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A Multi-Satellite Approach for Water Storage Monitoring in an Arid Watershed

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Abstract: The objective of this study was to use satellite imagery to monitor the water budget of Al Ain region in the United Arab Emirates (UAE). Inflows and outflows were estimated and the trend of water storage variation in the study area was examined from 2005 to 2014. Evapotranspiration was estimated using the simplified Penman-Monteith equation. Landsat images were used to determine the extent of agricultural and green areas. Time series of gravity recovery and climate experiment (GRACE) observations over the study area were used to assess the inferred water storage variation from satellite data. The change of storage inferred from the Water Budget Equation showed a decreasing trend at an average rate of 2.57 Mm^3 annually. Moreover, GRACE readings showed a decreasing trend at a rate of 0.35 cm of water depth annually. Mann-Kendal, a non-parametric trend test, proved the presence of significant negative trends in both time series at a 5% significance level. A two-month lag resulted in a better agreement (R^2 = 0.55) between the change in water storage and GRACE anomalies within the study area. These results suggest that water storage in the study area is being depleted significantly. Moreover, the potential of remote sensing in water resource management, especially in remote and arid areas, was demonstrated.

Keywords: GRACE; Water Budget; Landsat; evapotranspiration; UAE; water resources

1. Introduction

The United Arab Emirates (UAE) has an arid climate with low average annual precipitation around 100 mm. Despite water scarcity, water consumption in the country and the region is among the highest worldwide. The disparity between available water resources and the growing water demand implies that there should be a close monitoring of water resources in the region. Freshwater in the UAE comes from groundwater and unconventional sources such as desalination. Treated water is also used in landscaping. Groundwater is mostly used for agricultural purposes and accounts for almost three-quarters of the consumption, whereas potable water is provided from the desalination plants [1].

The development of appropriate water resources management policies in the UAE requires a strong understanding of available resources and their spatial and temporal variability with respect to the growing water demand. This allows policymakers to determine effective and sustainable planning and management strategies. However, existing records on water resources are usually collected during short field campaigns and are not sufficient to develop a clear idea of the trend of water variables. The sporadic behavior of hydrological processes in arid regions and the lack of gauged stations make the monitoring of water resources challenging.

In the UAE, most of the watersheds are ungauged with very limited data records. Most of the wadis are ephemeral, especially in the western part of the country that is at the edge of the Empty

Quarter. Rainfall records go back to the 1970s at only a few stations. The rest of the stations in the country are more recent. As a result, there is limited information on the hydrological behavior of the watersheds and the variability of water resources. To overcome this lack of data, the use of satellite imagery could be a potential option [2,3]. Remote sensing techniques can play a great role to fill in data gaps in ungauged watersheds, where in situ data is scarce, with their capability to provide spatial and temporal information on water resources [4,5]. This is particularly important in the case of intermittent variables like rainfall, where the common areal interpolation methods of ground records are not efficient due to the lack of dense networks of observation points. Global Precipitation products are often blended products that involve ground measurements, weather models, and satellite reading [6]. Despite the usefulness of satellite imagery for the retrieval of precipitation, the lack of ground observations impacts the quality of such products and limits their verification in arid regions [7].

In addition, water storage in reservoirs can be estimated using high resolution satellite data such as Landsat imagery and radar sensors [8–11]. The latter has been used successfully in the case of cloud presence. Storage fluctuation in reservoirs can be estimated from pre-established rating curves of volume-surface area relationships. Moreover, remote sensing techniques are used to measure changes in total water storage by quantifying the change in the total mass. Gravity recovery and climate experiment (GRACE) products were used to investigate the temporal and spatial changes of the terrestrial water resource [12,13]. This technique is more effective in areas where there is no other type of mass displaced by natural or anthropogenic mechanisms.

Recent achievements in technological advancement in remote sensing instruments are providing accurate high-resolution spatial data for key hydrological variables, especially for ungauged watersheds [14,15]. A number of hydraulic parameters such as water level height, width, and area can be captured remotely and used to estimate river discharge. In addition, river runoff, watershed concentration time, and flood wave propagation time were estimated directly from satellites with microwave sensors [9,10,16–20]. Nonetheless, most satellite products are at coarse spatial resolution, which is not suitable for studying hydrological processes like flooding and water storage monitoring.

