal area. Such topographic variation also influenced the depth to water table that shows deeper depth in the highlands compared to a shallower depth in the plain areas. The depth to water level varies between 5 m in the coastal zone to about 55 m in the highlands. The hydraulic head ranges in the dams area between 40 m above mean sea level to 0 m near the coast. Pumping test analyses in the Al-Khod Fan indicated a hydraulic conductivity of the unconfined aquifer ranging between 14 and 34 m/day and an average specific yield of 0.2.

3.1. Scenarios considered

According to the World Health Organization (WHO, 2011) the minimum standard for immediate relief in emergency situations is 20 l of water per capita per day for domestic use. However, for medium term survival need goes up to 70 l a day depending on the classification of priorities of each population. These priorities cover a larger category of needs like personal washing, clothes washing, cleaning, home sanitation, and waste disposal. In the Omani culture for instance, the need for
ablutions five times a day before praying is perceived as a second priority after drinking needs. Moreover, the WHO recommends the diversification of water resources for each use. Thus, water for sanitation cleaning does not have to be of the same quality as potable water.

The Al-Khod Wellfield is a protected area controlled by the PAEW and is composed of 59 wells among which only 48 are currently operational. The remaining 11 wells are out of use due to the damage caused by the flood during cyclone Gonu in 2007. During 2011, the total urban water supply in Muscat reached 326,000 m³/day for a total population of 775,875 inhabitants. Thus, the normal total urban water demand, including industrial, service, and domestic water per capita is estimated at 420 l/day. Zekri (2012) estimated the average domestic water demand in Muscat at 175 l/cap/day varying from a low of 140 l/cap/day in low-income districts to a high of 320 l/cap/day in high-income districts. During 2011, the urban water supplied from the Al-Khod aquifer was estimated at 6.83 Mm³/year or 18,895 m³/day. This corresponds to 24 l/cap/day at the current level of population. The 48 wells are currently operated during 6 hours/day at a pumping rate of 2,966 m³/h. The above figures show clearly that the capital city of Muscat can be supplied with enough groundwater from this particular wellfield during emergency situations to cover the immediate needs of its total population by providing more than the 20 litres recommended by the WHO (see Table 2). Furthermore, given an urban population growth of about 4.4%, the Al-Khod reservoir can guarantee an emergency groundwater supply of 20 l/cap/day up to the year 2016 when Muscat’s population is predicted to reach approximately 946,568 people. Although such a scenario is already in place, providing only 20 l/cap/day would result in huge economic losses due to the slowdown of the economic activity.

Four scenarios are examined in this paper. In all the four scenarios we assume that the current rate of pumping is maintained and more pumping will take place during emergency events. In addition to the current situation scenario (CS), Scenario 1 (S1) considers increasing the number of pumping hours during emergency events up to 14 h/day but maintaining the same number of operating wells and without any further investment in wells and pumps. In such a situation the aquifer could provide up to 54 l/cap/day during an emergency, which is slightly below the 70 l/cap/day recommended by WHO if the emergency lasts for few days. S1 thus represents the current level of preparedness of the city of Muscat to a water emergency situation. To increase the supply of water to 70 l/cap/day, Scenario 2 (S2) considers repairing the 11 damaged wells and increasing the number of pumping hours to 15 h/day. For the three scenarios, CS, S1 and S2, we will consider an emergency that will last for 10 days. We assume that the emergency will be repeated every year during three consecutive years. Furthermore, we assume that there will be no rainfall events during the same three years, so the aquifer will not be recharged. In other words, the pumping is assumed to take place during 10 consecutive

