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Groundwater economics in arid regions: Abu Dhabi Emirate case study

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ABSTRACT

In arid and semiarid regions, groundwater is scarce, limited and non-renewable but it is a vital resource that supports a variety of societal uses and benefits. With growing demand due to extension in agriculture and domestic sectors, groundwater resources are coming under greater pressure following reductions in surface water yields, due to reduced rainfall and over abstraction. Over abstraction due to increasing demand or climate, change-driven changes in spatial distribution of precipitation can result in a reduction in groundwater quantity and deterioration in quality. Increased population and economic development inevitably result in an increase in the generation of waste products and, if disposed of inappropriately, these have the potential to contaminate groundwater resources and lead to degradation and economic costs. This creates the need for a higher profile regulatory and management regime for this limited groundwater resources. Given climate variability and the environmental challenges, the importance of groundwater as a resource is ever increasing in arid regions. Abu Dhabi emirate is an arid region facing the challenges of renewable fresh water scarcity. In the year 2014, groundwater use accounts for about 63% of total water demand in the Emirate, with the remaining portion of demand being met through desalinated (28%) and recycled water (9%). Groundwater is used mainly for agriculture, forestry sectors, which together have accounted for over 95% of total annual withdrawals. Agriculture alone has accounted for 80% of total recent withdrawals. The total present annual abstraction from the groundwater aquifers is about 2,300 million cubic meters. However, the annual natural recharge to the aquifer systems ranges between 90 and 140 million cubic meters only. Numerous wellfields abstract groundwater of various qualities and in some areas massive over-abstraction has resulted in alarming groundwater declines and a severe deterioration in groundwater quality. This policy has led to a reduction in the groundwater table which caused numerous shallow wells to go dry and impact the farms. It is estimated that there is still 641 km³ groundwater resources available (saline, brackish and fresh), but only less than 3% of this reserve is fresh and, based on current abstraction rates, both fresh and brackish reserves will be depleted within the next 50 years. The purpose of this study is to assess the economic value of groundwater resources in the Abu Dhabi Emirate. A dynamic hydro-economic optimization model was developed and applied. This model evaluates the net benefits and economic tradeoffs across alternative water by simulating groundwater reserves and withdrawals for different regions, time periods, and development sectors. Using this model, we estimate the value of Abu Dhabi's groundwater resources (in total and per cubic meter).

Keywords: Groundwater; Recharge; Groundwater economics; Groundwater management; Desalination; Treated wastewater

1. Introduction

As an arid region with very limited renewable water resources, groundwater gains increasing recognition in Abu Dhabi Emirate, UAE. So, many governmental initiatives and projects were planned to protect and use efficiently this precious resource. Abu Dhabi Emirate is located in an arid region with scarce renewable freshwater resources. 50 years ago, the emirate freshwater requirements were met solely from groundwater resources through over pumping from non-renewable aquifer systems. Due to the deterioration of the groundwater quality and the severe drop in groundwater

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tables, the government started to invest in desalination industry. The construction of the first desalination plant in 1960 marked a milestone in the development of the Emirate allowing Abu Dhabi to grow well above the limitations imposed by its water scarcity. As per the 2015 water resources statistics, 63% of Abu Dhabi's water supply came from groundwater, 29% from desalinated water and 8% from treated wastewater as shown in Fig. 1. Only 3% of the emirate groundwater reserves are fresh, 18% brackish and 79% saline. That means that only 18% of the total groundwater reserve is usable, the remaining 79% cannot be used before treatment (desalination) as shown in Fig. 2. Water demand in Abu Dhabi Emirate has increased significantly over the last decade. The largest demand sectors are agriculture, forests and parks followed by the residential and government sectors. Recent previous studies indicated that the main driving forces are population growth, economic development and changes in lifestyle that have increased the water demand for irrigation, human consumption and industrial processes. Several public policies intensified this water demand. Some of these are the expansion of agriculture with a view to protecting the rural heritage and making Abu Dhabi less dependent on imported food; desert greening policies with a view to providing a habitat for wild animals and stabilizing the sand around roads; development of public parks to enhance the aesthetic value of outdoor spaces; residential and commercial megaprojects with a view to catering for the local population and a growing tourism industry; and industrialization driven by the government's diversification effort into non-oil industries. In 2015, the water demand was driven by six sectors: those that used mainly groundwater for irrigation: agriculture (50%), forestry (12%) and public realm amenities (10%); and those that mainly used desalinated water for a combination of indoor and outdoor purposes: residential (16%); commercial (6.5%) and government (4.5%). Some marginal demand also came from industry (0.5%) and others (0.5%) as shown in Fig. 3.

The shallow unconsolidated aquifers are the most common and productive aquifers and comprise both recent

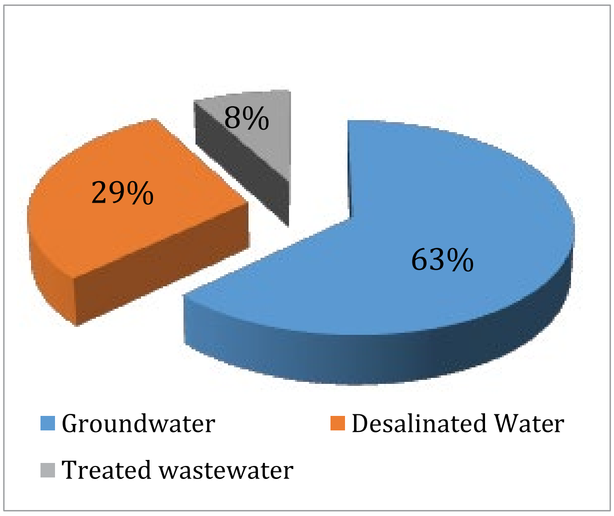

Fig. 1. water Resources in Abu Dhabi Emirate.

