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2014 Environ. Res. Lett. 9 075008

(http://iopscience.iop.org/1748-9326/9/7/075008)

OPEN ACCESS
IOP Publishing

Environmental Research Letters

Environ. Res. Lett. 9 (2014) 075008 (6pp)

doi:10.1088/1748-9326/9/7/075008

Water management during climate change using aquifer storage and recovery of stormwater in a dunefield in western Saudi Arabia

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Received 14 February 2014, revised 27 June 2014
Accepted for publication 2 July 2014
Published 28 July 2014

Abstract

An average of less than 50 mm yr^{-1} of rainfall occurs in the hyperarid region of central Western Saudi Arabia. Climate change is projected to create greater variation in rainfall accumulation with more intense rainfall and flood events and longer duration droughts. To manage climate change and variability in ephemeral stream basins, dams are being constructed across wadi channels to capture stormwater, but a large percentage of this stored water is lost to evaporation. A dam/reservoir system located in Wadi Al Murwani in Western Saudi Arabia was recently constructed and is expected to contain a maximum stored water volume of 150 million m^3. A hydrologic assessment of a dunefield lying 45 km downstream was conducted to evaluate its potential use for aquifer storage and recovery of the reservoir water. A 110 m elevation difference between the base of the dam and the upper level of the dunefield occurs, allowing conveyance of the water from the reservoir to the dunefield storage site by gravity feed without pumping, making the recharge system extremely energy efficient. Aquifer storage and recovery coupled with dams would allow water management during extreme droughts and climate change and has widespread potential application in arid regions.

Keywords: climate change, aquifer storage and recovery, wadi hydrology, wadi dams, dunefields

1. Introduction

Rainfall events occur sparsely in arid regions and commonly produce flash flood events in surface drainage networks with most of the water lost to evapotranspiration before it can recharge the underlying alluvial aquifer system. Recharge occurs primarily as channel loss during floods (Abdulrazzak and Morel-Seytoux 1983, Sorman and Abdulrazzak 1993, Al-Shaibani 2008, Maliva and Missimer 2012). Investigation of channel loss recharge in western Saudi Arabia wadi systems shows that between 3 and 11 percent of the annual rainfall actually recharges the aquifer underlying the wadis (Missimer *et al* 2012). In order to capture a greater percentage of the stormwater within the wadi channels, dams are constructed to impound the water and to facilitate recharge to the adjacent alluvial aquifer system. Wadi reservoirs can add a significant quantity of recharge to the aquifer system, but the free surface evaporation loss from the reservoir can range from 5 to 80% of the water on an annual basis (Al-Turbak 1989, Al-Muttair *et al* 1994, Bajjali 2005, Sharda *et al* 2006, Al Maktoumi 2013). Therefore, to conserve and manage the water in the reservoirs, it would be prudent to use aquifer storage and recovery of reservoir water in the alluvial aquifer or in another suitable downstream aquifer.

Artificial recharge of storm water and treated wastewater into dune aquifer systems has been used as a means of storing and treating water for later use in the Netherlands (Roosma and Stakelbeek 1990), Belgium (Vandenbohede *et al* 2009), Vietnam (Thoa *et al* 2006), Australia (Dillon 2005), and the United Arab Emirates (Dawoud 2012). Dune aquifers have rather uniform hydraulic conductivity with a relatively high specific yield which make them ideal for use in development of aquifer storage and recovery (ASR) systems.

Climate models predict that the Middle East region by the middle of the 21st century will have a relatively small and statistically insignificant change in precipitation, but a quite robust temperature increase in the range of 1–1.5 °K (Zhang *et al* 2005, Evans 2009, AlSarmi and Washington 2011, Almazroui 2013, Intergovernmental Panel on Climate Change (IPCC) 2013). The downscaling calculations conducted in the scope of the Coordinated Regional Climate Downscaling Experiment (CORDEX) for the Middle-East region with a 25 km resolution show that for emission scenarios RCP4.5 and RCP8.5 surface air temperature over the Arabian Peninsula increases by 1.5–2 K by the middle of this century. Although precipitation does not show a statistically significant trend, the soil moisture will go down because of increased evaporation. The increase in rainfall extremes, longer drought periods, and reduced soil moisture will cause a significant depletion of water resources in the region (reduced recharge).

