Water resource management towards a sustainable water budget in the United Arab Emirates

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Abstract. Water in the United Arab Emirates (UAE) is scarce and in addition to its life-sustaining role it is a limiting economic resource for the country. The current article presents a comprehensive study of the water resources of the UAE and analyses the water usage in the different economic sectors in order to provide suggestions for a sustainable water budget. We highlight the relation between Ophiolitic formations and the potential of natural groundwater contamination from hexavalent chromium, as well as the potential for offshore fresh water exploration below the Arabian Gulf seabed. The water flows in the various economic sectors of the UAE are analysed and compared to other countries in the region, the desert Southwestern states of USA and to EU countries in order to identify those sectors of the economy where the introduction of best practices and efficient water technologies can be of maximum impact. Given the scarcity of water the water budget of the country needs to be curtailed by at least a half to allow for expansion of industrial activities.

1. Introduction
The United Arab Emirates (UAE) occupies a corner of the Arabian Peninsula created about 50 million years ago when it separated from Africa, opening up and filling with sea water the area known today as Red Sea. UAE has a hyper-arid climate with mean precipitation rate from 40 mm/yr, in the southern desert region, to 160 mm/yr, in the north-eastern mountainous region, and standard deviation that often exceeds the mean annual precipitation. The evaporation rate is between 2 to 3 m/yr, whereas precipitation takes place from December to mid-April and varies widely spatially and temporally. The country has no surface water resources, 82% of its groundwater is saline or brackish, and desalination meets less than half of the annual water demand. The UAE has a very dynamic economy, which is expected to return to over 4% real GDP growth by 2018, and a population, consisting by over 85% of expatriates, which is expected to almost double by 2030. The aim of the current paper is to evaluate the water resources and to analyse the water usage in the different economic sectors of the UAE in order to provide suggestions for a water budget that is compatible with the water supply and needs of the country.

2. Water resources of the UAE
The UAE lacks any surface water bodies and the largely brackish groundwater constitutes the only available water resource. The main UAE aquifers and the quality of water are summarized in figure 1.

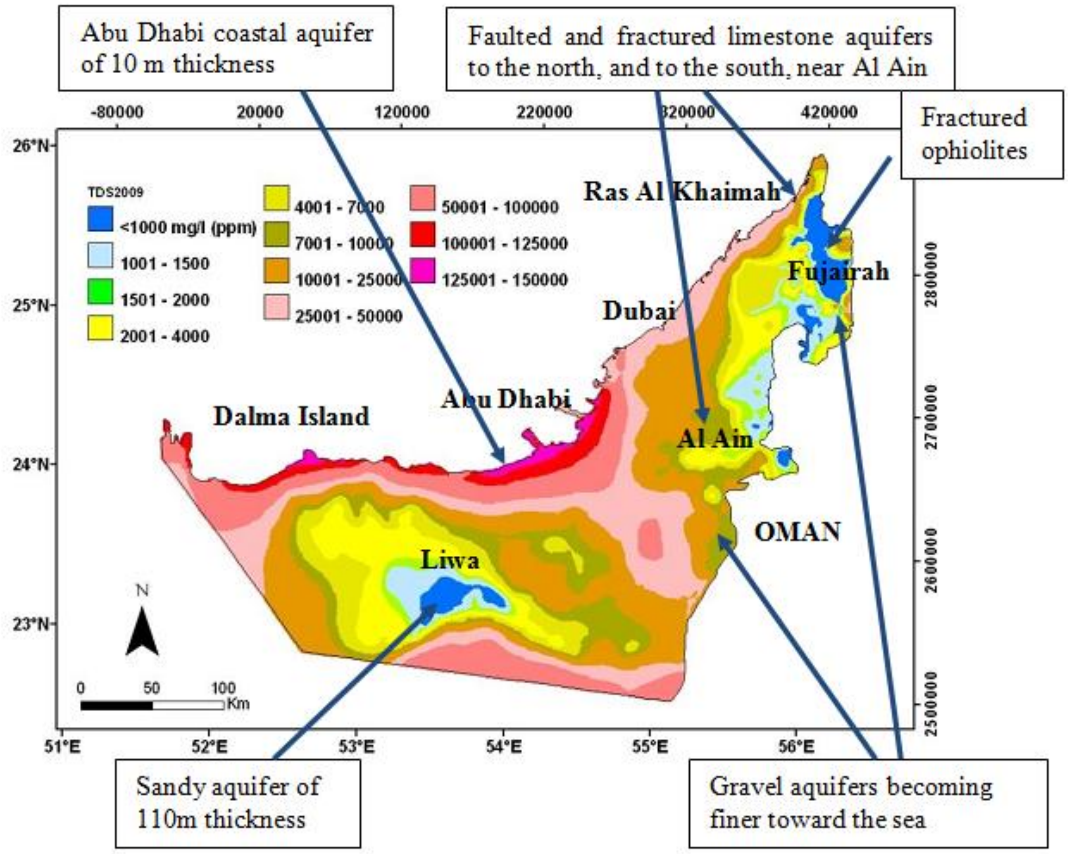


Figure 1. Groundwater salinity map and main aquifers of the UAE (adapted from [1,2]).