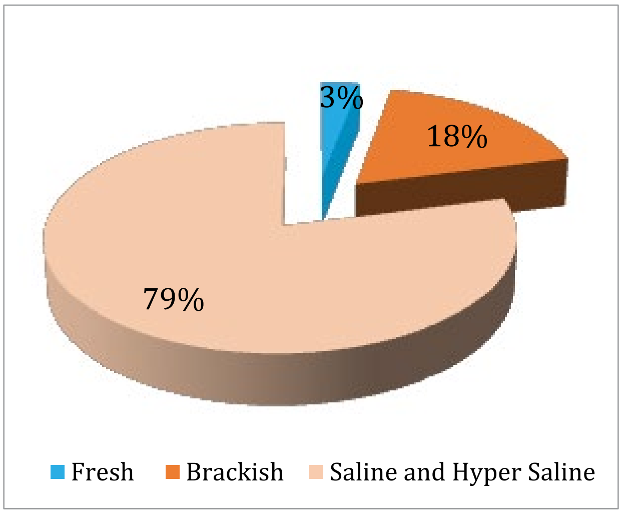

Fig. 2. Groundwater Resources in Abu Dhabi Emirate.

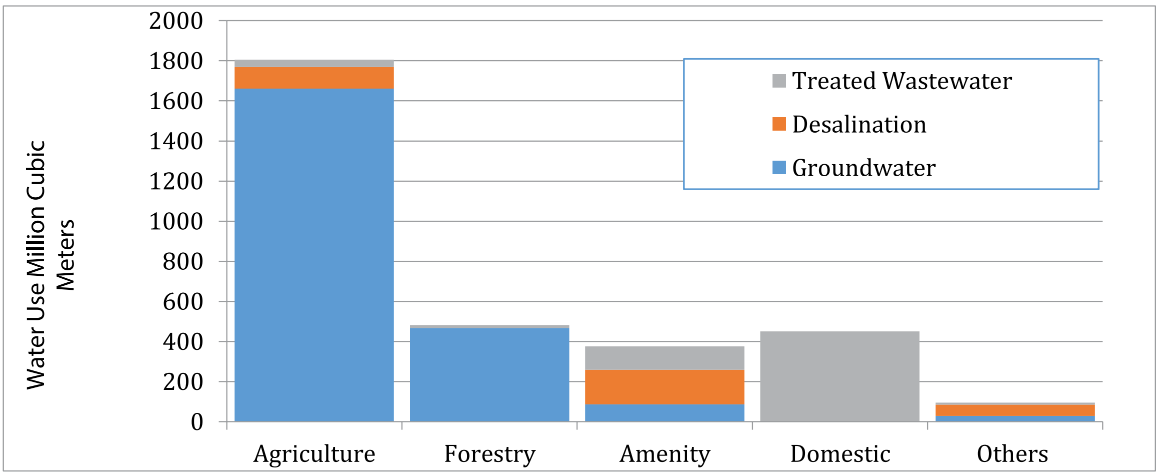

Fig. 3. Water resources demand in Abu Dhabi Emirate (2015).

sand dunes and alluvial deposits of varying age. Bedrock aquifers occur throughout the Emirate and are largely carbonate deposits laid down in shallow marine seas. Their potential as aquifers has not yet been fully proven; the aquifers occur generally at significant depth and have not been explored or exploited anywhere near to the same extent as the unconsolidated aquifers described above. Fig. 4 shows the hydrogeological map of Abu Dhabi Emirate. At the current rates of extraction, both fresh and brackish groundwater resources (about 2.07 billion cubic meters) will be exhausted in the next 50 years if the abstraction continues as it is today. Thus, it will be critical to ensure that groundwater resources are managed sustainably and in particular, the use of groundwater for irrigated agriculture, which is the largest consumer, has to be moderated by employing innovative strategies. Groundwater salinity is the concentration of dissolved solids in a defined unit of groundwater expressed as milligrams per litre. Most of the groundwater in the surficial aquifers is brackish, saline or brine. EAD considers most of groundwater in Abu Dhabi as 'useable' groundwater less than or equal to total dissolved solids not exceeding 15,000 mg/L (Dawoud, 2014). Beside the evident impact of evaporation on groundwater salinity, unsustainable groundwater abstraction contributed to the higher salinity causing movement of saline water upward as shown in Fig. 5 (EAD, 2016).