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Running hours</th>
<th>Pumping rate (m³/h)</th>
<th>Groundwater production from Al-Khod Wellfield (m³/day)</th>
<th>Potential water supply in emergency situation (l/cap/day)</th>
<th>% of the total water consumption in Muscat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current situation (CS)</td>
<td>6</td>
<td>2,966</td>
<td>18,895</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>Scenario 1 (S1)</td>
<td>14</td>
<td>2,966</td>
<td>42,623</td>
<td>54</td>
<td>13</td>
</tr>
<tr>
<td>Scenario 2 (S2)</td>
<td>15</td>
<td>3,669</td>
<td>51,371</td>
<td>71</td>
<td>16</td>
</tr>
<tr>
<td>Scenario 3 (S3)</td>
<td>14</td>
<td>15,429</td>
<td>216,000</td>
<td>278</td>
<td>66</td>
</tr>
</tbody>
</table>
days every year during three consecutive years for each one of the above-mentioned scenarios, with zero recharge. The objective of the simulations is to test for extreme situations consisting of repeated emergency situations and an absence of recharge due to drought conditions. So if the aquifer can respond positively in extreme cases then there is certainty that the city of Muscat will find enough emergency water in less constraining cases. Finally, Scenario 3 (S3) considers an abstraction from the aquifer of 216,000 m$^3$ per day for two consecutive days a year during three consecutive years. S3 is proposed to mimic the PAEW strategy of building concrete reservoirs in the Muscat region with a capacity of 216,000 m$^3$ to face an emergency situation. The main purpose of S3 is to test the capacity of the Al-Khod groundwater reservoir to respond to such demand and to compare the cost of supplying emergency water from the aquifer with the plan of the PAEW. S3 would require increasing the number of wells from 59 to 249. Thus, 190 new wells should be drilled downstream and upstream of the recharge dam of Al-Khod. S3 would allow the supply of 278 l/cap/day, far more than the strict domestic water demand of 175 l/cap/day, but still below the current total urban demand of 420 l/cap/day.

4. Results and discussion

4.1. Water table fluctuation

The WTF gives the drawdown in the downstream and upstream areas of the dam. Results for the four emergency scenarios are shown in Table 3. The results correspond to the drawdown at the end of the third year, accounting for the cumulated abstraction during three consecutive years and assuming no recharge. As shown in Table 3, the drawdown actually varies from 1.38 m for the current situation to 1.47 m for S3. The results show no significant differences among the scenarios considered.

One of the major uncertainties embedded in the WTF method lies in the estimate of the specific yield, which was carried out during this study on the basis of a pumping test conducted by the Ministry of Regional Municipalities and Water Resources (MRMWR) in the Al-Khod area (Macumber, 1997). Specific yield estimates cited in the literature show a great deal of variation depending on the aquifer’s grains’ size, shape, packing and sorting as well as the degree of heterogeneity and anisotropy. The Al-Khod alluvium aquifer is characterized by significant heterogeneity and anisotropy owing to its geological nature. Therefore, storativity estimates should be expanded to cover a wider area (vertically and spatially) than conducted by Macumber (1997) before the installation of additional wells. The WTF method was also used to estimate the groundwater recharge induced by the dam in the Al-Khod area for the decade, 1997–2006, and was found to be 64 Mm$^3$, which accounts for an average annual recharge of 6.4 Mm$^3$ (Abdalla & Al-Rawahi, 2013). This recharge volume approximately covers the current rate of annual abstraction from the aquifer.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cumulated volume of groundwater pumped (m$^3$) over 3 years</th>
<th>Storativity</th>
<th>Downstream area of the dam (m$^3$)</th>
<th>Water table drawdown (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current situation (CS)</td>
<td>20,690,025</td>
<td>0.2</td>
<td>75,000,000</td>
<td>1.38</td>
</tr>
<tr>
<td>Scenario 1 (S1)</td>
<td>20,817,894</td>
<td>0.2</td>
<td>75,000,000</td>
<td>1.39</td>
</tr>
<tr>
<td>Scenario 2 (S2)</td>
<td>20,844,138</td>
<td>0.2</td>
<td>75,000,000</td>
<td>1.39</td>
</tr>
<tr>
<td>Scenario 3 (S3)</td>
<td>21,986,025</td>
<td>0.2</td>
<td>75,000,000</td>
<td>1.47</td>
</tr>
</tbody>
</table>
Table 4 shows the average groundwater production in Muscat during the last four years. The average annual groundwater production in Muscat is about 7 Mm³/year, equivalent to 18.897 m³ per day. The Al-Khod reservoir thus covers 6% of the total urban water demand of the city, estimated at 119 Mm³/year, corresponding to 326,191 m³ per day. The regular pumping hours from the Al-Khod Wellfield are about 6 hours daily.

4.2. Numerical approach: transient simulations

Figure 3 shows the hydraulic head level along a selected row that passes through the middle zone of the wellfield for scenarios CS, S1 and S2 simulations at the end of each stressed 10 days of abstraction in year 1 plot (a), year 2 plot (b) and year 3 plot (c). During the model calibration, $K$ values were adjusted to obtain the best match between the measured and calculated head values. As the recharge value was considered 0 during the simulation (to avoid uncertainties in recharge estimates and to assess the aquifer abstraction at the most conservative approach) it was found that the model was sensitive to variations in $K$ values, which consequently produces variations in heads and drawdown. The simulated $K$ values closely match the values obtained by pumping tests conducted in five different sites in the study area (Macumber, 1997).