Figure 1 showing the distribution of total dissolved solids (TDS) in groundwater, indicates that coastal sabkha aquifers and the majority of interior aquifers are either brine (over 100,000 ppm), saline (10,000 ppm to 100,000 pm), or brackish (1,500 ppm to 10,000 ppm), and hence inappropriate even for irrigation. Only the areas shown in light and dark blue can be considered suitable, given the UN Food and Agriculture Organization (FAO) recommendation of 450 ppm<TDS<2,000 ppm for water in irrigation, with restrictions on the use of crops, or the U.S. National Secondary Drinking Water Regulations of TDS<500 ppm in drinking water, respectively. In addition, part of the Liwa aquifer is protected and the top, sandy aquifer, bound about 150m below ground surface by an aquiclude, and containing consecutively from the bottom up saline, brackish, and fresh water is now being artificially recharged with desalinated water to create an emergency strategic reserve of potable water for Abu Dhabi [3]. It was announced in January 2018 that three-months of water reserves had been built up in the Liwa aquifer.

The only other significant area of fresh water is located northeast (figure 1, in dark blue), and is naturally recharged at an estimated rate of 90 – 140 Mm^3/yr through the Oman aquifers that are replenished by mountain rains [4]. However, ophiolitic formations, in the Al Hajar mountain range in the northeast, are probably not safe water sources because of the presence of chromite, which has been linked to natural Cr-VI pollution. Several authors [5-7] have found that Cr-III that is tied in the chromite, and which is insoluble and has poor water mobility can turn, naturally, in locations of low precipitation and poor organic content, into Cr-VI under certain geochemical conditions. These include H+ consumption during Si-rock dissolution by slow-moving groundwater, desorption of Cr-III from the chromite, which is assisted by the increase of the PH, and passage of the insoluble Cr-III into the water. The only natural oxidizing agent of Cr-III in PH<9 are oxides of Mn, found in ophiolites as mineral coatings and in rock fractures. When Cr-III is transported to Mn-sites it is transformed into

Cr-VI and concentrations exceeding 50 μg/l have been observed in water within a few days. The US national Maximum Contaminant Level (MCL) regulation for total chromium in drinking water is 0.1 mg/l (100 ppb) since 1991. Because of concerns regarding the presence of hexavalent chromium in groundwater, the U.S. Department of Health and Human Services [8] conducted a multi-year study to assess its potential carcinogenic effects in drinking water, whereas the California Environmental Protection Agency promulgated a Public Health Goal (PHG) for hexavalent chromium in drinking water of 0.02 ppb [9].

The excessive groundwater overdraft and the consequent water table drops have led many wells to become dry. Overdraft has occurred because of the large groundwater quantities extracted primarily for agriculture - there exist about 80,000 well permits only in the Emirate of Abu Dhabi [4] - and forestry, but also due to the continuous dewatering activities during construction in the two major cities of UAE, Abu Dhabi and Dubai, where the water table is found, in many cases, within one meter from land surface. This has raised concerns about the potential for contamination, land subsidence [10] and the effect of increased groundwater ionic concentrations on buildings' foundations [11]. Areas of maximum groundwater depletion concentrate on the upper eastern and southern parts of the country [4] with the UAE Ministry of Environment and Water [2] estimating groundwater level drops of ten meters per decade until the mid-nineties, and about 70m total drop after that period.

Mineral and thermal springs are evidence of long travel times of groundwater from deep layers, during which dissolution of higher layers of evaporites takes place as well as radioactive decay of uranium, which may be a reason for elevated groundwater temperatures [12]. Distances travelled can be large and groundwater from the Liwa Oasis has been seen to consist of paleo-moisture originating from the Indian Ocean [13]. Groundwater springs also appear in the sea. The marine springs of Dalma Island discharge fresh water from openings in the sea floor and contain groundwater originating from the Zagros Mountains, Southern Iran, and reaching UAE after having travelled under the Arabian Gulf. The reliability of this fresh water source is documented by the consistent habitation of the island for long periods of time. The Abu Dhabi Island Archaeological Survey (ADIAS) has found 5,000 BC settlements at Marawah and Dalma islands, and Beech and Elders [14] postulated that the "…community living on Dalma was perhaps to a certain extent self-sustained…" and remained there possibly until rising sea-levels, reaching a maximum of 1m to 3m above modern sea levels, forced abandonment of these locations at about 4,000 to 2,000 BC. Thus, offshore fresh water exploration constitutes a way to potentially expand the UAE water reserves [15,16].