2. Groundwater economics

Groundwater aquifer systems are very important contributors to Abu Dhabi economy. It contributes to the economy through producing fresh and brackish groundwater for use in various forms of production and consumption, and through supporting a range of ecosystem functions, which in turn deliver valuable ecosystem services into the economy. Many factors affect the economic value of groundwater

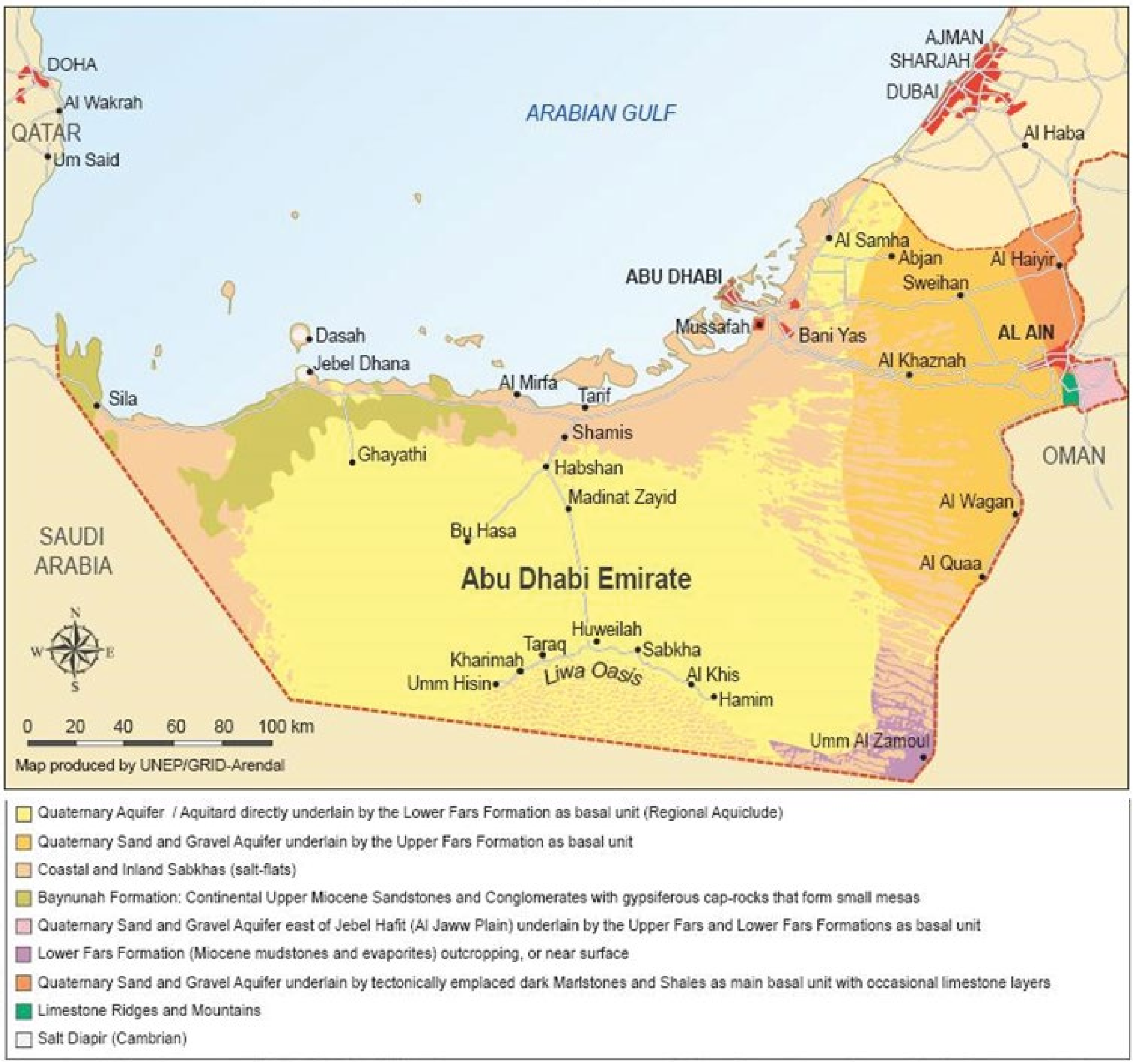

Fig. 4. Hydrogeological map of Abu Dhabi Emirate.