The drop in the water level increases significantly as the total abstraction volume increases with the highest drawdown occurring within the wellfield zone that is located between 2,600 and 3,200 m from the upstream boundary. The head drops from 22 m, at steady state, to an average value of 20 m at the end of the first abstraction event for CS, 19 m for S1, and 18.5 m for S3. By the end of the third pumping event in year 3, the head drops to 10.5 m for CS, 9.5 m for S1, and nearly 8 m for S2. The small differences in head drops among the different scenarios could be explained by the wider area of influence and the comparable volumes pumped. In fact, the area of influence gets larger as the abstracted volume increases. Figure 3 shows that the radius of influence reaches 3,000 m – in the horizontal dimension – by the end of pumping period 3 for S2 while it is 1,000 m for CS and S1. This implies that a larger volume of the aquifer contributes to the release from storage as a response to the abstraction. This is also clearly illustrated by comparing selected contour lines in the equipotential plots in Figure 4.

The drop in water table reaches nearly 14 m within the wellfield after three abstraction events in three years. Considering the necessity to supply water during an emergency situation, the level of water table decline is acceptable as we are only depleting 0.2 Mm³ in excess of the average annual recharge volume which is estimated by Abdalla & Al-Rawahi (2013) at 6.4 Mm³/year.

The curves and plots in Figures 3 and 4 show that the influence zone extends to a point 5.5 km upstream of the coastal boundary. Consequently, the assigned abstraction rate during the emergency situation would

<table>
<thead>
<tr>
<th>Water Source</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Khod wellfield</td>
<td>9,315,496</td>
<td>5,304,950</td>
<td>5,798,709</td>
<td>6,896,844</td>
</tr>
<tr>
<td>Other wells (Wadi Adai)</td>
<td></td>
<td></td>
<td></td>
<td>623</td>
</tr>
<tr>
<td>Desalinated water</td>
<td>87,226,366</td>
<td>99,606,413</td>
<td>100,217,565</td>
<td>112,162,322</td>
</tr>
<tr>
<td>Total water distributed in Muscat</td>
<td>96,541,862</td>
<td>104,911,363</td>
<td>106,016,274</td>
<td>119,059,789</td>
</tr>
<tr>
<td>Groundwater supply (%)</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Source: Public Authority of Electricity and Water (2012).
Fig. 3. Hydraulic head level across a section that passes through the middle of the abstraction zone at: (a) end of heavy abstraction period in year 1, (b) end of heavy abstraction period in year 2, (c) end of heavy abstraction period in year 3.
Fig. 4. Equipotential lines for steady state, CS, S1, and S2 at the end of abstraction period year 3.
not induce a significant effect in accelerating seawater intrusion. However, further investigation is required to assess more closely the dynamics of seawater in the downstream part of the aquifer system.

Scenario 3 simulates the ability of the aquifer to supply 216,000 m$^3$ per day during two consecutive days. We assume that the emergency event of two consecutive days is repeated every year during three consecutive years. In order to supply the above volume of water and based on historical information of constructed wells, a total number of 249 wells has been assigned to the model, out of which 190 wells are newly suggested. Other than the two days of heavy pumping, the abstraction continues as in the CS scenario. Figure 5 presents the head along the horizontal distance for a selected row that passes through the wellfield.

The water table drops by approximately 19 m at the upstream inlet of the study area after the third abstraction event in the third year. It is worth mentioning that the aquifer is treated as a reservoir of a finite volume of water subjected to a certain abstraction pattern and receiving zero input through all types of recharge during the three consecutive years of simulations. This assumption explains the severe drop in the water table which is expected to be lower in the case where recharge is assigned. Results show that there are no significant differences between the S2 and S3 scenarios. This is due to the fact that for S3 we assume a pumping over two days only while for S2 the pumping is in smaller volumes but lasts over longer periods of 10 days (Figures 3–6). The results obtained with the numerical approach are quite different to those obtained using the WTF method. The reason for the difference is found in the radius of influence of the pumping. The WTF considers a homogeneous effect all over the downstream and upstream area of the dam while the numerical approach takes into consideration the exact location of the wells and their area of influence.