The UAE as many desert locations suffers from flash-flooding (figure 2). Surface runoff emanates from the neighboring Sultanate of Oman, and flowing onto gravel and boulder-filled channels crosses into the UAE through the Al Hajar Mountain group. The total estimated catchment flow is about 7.6 Mm^3/yr of surface flow and 31 Mm^3/yr groundwater throughflow [17].

Figure 2. Flash-flooding in Fujairah, UAE (photos by the authors, October 2016).

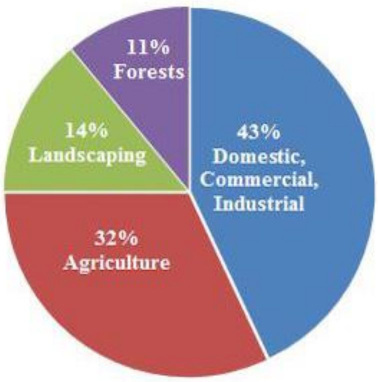
Finally, in 2013 there existed 130 small dams and levees in the UAE, constructed, primarily, for flood protection purposes, and capable of storing 120 Mm^3 of water. However, the 2013 estimated total dammed water was only about 16 Mm^3, representing about three days of emergency water reserves for domestic consumption, for the country.

3. Methodology

In the subsequent sections we analyse the water usage in the UAE per economic sector in order to arrive at suggestions toward a sustainable water budget. In terms of agricultural water use the method of analysis is to calculate the annual volume of water per agriculturally productive acre and to compare this with equivalent measures at comparable climatically regions. The number of litres that is consumed by a person per day is the metric utilized to evaluate the domestic water consumption in the country. Subsequently comparisons are provided with the desert states in the USA and other countries in the region, taking into account GDP and population projections to identify threats and risks to this use. There is lack of detailed water usage data to allow analysis, assessment of the consumption patterns, and suggestions per specific industrial and commercial activity. Specifically, for construction, which is the highest-contributing economic activity to the GDP of the country, proxies are suggested that utilize total water withdrawals per contractor's monetary value output.

4. Analysis of water consumption in the UAE

The most recent data from the UAE Ministry of Environment and Water [2] show that total water consumption in 2013 stood at 4,200 Mm^3. Of this, 42% was supplied by desalination, 44% (about 1,850 Mm^3) by groundwater, 14% (about 584 Mm^3) by treated wastewater, and less than 1% by surface-impounded water at 16 Mm^3, respectively. The distribution of water use in the various economic sectors of the UAE [2] and of Abu Dhabi [4] is shown in figure 3.



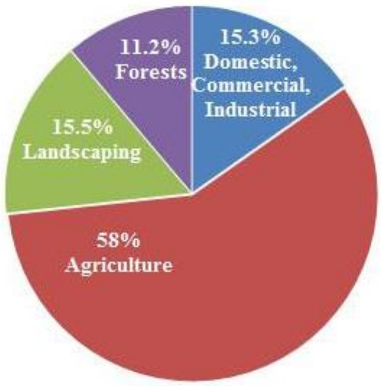


Figure 3. (a) Water demand in the UAE, and (b) in Abu Dhabi, per economic activity.

Desalinated water had reached about 1,750 Mm^3 in 2013 and is produced by 33 desalination plants [2]. The population increase and the needs for water have led to a tripling of desalination production during the first decade of this century. As the only essentially source of water desalination is expected to be heavily stressed in the near future by competing demands from various economic sectors and the high cost of energy associated with this activity.

4.1. Agricultural water use

The charts in figure 3 indicate the importance of the Emirate in agriculture, and its lower water consumption, relative to the national average, in the domestic, industrial, and commercial sectors. According to these at the national level 1,344 Mm^3 of water were used by agriculture, which consisted of 35,704 farms covering an area of about 260,090 acres. The MOEW-reported [2] water use corresponds to an average application rate of 5,167 m^3 per agriculturally productive acre. The same source indicates that agriculture that emerged as an economic sector in the early 1970s utilized sprinkler, drip, and fountain irrigation systems up to 91% by 2011.