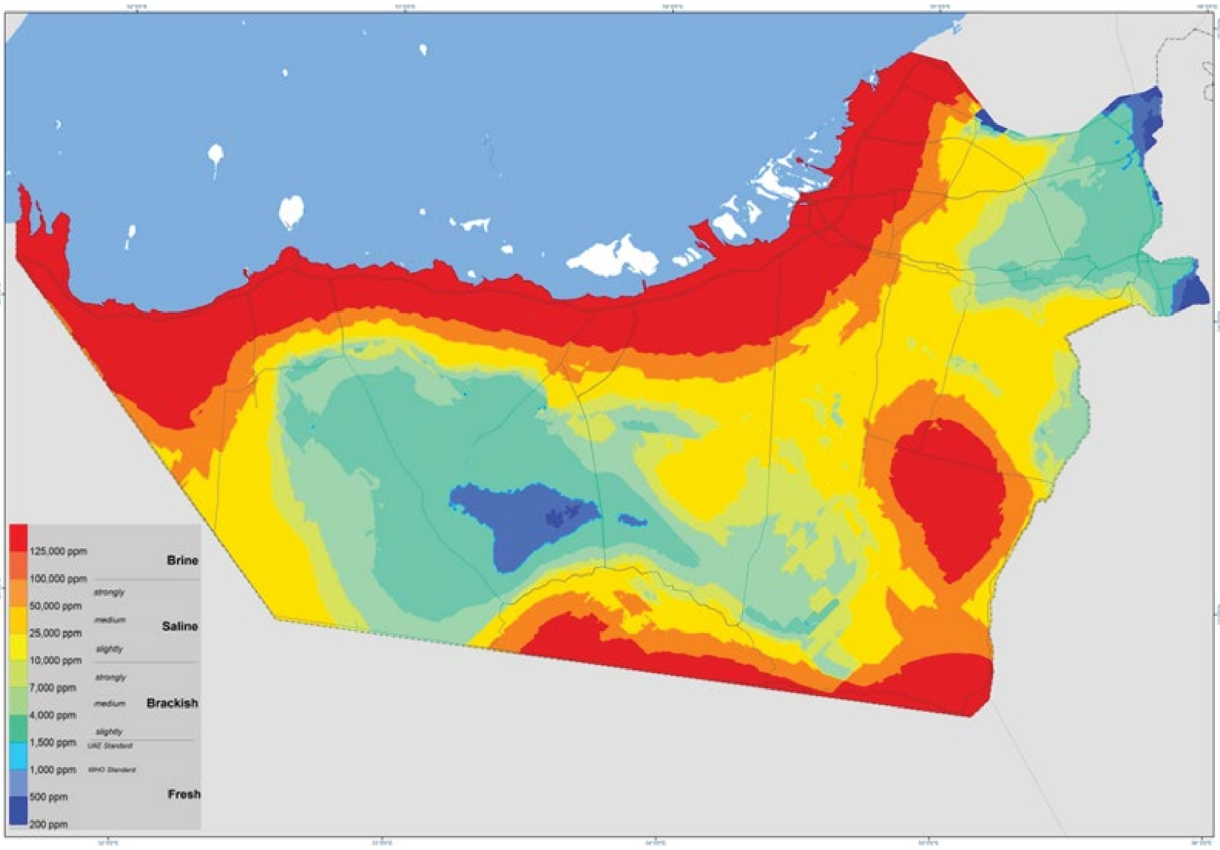

Fig. 5. Groundwater salinity in Abu Dhabi Emirate (2016).

aquifer systems in Abu Dhabi. So, it is important to distinguish between the concepts of natural asset value and ecosystem service value. Ecosystem services are the benefits that humans receive from ecosystems, and are officially defined by the Millennium Ecosystems Assessment. Ecosystems produce these ecosystem services on an annual basis, and the value of these services accrue on a country's national income statement, and should ideally be measured through indicators that relate to gross domestic product (GDP). Thus the total value of aquifer ecosystem services can be thought of to contribute to green GDP. Aquifers themselves are natural assets. They form part of the ecological infrastructure of a country and the values of these assets theoretically appear on a country's natural resources balance sheet. The asset value can be determined by calculating the net present value (NPV) of the perpetual stream of aquifer ecosystem services delivered. Natural assets of this kind are characterized by complex inter-temporal and inter-ecosystem service characteristics. For instance, although overharvesting an aquifer may yield short-term benefits (on the income statement), it will reduce the asset value of the aquifer if it reduces the future water yield of the aquifer and/or if it reduces the delivery of ecosystem services supported by the aquifer. Thus it is important to understand the links between the hydrogeology of aquifers systems and the groundwater-dependent ecosystems that are linked thereto. Only by incorporating these wide range of factors will be possible to comprehend the significance of the extractive and non-extractive uses of groundwater. Qureshi et al. (2012) present a diagram to elaborate groundwater resource linkages/interactions as shown in Fig. 6.

These in essence represent the supply side considerations relating to the assessment of groundwater resources. Simply put, they determine the cost of extraction, the amount of water available to be extracted, the quality of the water available and the linkages of groundwater to other

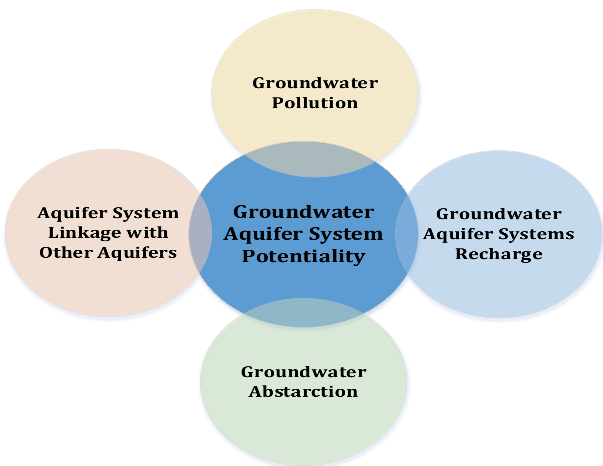

Fig. 6. Hydrogeological considerations relevant GW economic assessment.