A key strategy to mitigate these changes is to increase storage of water during isolated flash floods or short-duration wet periods. To maintain or improve water capture and storage in many arid lands, it will be necessary to construct dams across ephemeral streams and to link the dams to ASR schemes to product effective storage. Storage can occur within alluvial aquifers lying beneath the ephemeral channels or in suitable geologic environments near created reservoirs. One significant environment capable of storing large quantities of water is dunefields.

A dam and reservoir was recently constructed in Wadi Al Murwani with an estimated annual contribution to the water supply of about 31 million m^3 (Lemaire 2009). The water is fresh and of generally good quality and about half of this water will be treated at a downstream drinking water treatment plant for potable use and the remaining water will be stored in the reservoir with a large percentage being lost to free-surface evaporation. The calculated potential evaporation loss using the Penman-Monteith method is 4.7–6 m $year^{-1}$ (Allen *et al* 1998). In this study, the hydraulic properties of a dunefield located 45 km downstream of the Murwani dam and a conveyance scheme were evaluated in order to determine the feasibility of designing an ASR system to provide storage of the reservoir water to avoid evaporative loss.

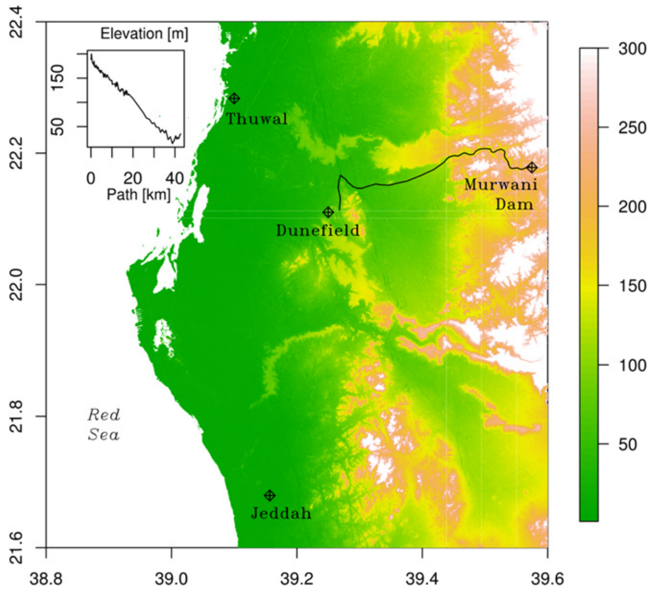

Figure 1. Location of the Murwani Reservoir and the dunefield site.

2. Background

Wadi Khulays, located 50 km northeast from Jeddah (figure 1), used to be a major supply of water and agricultural products for Jeddah (Lemaire 2009, Sagga 1998). It consists of several valleys that drain from the western slopes of the Arabian Shield into the wadi Khulays plain. The underlying wadi aquifer system consists of Quaternary-age deposits of alluvium, alluvial terraces and aeolian sand, laying on Pre-Cambrian-age Arabian Shield rocks (Lemaire 2009). Wadis Fatimah and Khulays collectively provided the first large-scale water supply for Jeddah, and it is estimated that at full capacity, after an intense rain event, they could serve up to 5% of the current city annual needs. Water demand in the Khulays region is estimated to be of 1540 m^3 d^{-1} which meets the needs of over 20 000 people.

The Al Murwani Dam project was initiated in 2004, by the National Water Company-Riyadh and consists of the construction of a surface reservoir, a groundwater dam, and a drinking water treatment plant (DWTP). The dam (figure 2, left) is designed to make an average annual water supply contribution of 31.5 million m^3. The capacity of the DWTP will be 40 000 m^3 day^{-1} (uses only one-half of storage). Since the wadi system is located within cratonic Precambrian shield rocks, the area bordering the reservoir has a very low permeability which is not conducive to recharge.

The wadi Khulays dunefield lies on a slightly sloped surface west of the Khulays village, about 45 km downstream from the Murwani dam. A prevailing northwesterly wind creates the dunefield with the sand source being alluvial deposits on a sheet wash plain. Inside the dunefield, there is no significant local relief and vegetation is sparse (figure 2, right). The dunefield covers an area of approximately 25 km^2 with about 10% of the area containing naturally stabilized dunes and the remaining area covered by migrating barchan

Figure 2. Murwani Dam in the Wadi Khulays drainage system after a flood (left) and the Wadi Khulays dunefield site (right).

dunes. The thickness of unsaturated sand in the dunes ranges from 5 to 10 m depending upon location.