![Fig. 5. Hydraulic head level along the horizontal distance for a selected row that passes through the middle of the abstraction zone (SP1 – end of first abstraction event, SP2 – end of second abstraction event, SP3 – end of third abstraction event).](https://iwaponline.com/wp/article-pdf/16/2/340/405318/340.pdf)
4.3. The economic approach

The drilling costs and pumps’ cost were obtained from the PAEW. The electricity cost was taken as 0.026 US$/kWh. Table 5 shows the total investment cost, the annual total cost and the cost per m$^3$ for each one of the four scenarios examined in this paper. The lowest investment corresponds to the SC and
S1 scenarios with US$1.422 million. Repairing the 11 damaged wells would bring the total investment for S2 to US$1.733 million. Scenario 3 would require the drilling of 190 new wells in the Al-Khod wellfield, thus bringing the total investment cost to US$5.728 million. Finally, the PAEW plan of building the concrete reservoirs, with a storage capacity of 216,000 m³, will require an investment estimated at US$104 million (Oman Observer, 2011). The investment cost in the concrete reservoirs represents 18 times the investment required to install the 190 new wells needed in S3. Furthermore, S3 will provide emergency water for two days at 216,000 m³ per day, which is double the volume of water stored in concrete reservoirs. The estimated capital investment costs corresponding to the use of the Al-Khod aquifer are quite reasonable to prepare for emergency situations.

The last row of Table 5 shows the cost per m³ for each scenario. The cost for the first three scenarios CS, S1 and S2 are US$0.18, US$0.65 and US$0.58 per m³, respectively. This cost is much lower than the total cost of supply of desalinated water, which is around US$1.82 per m³. Consequently, the city of Muscat can be supplied by enough emergency water for 10 consecutive days with volumes varying between 24 and 71 l/cap/day from the Al-Khod Wellfield at a low cost and requiring an investment of only US$1.733 million. Increasing the supply of water up to 278 l/cap/day is hydrogeologically feasible and economically sound as the cost per cubic metre is US$1.49 as shown in column 5, last row of Table 5. This cost is higher than the cost of urban water supply during regular conditions. This is due to the fact that the required investment of US$5.728 million will be used only during two days per year, which makes the cost of emergency water a little bit high. However, when compared with the alternative of building concrete reservoirs, the cost of supplying emergency water from the Al-Khod Aquifer is much lower. In fact, the cost of emergency water from surface concrete reservoirs is extremely high and is estimated at US$38.6/m³. This cost is more than 26 times higher than the cost of supplying water from the Al-Khod aquifer and is very close to the market price of bottled water. Nonetheless, the concrete reservoirs have at least one advantage over the Al-Khod aquifer. Water from the reservoirs can be released during the demand hours of the day, so supply can meet demand exactly, because the reservoirs are well located in the city and there will be no constraints related to the pipeline carrying capacity. Conversely, the wellfield is one single locus in the city, thus the existing pipelines cannot carry the 216,000 m³ during the few hours of the day during which demand is concentrated. For this reason the pumping from the aquifer should be spread over 24 hours to accommodate the carrying capacity of the pipelines. In such a case, the city district should carry out rotational water distribution. Note that the estimated cost for the provision of the 216,000 m³ was done on the basis of 14 h/day. It is

<table>
<thead>
<tr>
<th></th>
<th>Current situation</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Concrete reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater pumping rate (m³/h)</td>
<td>2,966</td>
<td>2,966</td>
<td>3,669</td>
<td>15,429</td>
<td>0</td>
</tr>
<tr>
<td>Pumping hours</td>
<td>6</td>
<td>14</td>
<td>15</td>
<td>14</td>
<td>n/a</td>
</tr>
<tr>
<td>Duration of operation (days)</td>
<td>365</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Daily supply (m³)</td>
<td>18,895</td>
<td>42,623</td>
<td>51,371</td>
<td>216,000</td>
<td>216,000</td>
</tr>
<tr>
<td>Consumption in Muscat (%)</td>
<td>6</td>
<td>13</td>
<td>16</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Capital cost (US$ million)</td>
<td>1.422</td>
<td>1.422</td>
<td>1.733</td>
<td>5.728</td>
<td>104</td>
</tr>
<tr>
<td>Annual cost (US$)</td>
<td>1,242,655</td>
<td>275,438</td>
<td>320,428</td>
<td>609,123</td>
<td>8,345,229</td>
</tr>
<tr>
<td>Unit cost (US$/m³)</td>
<td>0.18</td>
<td>0.65</td>
<td>0.58</td>
<td>1.49</td>
<td>38.6</td>
</tr>
</tbody>
</table>