Most of the agriculture concentrates on the Emirate of Abu Dhabi, which covers 87% of the UAE's total area, and contains about 24,000 farms covering an area of approximately 186,000 acres. Higher than the national water consumption figures were given by Environment Agency-Abu Dhabi (EAD) for agricultural water use and groundwater abstractions in 2009. According to EAD [4] groundwater accounted for: 95% of the total 1,805 Mm^3 of water utilized by agriculture (the rest being supplied by desalination); 23% from a total of 482 Mm^3 for parks (46% by desalination and 31% by recycled water); and 347 Mm^3 for forests. Thus, total groundwater abstraction, 2,172 Mm^3, and agricultural water use, 1,805 Mm^3, by EAD [4] differ from the corresponding numbers of 1,850 Mm^3, and 1,344 Mm^3, respectively, reported for the whole country by the MOEW [2]. If one were to use the EAD figures then the average application rate almost doubles for Abu Dhabi compared to the national average, and is 9,704 m^3 of water annually per agriculturally productive acre.

In comparison the irrigated land in USA consisted of 62.4 million acres, consuming 2,553 m^3 of water annually per agriculturally productive acre. Of the desert Southwestern states Arizona with 993,000 irrigated acres, New Mexico with 878,000 irrigated acres, Texas with 5.92 million irrigated acres, and Utah with 1.34 million irrigated acres used 6,352 m^3, 4,243 m^3, 1,591 m^3, and 3,330 m^3 of water annually per agriculturally productive acre, respectively [18]. So, in relation to US states with relatively comparable climatic and geomorphologic conditions, the UAE, although at the high end, is within the range of their water application rates, with the application rate at Abu Dhabi clearly an outlier.

Given that the maximum annual recharge rate of the UAE aquifers is about 140-150 Mm^3 compared to annual groundwater abstractions of close to 2,000 Mm^3, this intense water utilization is not sustainable. Hence the UAE needs to target an annual agricultural water use of about 1,000 Mm^3 in order to balance water resources and irrigation needs and to implement water strategies, with different scenarios of expected yields from a variety of appropriate crops, and water pricing schemes that would guarantee a desired target rate of water use [19,20].

4.2. Domestic water use

The MOEW [2] does not differentiate the water use between domestic, commercial, and industrial sectors nor does it provide a breakdown of water use for different industrial sectors. Figure 3 yields a combined water use for all these three economic sectors of 1,806 Mm^3. EAD [4] reported 332 Mm^3 of water domestic purposes in 2009, all provided by desalination. The population of Abu Dhabi that year was 1,572,906 people [21], which returns a domestic water use of 578 lt/capita/day.

Average domestic water use in USA in 2010 was 88 gal/capita/day (333 lt/capita/day). Considering the desert southwest, Arizona had an estimated domestic water consumption of 556 lt/capita/day; New Mexico (341 lt/capita/day; Texas 348 lt/capita/day; and Utah 632 lt/capita/day [18].

Compared to other countries in the Arabian Peninsula UAE was shown by the UN [22] to consume, instead, about 400 lt/capita/day, almost double of the domestic water consumption in Saudi Arabia, Lebanon, and Egypt, which had a fraction of the UAE's GDP per capita, but having a lower consumption than Kuwait's 450 lt/capita/day, Qatar's 500 lt/capita/day and Bahrain's 670 lt/capita/day. One needs to account in the domestic water use the fact that, in 2012, 16 million tourists visited the UAE. Thus, although domestic water consumption is high in the UAE, it does not appear exorbitant when compared to desert USA states and similar Arabian Gulf countries. However, considering the available water resources of the country, water pricing policies and water savings measures must be implemented to curtail domestic water consumption. This becomes even more pressing given the projected population increase in the UAE. Thus, for example, the 2015 population of the Emirate of Abu Dhabi [23] was 2,784,490 with an average annual growth rate of 7.3% between the years 2005 and 2015. If the same population growth rate were to continue this would result in almost tripling of the Abu Dhabi population by 2030. In terms of Dubai, its 2015 population [24] was 2,446,675 people with a growth rate of 5%, annually, and with its population expected to double by 2030. Thus, the increase in the UAE population will increase the pressure on desalination and may force decisions on the marketization of water and the relative water allocation between agricultural and municipal sectors [25].