3. Methods

The Wadi Khulays dunefield sediments were evaluated using standard laboratory methods for the determination of hydraulic conductivity, grain size distribution and porosity. About 50 samples were collected along two transects each about 800 m long. Samples were taken from the upper 5 to 10 cm at different locations on the dunes covering a cross-section of the dune from the slip face to windward slope. An additional 24 samples were collected from dune crests covering a surface area of about 37 500 m^2. Grain size and hydraulic properties of the sediments were measured using standard laboratory techniques (Tanner and Balsillie 1995, American Society for Testing and Materials (ASTM) 1995, 2006). The grain size distribution of the 24 samples collected from the dune crests were obtained, and the hydraulic conductivity for these samples was determined from the grain size distribution by use of an empirical method described in Rosas *et al* (2013).

The storage capacity of the dune aquifer system was obtained by measuring the average thickness of the dunefield relative to the desert pavement and estimating the specific yield. The extinction depth for diffusive evaporation losses in the dunefield was also considered for the estimation of the available storage volume and was measured in other local research (Mughal *et al* 2012). Porosity of the samples was obtained from the ratio of water volume added to a 250 mL cylinder in which the sample is poured, similar to the procedure done in the permeameter to avoid air entrapment. The specific yield is assumed to be 5–10% less than the measured porosity.

The available water flow rate considering a gravity-feed system from the reservoir to the dunefield was obtained by applying the Hazen-Williams equation for pipe friction losses, considering a 45 km pipeline with a diameter of 50 cm and a course following the wadi channel (buried to avoid damage) with an elevation difference of 110 m between the dam base and the dunefield.

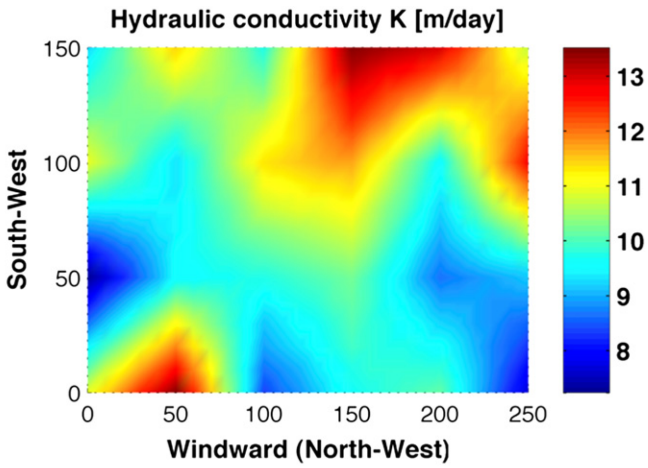

Figure 3. Spatial distribution of estimated hydraulic conductivity within the dunefield.

4. Results

4.1. Dunefield aquifer properties

The grain size properties along the cross-section of the dunes revealed values of d_{10} from 0.06 mm up to 0.085 mm, with a mean of 0.07 mm. The dune sands showed a mean mud percentage of about 2%, with values up to 6–8% found within the interdune areas. Porosity was relatively uniform with a mean of 0.4 and values ranging from 0.37 to 0.43. The main body of the dune had a hydraulic conductivity about 9 m day^{-1}, with values ranging from 7 to 14 m day^{-1}. Samples collected from the interdune areas have lower hydraulic conductivity values, with a mean of 6 m day^{-1} and ranging from 4 to 10 m day^{-1}.

The patterns along the cross-section of the dunes were similar for the d_{10} value, the mud percentage and the hydraulic conductivity; dune crests showed higher hydraulic conductivity and d_{10} values, as well as the lowest mud content, which were progressively lower (hydraulic conductivity and d_{10}) and higher (mud percentage) towards the lower parts of the dune. The spatial distribution of the hydraulic conductivity along the dune crests is shown in figure 3. Samples collected from the desert pavement showed a mud percentage

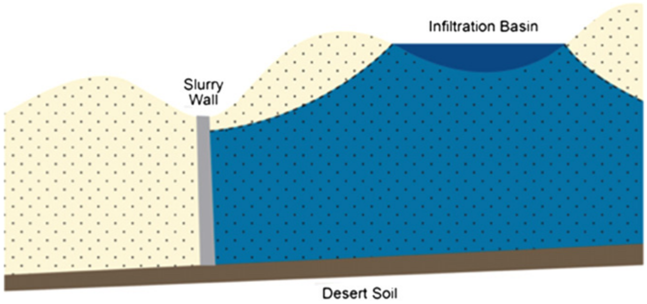

Figure 4. Design concept of the dune aquifer stormwater storage system.

of more than 50%, suggesting that the system is basally-confined by this low-permeability layer.