ecosystems that be of value, and that may be affected by abstraction. These include surface water impacts of groundwater abstraction (Qureshi et al. 2012, Katic and Grafton 2012). Thus, in order to understand the value of aquifers, we need to understand the full range of ecosystem services which it supports (including ground water provisioning). Another consideration in the value of aquifers is the relative scarcity of water. Where surface water resources are abundant, sufficient and inexpensive compared with groundwater, it is likely that aquifers play a relatively small role in the economy, and thus the value of the aquifer will be low. This situation may vary geographically, and may also change over time as water demand increases. The long residence time of groundwater in and of itself provides a particular kind of economic value. It gives groundwater a greater annual assurance of supply relative to surface water sources (Colvin 2009). The quantity of water captured by a surface water storage scheme such as a dam is the function of two or three (possible) seasons of rainfall and runoff. The amount of water contained within an aquifer is the function of a much longer set of consecutive seasons of rainfall, runoff and infiltration; thus the water content of an aquifer is muted from the fluctuation of the climatic cycles, a property which makes groundwater resources particularly resilient to climatic shifts and periods of drought. This adds a strong inter-temporal consideration to the abstraction and use of groundwater resources. Qureshi et al. (2012) states that "from an economic perspective optimal (aquifer) management is defined by the rate of extraction over time and space that maximizes the NPV of benefits minus costs, subject to the physical hydrology of the aquifer and the related water sources". The marginal value of water can be represented with a downward sloping demand curve, which illustrates that inverse relationship between price and quantity demanded. An important consideration derived from the simple curve is that users allocate water to the highest value uses first and subsequently to lower value uses (Qureshi et al. 2012, Hansen 2012). This has very powerful implications for scenarios where is water resources are becoming particularly scarce. This also implies that the marginal value decreases as more value is used. Under such circumstance, the market forces will begin to reallocate water to users with a relatively higher marginal use values. The assessment of the available supply of groundwater is an important step towards sustainable groundwater use. Of course, this needs to be placed into the context of groundwater demand, and the uses that are driving that demand.

3. Materials and methods

Due to over abstraction of non-renewable groundwater resource, its quality was deteriorated and there was a severe drop in groundwater tables during the last 20 years as shown in Fig. 5. However it is still the main resource for irrigation and contributes with about 62% out of total water use in the emirate (Heal 2003). It is important to value the groundwater resources economically to understand its value against other alternatives water resources (Baker and Murray 2009). Groundwater use value is equal to the market returns from agriculture and the ecosystem services provided by forests: carbon storage, wildlife habitat, cultural heritage, and road protection; non-use value equal to the cost of establishing the strategic reserve as insurance against future threats or shocks (Brown 1997). To estimate the value of groundwater resources in Abu Dhabi we apply a hydroeconomic framework that integrates key features of the groundwater hydrology into an economic valuation analysis. This framework accounts for important interconnections between human systems (including the economy) and groundwater systems. Using this framework, we apply a dynamic (i.e., multiperiod) optimization approach to assess the value of groundwater resources in Abu Dhabi. The fundamentals of this approach are shown in Fig. 7. It assumes that users will continue to extract additional units of water as long as the value they get from the additional unit (marginal value) exceeds its price. The stopping point is where the marginal value equals price. Therefore, the optimal price (and marginal value) of groundwater is what maximizes the long-term value of the groundwater asset (stock value). If it is set too low, users will not manage groundwater efficiently and high extraction rates will lead to rapid depletion of the aquifer or quality degradation to the point that remaining groundwater is not economically usable. Using a dynamic optimization approach, we project both the optimal price (marginal value) of water withdrawals (in United Arab Emirates dirhams [AED] per cubic meter) and the corresponding total value of groundwater stocks. Dividing the total stock value by the size of the current stock, we will also estimate the average value per unit of groundwater stock (in AED per cubic meter). It is important to emphasize that, even though they are both measured in AED per cubic meter, the optimal price (flow value) and the average stock value are not the same measure of value. In a dynamic setting, it is also essential to compare values for groundwater use across periods. This is particularly true for resources that do not replenish themselves quickly, such that the availability of the resource for future users depends critically on how much is used in the present. To address these intertemporal tradeoffs in groundwater use, we apply a conventional "discounting" approach. Under this approach, benefits received (and costs incurred) farther in future periods receive less weight than those received closer to the present. For our analysis, we apply a 3% annual rate of discount, which is on the lower end but still within the range of conventional practices.

3.1. Model representation of groundwater hydrology

A key component of the hydro-economic model is the physical model representing groundwater stocks and processes in Abu Dhabi. Although there are many dimensions and complexities associated with the hydrogeology of the region, we develop a simplified representation of the groundwater system, to make best use of limited data regarding existing groundwater resources and address the needs of the analysis. The first step in developing the hydrological model was to designate general water use zones (sub-regions) that (1) represent areas with different average groundwater availability and quality conditions and (2) match the spatial resolution and dimensions of the economic model. Fig. 5 provides a map depicting the zones designated for our analysis. Each zone was then further subdivided into three layers representing different salinity conditions—fresh