Source: Our estimation based on data provided by PAEW (2012).
worth noting that if the pumping is spread over 24 hours the cost per m$^3$ will go down to US$0.93 instead of US$1.49/ m$^3$. Finally, the concrete reservoirs will allow several emergency events to be faced in a single year, as they just need to be refilled after every emergency event, while the response of the aquifer will be limited to two days only if the objective is to cover 66% of the regular demand. But in all cases, the aquifer can provide emergency water of 20 l/cap/day during 365 days up to year 2016 according to the estimate of population growth in Muscat. Beyond that date more investment is needed to drill and equip new wells to ensure the minimum water emergency per capita. Given the high cost of concrete reservoirs, the PAEW might think of decentralizing the water storage at house levels by requiring every new house to build a reservoir on top of the roof to face water emergencies. The other option is to reduce the daily pumping from the aquifer during drought years to conserve more water for emergency situation. Finally, the PAEW might even think about recharging the aquifer with desalinated water. All these options require further investigation according to rainfall data and recharge cost.

5. Conclusions

This paper focuses on the identification of a water resource alternative to face a water emergency in Muscat City. The Al-Khod Aquifer is a potential water resource alternative because of its hydrogeological characteristics; it is readily connected to the distribution network and currently supplies 6% of the total water demand in Muscat on a daily basis. The numerical simulations of groundwater pumping, in the absence of recharge, have shown that the aquifer can supply emergency water in a safe way without apparent risk of seawater intrusion. From an economic perspective, the results show that Muscat can efficiently supply emergency water for up to 10 consecutive days with volumes varying between 24 and 71 l/cap/day from the Al-Khod Wellfield at a low cost varying from US$0.18 to 0.65 per m$^3$ and requiring a minor investment of US$1.733 million. Such a supply represents 6 to 16% of the total water demand in normal conditions. The supply of emergency water can be assured for three consecutive years, with a single emergency event of 10 days per year even in the complete absence of the aquifer recharge.

Increasing the supply of emergency water to cover up to 66% of the total regular demand is technically feasible and would require an investment of US$5.728 million and would bring the cost to US$1.49 per m$^3$ if water is pumped from the aquifer or an investment of US$104 million and a cost of US$38.6 per m$^3$ for concrete reservoirs. Water will be provided for two days if pumped from the aquifer and only one day for the concrete reservoirs. Overall, the results of economic studies revealed a low unit cost for groundwater and an extremely high cost of concrete reservoirs’ water storage due to the high capital cost to be used during only few days a year. The cost per cubic metre of using concrete reservoirs is close to bottled water market price. Finally, the PAEW might think of decentralizing the water storage at house levels by requiring new houses to be equipped with reservoirs on the roofs to cope with water emergencies.

In terms of sustainability, producing groundwater might have negative impacts on the water table and might drive salinity intrusion. Thus, a more detailed simulation model should be used to further investigate this risk. Moreover, further studies should evaluate potential remediation to water depletion after emergency groundwater exploitation. In this context, it is important to consider reducing the daily pumping from the aquifer to lower levels. A second option considers ASR, a technique for artificially
recharging the aquifer for recovery during emergency periods. Recently, ASR and other MAR technologies have been increasingly used to cope with long-term water emergencies (Maliva & Missimer, 2010).

According to Missimer et al. (2012), the ASR is probably the most cost-effective technology to allow strategic water storage. This facility is currently present in several parts of the world with more than 100 sites in the USA, varying from pilot projects to full operations (USGS, 2012). Even in arid countries like the United Arab Emirates, a similar project has been adopted for supplying 90 days’ water emergency reservoir to Abu Dhabi (Dawoud, 2011).

By reducing or eliminating the need for constructing dams and expensive reservoirs, ASR systems are usually considered to be environmentally friendly. However, implementing this technique can be a challenging question because of the hydraulic and geochemical constraints of the aquifer in which the system would be developed, such as high hydraulic conductivity, high specific yield, a large volume of unsaturated sediments, etc. (Missimer et al., 2012). All these options require further investigation according to rainfall data and recharge cost using a stochastic rather than a deterministic approach.

Acknowledgements

The authors acknowledge the financial support of Water Research Centre at Sultan Qaboos University, Oman through the research grant# IG/DVC/WRC/10/01 and the PAEW (Public Authority for Electricity and Water) for their close cooperation and availability in providing us with the available data.

References


Received 17 December 2012; accepted in revised form 20 September 2013. Available online 6 November 2013