4.2. Design of gravity-fed ASR system

The conceptual design for the ASR system at the dune aquifer system is shown in figure 4. Because of the westerly slope of the desert pavement at the dunefield, a bentonite slurry wall would be constructed on the western side of the dune aquifer system to prevent water losses downstream. The bentonite slurry wall would have an approximate height of 7 m. The interdune areas can be easily adapted to work as low cost infiltration basins by surrounding them along the sides with impermeable materials and by allowing them to fill with sand as the added water stabilizes the system. The base of the dune system contains a low permeability, estimated to be <0.01 m day^{-1}. This 'desert pavement' is a compacted siliciclastic unit containing mud and in some places is cemented with carbonate or silica.

The dune aquifer system would store stormwater collected at the Murwani reservoir, which would be conveyed by gravity flow through a 45 km pipeline following the wadi channel. The stormwater would be collected from an intake system at the reservoir consisting of a series of gates that could be opened at different depths depending on the seasonal water levels within the reservoir. The desired intake depth should be about 1 to 2 m below surface in order to guarantee the lowest turbidity possible to avoid clogging of the aquifer during recharge. The flow through the pipeline will have to be regulated with breaking valves to protect it against high velocities that could cause water hammer effects.

4.3. Capacity and system use analysis

The available water in the reservoir is about half the total annual contribution or about 40 000 m^3 day^{-1}. Flow capacity of the system was determined by the friction losses within the pipeline considering a gravity-fed system requiring no pumps. The flow rate was calculated by applying the Hazen-Williams equation to a 50 cm diameter pipeline 45 km long with an average elevation loss of -2.75 m km^{-1} and a friction factor of 150, typical for HDPE pipe. The resulting flow rate is about 20 000 m^3 day^{-1}; sufficient to supply ten times the demand of the Khulays population considering a recovery factor of 80%.

The capacity of the dune aquifer system is a function of the specific yield, the evaporation extinction depth and the aquifer thickness. The spatial distribution of the latter is difficult to evaluate because of the irregular shape of the dunes. An average thickness was obtained by measuring the elevation difference between the interdune areas and the desert pavement. The specific yield was assumed to be 5% less than the average porosity, yielding a value of about 0.38. The extinction depth of the dunefield was measured to be 1 m below the surface (Mughal *et al* 2012). The appropriate area for storage within the dunefield, considering the density of dunes and the presence of interdune areas, was found to be of about 0.6 km^2 at the eastern side of the dunefield. Using this information, an estimation of the storage capacity of the dunefield using a recovery factor 80% yields 1.27 million m^3 of available water storage.

5. Discussion

Excess stormwater retained within the Murwani Reservoir is subject to evaporation loss (up to 6 m yr^{-1}). Water entering the reservoir typically contains high concentrations of silt and clay particles (mud) that are deposited on the reservoir floor, reducing recharge potential of the connected aquifer. Conveyance of reservoir water downstream to the dune ASR system would save water and optimize use.

A sufficient water flow rate can be achieved without pumping, by taking advantage of the elevation difference between the reservoir and the dunefield. The potential flow rate for a 50 cm diameter pipe was estimated to be $>$20 000 m^3 day^{-1}. A higher flow rate may be achieved if desired by using a larger diameter pipeline; however, the final design diameter must be optimized according to the desired flow rate and demand. The pipeline design must also include breaking valves to avoid water hammer effects with sudden flow changes that could occur during operation.

The natural interdune areas in the dunefield could be adapted to be used as infiltration basins. The dune sands have a sufficient hydraulic conductivity to make infiltration basins feasible. Clogging of the infiltration basins could be mitigated by regular maintenance involving drying by sun and wind action with some possible scrapping or surface sediment removal (alternative basin recharge using two basins).

The dune aquifer system is confined at the bottom by low-permeability desert pavement sediments. The desert pavement at the wadi Khulays dunefield has a slight slope towards the west, necessitating the construction of a slurry wall to contain the water stored in the aquifer. The wall height and shape should be designed to fully contain the water stored in the aquifer.