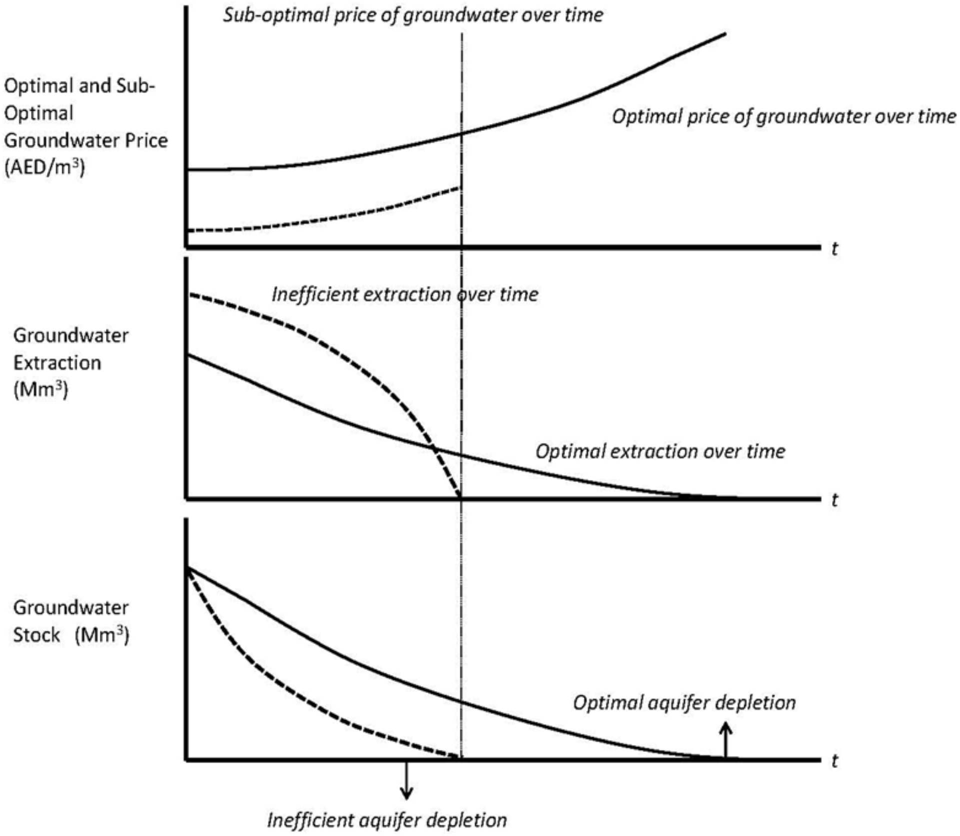

Fig. 7. Comparison of optimal and inefficient time paths of groundwater extraction.

water, brackish water, and saline water. For the Western region, information on the total saturated thickness of the aquifer (provided by EAD), combined with the conceptual model of geologic formations and hydrogeology provided a means for estimating the thickness and total volume of each layer (fresh, brackish, and saline) in each zone. Due to data limitations, a simpler framework was applied to the Eastern region.

3.2. Model representation of groundwater use sectors

3.2.1. Agricultural sector use

Agriculture is the largest source of groundwater consumption in Abu Dhabi by a wide margin, accounting for roughly 2 billion m^3 per year. Although this rate has recently declined and will most likely continue to decline as subsidies for Rhodes Grass production are phased out, agriculture is expected to be the main consumer of groundwater for the foreseeable future. To estimate the economic value of groundwater for agricultural irrigation, we developed an optimization model that maximizes producer returns to production (crops, livestock, and date palms) given various land and water resource constraints. A necessary first step is to understand the amount of water required to grow particular crops or raise livestock. Using a standard Food and Agriculture Organization (FAO) approach, we estimated crop-specific water requirements as a function of crop evaporation, crop water needs, crop-specific irrigation response factors, and maximum achievable yields. We developed similar water requirements for livestock using FAO daily water requirement guidelines for Sahelian desert conditions.

3.2.2. Forestry sector use

Next to agriculture, the forestry sector has been the largest consumer of groundwater in Abu Dhabi over the last decade. However, in contrast to agricultural lands, forests in Abu Dhabi are not cultivated and managed for harvesting and commercial production. Rather, they have mostly been planted since 1970 to support the late HH Sheikh Zayed Bin Sultan Al Nahyan's vision of "greening the desert" to provide environmental benefits for Abu Dhabi residents. The value of groundwater for the forest sector must, therefore, be assessed by examining the value of the nonmarket benefits provided by these forests. The next steps are to estimate the annual nonmarket benefits provided by these forests. For our analysis, we focus on the following four main types of ecosystem services.

- *Carbon storage*: To estimate the amount and value of carbon stored in each forest unit, we first estimated the above-ground biomass present and assumed that half of this weight is attributable to carbon. Next, we estimated the value of stored carbon as the avoided social cost of emitting that carbon to the atmosphere. Based on estimates from the United States Government's Interagency Working Group on Social Cost of Carbon (2013), we estimate the unit value of stored carbon to be roughly 560 AED per metric ton. Converting this stock value using a 3% discount rate, the resulting annual value of carbon is 16.8 AED per metric ton per year.

- *Habitat provision for wildlife and certain endangered species*: To estimate the value associated with forest wildlife habitat, we focused on the value of protecting endangered species. In the case of Abu Dhabi forests, a species of particular interest is the Arabian oryx. To our knowledge, no studies have specifically estimated the societal value of protecting the oryx or other endangered species in Abu Dhabi; however, a number of valuation studies conducted in the United States have estimated households' average willingness to pay (WTP) for protecting various species. These studies are summarized in a meta-analysis (Richardson and Loomis, 2009), which also provides a predictive model for estimating average WTP under defined conditions. Using this function, we estimated that the average WTP for protecting a charismatic terrestrial species is the equivalent of 178 AED per year for households in Abu Dhabi. Multiplying this value by an estimate of the number of households living in Abu Dhabi, we estimate an aggregate annual value of 126 million AED per year to protect forest-dwelling species. To apportion this aggregate habitat protection value to the individual forest units in the Emirate, we assume that, across the 50 forest units providing animal habitat, each planted donum contributes equally to this aggregate value (i.e., roughly 330 AED per donum per year).
- *Support of cultural heritage*: To estimate the cultural heritage value associated with these forests, we use an approach similar to the one for wildlife. As in the previous case, we are not aware of studies that specifically value cultural resources in Abu Dhabi; however, a number of cultural valuation studies have been conducted in other parts of the world. A review of this literature by Noonan (2003) provides a WTP function that can be used to predict values for different types of cultural resources. Using this function, we estimate an average annual WTP of 541 AED per household for protecting all forests with outstanding legacy value. Multiplying this value by the number of citizen households, the estimated aggregate value is 44 million AED per year to protect outstanding legacy value forests. Apportioning this value to the 36 units providing outstanding legacy value, each donum is estimated to provide an annual cultural heritage value of roughly 142 AED per year.
- *Protection of roadway infrastructure*: For these benefits, we estimated how the ground stabilization provided by forest cover reduces the costs of sand removal from nearby roadways. To estimate these values, we first used data from the Department of Transport to estimate the average annual cost of sand removal per kilometre of roadway in different regions of the Emirate. We found that average costs were higher by roughly 70% in the western areas where more roads are unprotected by forests. Assuming that half of this cost difference (35%) is attributable to forests, we estimated an annual cost savings of 860 AED per kilometre of roadway within 200 m of forest planted areas.