4.3. Commercial, and industrial water use

An estimate of the national commercial and industrial water use can be arrived by multiplying the UN domestic water consumption data [22] and an estimate of the 2013 population, subtract this domestic consumption from the combined 1,806 Mm ^{3} reported by MOEW [2] to arrive at about 400 Mm ^{3} of water for the commercial and industrial sectors. The corresponding quantities in 2009 for Abu Dhabi by EAD [4] were 79 Mm ^{3} for the commercial and 66 Mm ^{3} for the industrial sector, respectively. Thus, these sectors accounted for 9.5% of the water, nationally, and 4.6% for the Emirate of Abu Dhabi, respectively.

Data from the Eurostat [26] show that in most countries of the European Union (EU) more than 50% of the fresh water was utilized in the manufacturing industry and for electricity production. These industries received also the majority of the recycled water stream with Sweden and the Netherlands topping the list of the European countries exploiting this water source. In terms of construction the highest water use in the EU was done in the Netherlands, Germany, Hungary and Bulgaria.

Data also exist from several European countries that can be used as proxies to estimate water use during construction phases in the UAE. In the UK for example, the total water used for construction activities was estimated by considering information from two separate sources. The first was a 2007 Envirowise study, which provided water volumes in construction per GBP million contractor's output. Another source was the mains water withdrawals tabulated by the UK Environment Agency. Combining these two separate data sources yielded an estimate of about 147m^3 of water used for construction purposes for every million GBP of space created in the UK [27].

For USA public water supplies for industrial uses were not reported for 2010 [18, Industrial, p. 34], only the self-supplied quantities being quoted. In terms of mining and self-supplied water for industrial operations (but excluding thermoelectric power generation) water consumption in the desert Southwestern US states [18, tables 10 and 11] stood as follows: Arizona utilized about 137.5 Mm ^{3} of water annually; New Mexico 66.5 Mm ^{3}; Texas 3,178 Mm ^{3}; and Utah 508 Mm ^{3} of water annually.

In conclusion, as the UAE economy moves away from oil towards manufacturing and other industrial activities the current share of the total water budget for commercial and industrial operations is inadequate compared to similar economies and is expected to increase significantly if the economy of the country is to grow according to predictions.

5. Summary and conclusions

The UAE constitutes a model of economic and social development in the Gulf Region with intense efforts to diversify its economy from oil production, followed by a population expansion. However, this evolution is threatened by its scarce water resources needed for sustenance of the current and the 2030-predicted population, and to drive new economic activities. The current article presents a comprehensive assessment of the water resources and water usage in the different economic sections of the UAE in order to provide suggestions toward a sustainable water budget.

The majority of the surface aquifers in the UAE contain saline or brackish water, which is unsuitable for irrigation or drinking. An important area of fresh groundwater exists in the northeast of the country. However, the presence of Ophiolitic formations in that region and their potential to create natural groundwater contamination from hexavalent chromium needs to be carefully considered. The geologic history of the UAE indicates that there is potential for significant fresh groundwater reserves to exist below the Arabian Gulf seabed and offshore groundwater exploration may constitute a way to extent the fresh water reserves of the country.

There exist some issues of data discrepancies reported from various official sources, as well as lack of detailed information on the water consumption by individual economic sectors. A thorough understanding of the water use in sub-categories of the commercial, industrial, and energy sectors is needed in order to identify deficiencies and to implement industry-specific water savings measures.

The average annual, national application rate of 5,167 m^3 per agriculturally productive acre is almost double of the equivalent 2,553 m^3 of the water used annually in the USA, but within the range, although at the high end, of the application rates used in the desert Southwestern states of Arizona, New Mexico, Texas, and Utah. The 9,704 m^3 of water used per agriculturally productive acre in the Emirate of Abu Dhabi is an outlier. Although, this comparison may oversimplify different climatic and soil characteristics found in these regions it indicates, nevertheless, that significant water savings should be targeted for agriculture. Given that in 2009 Abu Dhabi was already utilizing desalination to meet 5% of its agricultural water needs, and that increased demands on desalination will be placed by industrial activities and the population it becomes critical, to reduce water application rate per acre, concentrate on less water-intense crops, and substitute desalinated by recycled water in agriculture.

The per capita domestic water use in the Emirate of Abu Dhabi of 578 lt/day, according to data by the Environment Agency-Abu Dhabi [4], or the national per capita domestic water use of 400 lt/day, according to the United Nations [22], is high compared to the available water resources of the country, but not unreasonable compared to the desert Southwestern US states and to other countries in the region with similar per capita GDP.

Finally, in the absence of data that would provide a detailed breakdown of the water use in different categories of the industrial and commercial sectors it is not possible to conduct a comparison with the EU or the USA. In particular for the construction sector, which in the UAE has taken the form of nation-building, a potential solution is to use the value and volume of the constructed space as proxies to estimate current and future quantities of consumed water.

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