The use of this gravity fed ASR system would enable storage of excess stormwater into a dunefield located 50 km from one of the most important cities in the Kingdom, the city of Jeddah or could be used to supply a small village in the wadi as well as number small date farms. There is a pipeline that connects the water treatment plant at the dam to Jeddah. The ASR system could be connected to this pipeline.

The main source of freshwater for Jeddah and other metropolitan areas in the Kingdom is seawater desalination. Water desalination plants are subject to emergency shutdowns caused by a number of unfortunate natural events, such as red tides, or oil spills and mechanical failures. An alternative, reliable supply of freshwater is needed to meet the demands during emergency situations or to help meet seasonal peak demands. Stormwater captured at the Murwani Reservoir has a high elevation, allowing water to be transferred by gravity downstream to meet these demands. The Wadi Khulays dunefield may be used as an emergency storage facility for Jeddah and northern communities such as Khulays, Thuwal, KAUST and KAEC, with the advantage of treating the water by percolation through the dune sands and to significantly reduce the evaporation losses. The cost of this water would be significantly lower than desalinated seawater and the system described could potentially supply the annual needs of a village with a population of about 7000. The relative cost of using desalinated seawater compared to the ASR system to supply freshwater to a small village is 3 to 5 times greater than stormwater use, not considering the dam cost in the analysis.

While the dunefield ASR scheme described has a relatively small capacity, the concept could be up-scaled where a dunefield or other receiving aquifer type has a greater unsaturated thickness. Gravity fed systems from dam-reservoirs could be used to recharge coastal dune aquifers in some regions to create water supplies and to alleviate saltwater intrusion or to recharge sensitive coastal aquifers, such as the karst aquifers along the Levant coast of Syria and Lebanon or many countries bounding the southern coast of the Mediterranean Sea.

6. Conclusions

An important potential supply of freshwater in arid regions occurs within alluvial aquifers that are recharged after flash floods running through wadi channels. Only a small fraction of the precipitation in these storm events recharges the aquifer system. Climate change will bring storms of greater intensity, more climate variability, and longer duration droughts, thereby necessitating the creation of more storage. Retention structures in the form of dams have been constructed to facilitate the percolation of stormwater into the aquifer system for centuries. However, the sedimentation in these reservoirs with time reduces the recharge of water into adjacent parts of the alluvial aquifer system. Furthermore, water stored in these facilities is subject to evaporation and contamination with corresponding water loss being significant.

Dune aquifer systems, such as the Wadi Khulays dunefield, have been proven to be potential candidates for aquifer storage and recovery. The hydraulic properties of this site were estimated using standard techniques and the study revealed that the Wadi Khulays dunefield could be used to store up to 1 million m^3 of stormwater, by using a gravity system with water being transported from the Murwani Reservoir. Storing water at this location could be used to create strategic water storage for the city of Jeddah, for seasonal supply for coastal communities north of Jeddah, for emergency demands or to meet seasonal peak demands within the framework of ASR. Construction and operational costs are minimal since the infrastructure needed is a 45 km pipeline, a slurry wall, shallow production wells, and the adaptation of the interdune areas as infiltration basins, while the maintenance of the infiltration basins is done by natural processes or scraping after drying. Therefore, this system would benefit local needs by use of a water source that is less expensive (up to 80% less) to operate and has lower energy consumption compared to the use of desalinated seawater.

The concept of linking a wadi dam with downstream aquifer storage and recovery systems is particularly applicable to systems in which the rock bounding the reservoir has poor permeability that does not allow significant horizontal recharge. Also, it has rather broad application in all arid regions where there are very high free-surface evaporation rates. The concept of using the natural slope from a dam to convey water downstream via pipes to storage, without having to use pumps, has widespread applications in many global regions, particularly in developing nations wherein electric energy is not plentiful. Specific applications could be used in Oman and the United Arab Emirates where wadi dams have been constructed. Similar systems could be developed in many locations in North Africa, and in other arid regions that contain ephemeral streams within a relatively high relief setting that have potential down-gradient storage aquifers located near population centers.

Acknowledgements

The funding for this research was provided by the Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia and from discretionary faculty funds provided by the university. Field assistance was provided by Samir Al-Mashharawi. One figure was drafted by Gina Lipor.

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