Finally, to estimate the value of groundwater use in each forest unit, we assume that it is equal to the total benefits that is, carbon storage, wildlife habitat, cultural heritage, plus road protection provided minus the groundwater extraction costs.

3.2.3. Amenity use

A relatively simple approach was used to value groundwater consumption for amenity purposes. Since the majority of the water used for amenity purposes comes from desalinated water and treated wastewater, the implicit social willingness to pay (or economic value) for water in this use is the costs of treating and distributing the water. Thus, we assume that the economic value of groundwater consumed for amenity purposes is equal to the costs of desalinating and distributing water. In our model, total amenity consumption of groundwater is restricted to certain zones, and the total is capped at 51 million m^3 per year, consistent with observed water resource usage rates.

3.2.4. Strategic reserve value

In addition to consumptive use values for irrigating farms, forests, and vegetation that provides amenity value, we consider the nonuse option value of maintaining fresh groundwater supplies. This option value represents the social benefit of preserving groundwater as a type of insurance for uncertain future needs. Maintaining a stock of accessible groundwater that is suitable for public consumption can provide an array of benefits, including alleviating future water and food security concerns and insulating Abu Dhabi from threats against public water infrastructure. The inclusion of this strategic reserve value in this analysis is justified given the existence of current groundwater injection projects. These projects imply a social WTP for groundwater preservation. Thus, total project costs of an existing injection project targeted at the Liwa region in Western Abu Dhabi are used as a proxy for the social WTP for the strategic reserve. Combining the four demand sectors: agriculture, forestry, amenity and strategic reserve as shown in Fig. 8, a dynamic optimization model was developed to maximize the total value of consumptive and non-consumptive groundwater use over a long time horizon of 100 years (Allen et al., 1998) as shown in Fig. 9.

4. Results and discussion

Three simulation scenarios were constructed for this analysis to project the total, average, and marginal values of groundwater over a 100-year simulation horizon, and assuming full (unsubsidized) energy costs for groundwater pumping. Three assumed discount rates were applied to the scenarios (3%, 5%, and 8%) to evaluate the implications of this important parameter on long-term groundwater management projections and estimates of the total economic value of groundwater. The total economic value of groundwater reserve in Abu Dhabi Emirate was estimated as

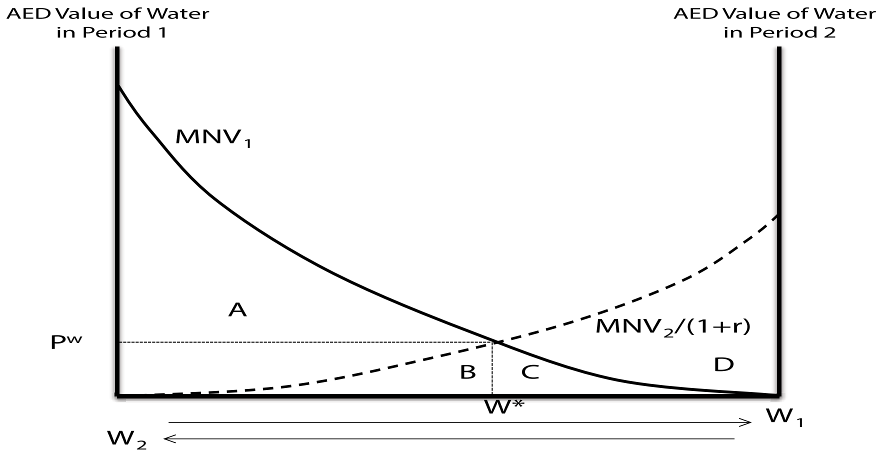

Fig. 8. Conceptual diagram of groundwater valuation model.

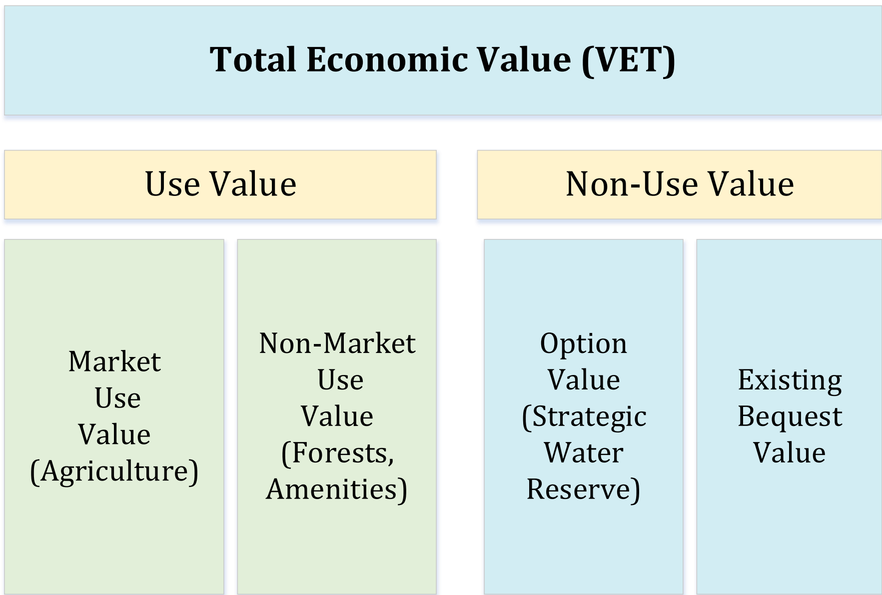

Fig. 9. Groundwater economic valuation.

Table 1
Total groundwater value over 100 year (in Billion AED)

Discount rate	Agriculture value	Forestry value	Amenity value	Strategic reserve value	Groundwater consumption costs	Total economic value
3%	164	74	233	372	63	781
5%	129	19	71	304	51	472
8%	93	4	21	365	41	443

shown in Table 1, and the marginal economic value ranges 4.5–6.0 AED/m³ compared with 7.0 AED/m³ for wastewater and 11.3–15 AED/m³ for desalinated water.

5. Conclusions and recommendations

Groundwater is a vital resource in arid region such as Abu Dhabi and calculating the groundwater value can help for a better understanding and sustainable use of this resource. Many actions should be taken by the government to sustain these resources in the future such as:

- Future agricultural policy including prices and costs
- Estimating food security benefits of irrigated agriculture
- Future non-market values for forest ecosystem services
- Future population growth rates and composition

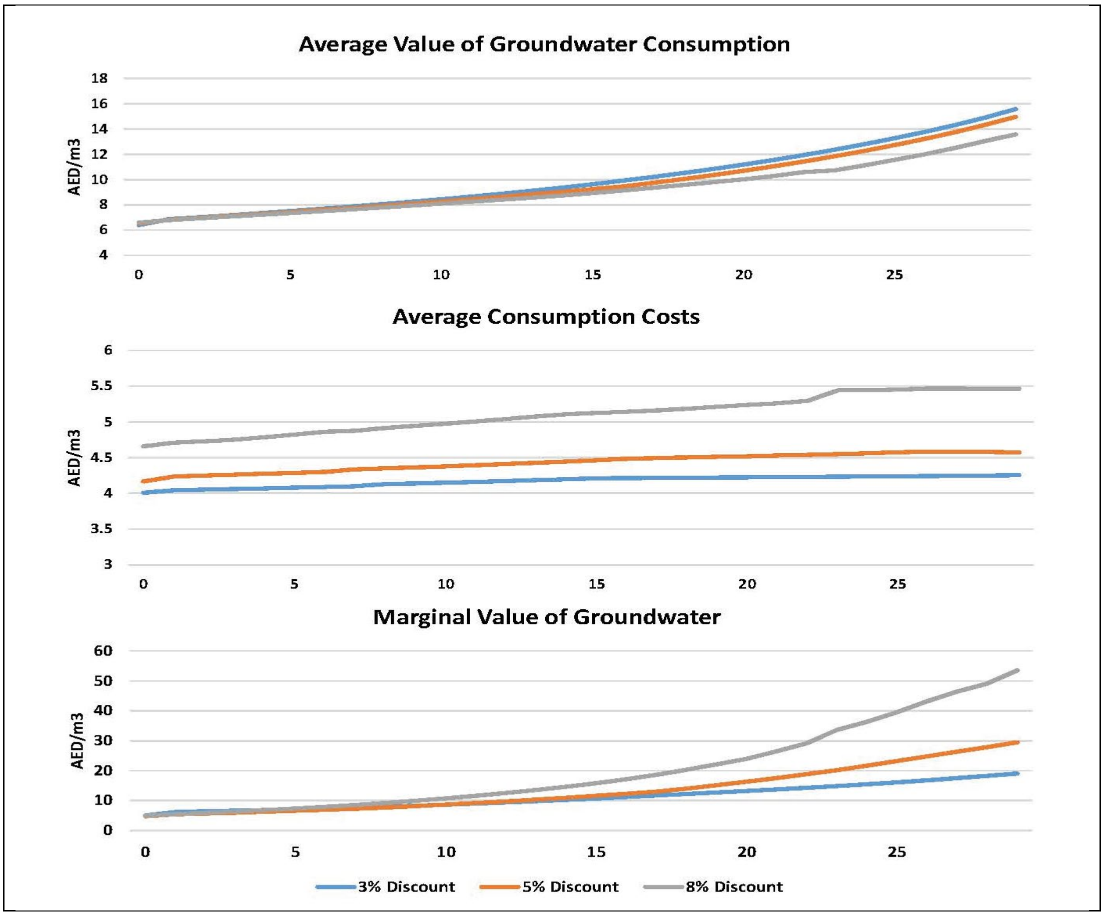

Fig. 9. Marginal groundwater value (in AED/m^3).

- Climate change impacts on the groundwater resources
- Reform the legal and intuitional water sector framework including groundwater regulation and legislations
- Infrastructure investment options
- Greenhouses, more efficient irrigation systems, and new innovative technologies in agriculture sector, etc.

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