In arid watersheds, like the one studied here, the scarcity of in situ data records fosters the use of satellite data at spatial and temporal resolution that would make it possible to capture the variability of water resources. To this goal the use of multi-satellite data to estimate key hydrological variables should be an attractive alternative.

In the UAE, several attempts were carried out to study the variability of water resources using remote sensing technologies. Sherif et al. [21] modeled flash floods in adjacent areas in Northern UAE. In their study, the authors used land cover maps to estimate the Curve Number (CN) across the watershed. Brook et al. [22] reported that most of the groundwater in the Al Ain region originates from eastern mountainous areas in Oman where orographic processes and microclimates trigger local precipitation events that enhance the recharge locally. The groundwater then flows westward towards the Gulf. Regionally, Milewski et al. [23] proposed a remote sensing and Geographic Information System (GIS)-based solution for estimating recharge and runoff in arid regions. Their approach was developed and tested at the regional scale. Al-Dousari et al. [24] used remote sensing data to build a Soil and Water Assessment Tool (SWAT) model for an arid watershed in Kuwait. In another study, Elmahdy and Mohamed [25] employed GIS and remote sensing data to study the variability of groundwater and its quality in the Al Ain region; but did not close the water budget and lacked a demonstration of the variability of key hydrological variables.

The city of Al Ain was selected as a case study to employ remote sensing data close the water budget. The main reason for selecting Al Ain is because the city has seen significant expansion in the agricultural sector in the last decade. Moreover, Al Ain, the third largest city in the UAE, holds a high potential of fresh groundwater in the UAE which explains the great interest in monitoring changes in water storage. The previous Water Balance studies in the area were carried out on an annual basis and, hence, they lack information on temporal evolution of water storage in the area [25,26] with limited use of satellite imagery. Additionally, the spatial coverage in previous studies was not inclusive of all the areas but rather concentrated in the city and its suburbs. Moreover, the evapotranspiration was not accurately estimated because the whole agricultural area and green areas and their expansion in time throughout the years were not accounted for.

In this study, to develop the abovementioned attempts, the potential of satellite imagery in monitoring water resources in arid regions was studied. We particularly focused on the city of Al Ain, in the UAE, and investigated the closure of the water budget using satellite data. The inland city of Al Ain is known in the UAE as the Garden City because of the relatively higher water resources potential. Close to the city, there is a lake (Lake Zakher) that receives treated wastewater which could be used as an indicator of changes in water storage in the watershed. The goal of this study is to close the water budget and examine the water storage variability in Al Ain region. The study mainly employed satellite imagery for the estimation of water storage in the lake as an indicator of changes in inflows and outflows. Water storage variability in the watershed was then compared to GRACE time series records that reflect total water storage anomalies. Although this study examined the applicability of such techniques on a small watershed scale that lies in an arid region, where most of the water inflows and outflows are controlled, results would be of paramount importance to apply similar techniques at larger watershed scales and at the country level in the UAE.

2. Data and Methodology

2.1. Study Area

The city of Al Ain is located in the Southeastern region of Abu Dhabi Emirate, about 130 km south of Dubai and approximately the same distance east of the capital Abu Dhabi. Its geographical coordinates are 24°12′27″ N, 55°44′41″ E. The total area of the city is approximately 13,100 km^2, with a total population of 518,316 according to 2012 census data. This area is rich in fresh groundwater compared to the other regions of the Emirate of Abu Dhabi where brackish water is dominant, especially in the western and coastal part of the country [25].

The climate in the area is hyper-arid with average annual rainfall of 100 mm [27]. Despite its arid climate, the city is attracting local and international agricultural investors due to its rich groundwater resources. The city is producing fruits and vegetables covering a significant portion of the local market demand and also features many livestock farms. Moreover, the city's industrial sector is also growing rapidly contributing to the increasing demand for water.

This watershed around the city was selected in this study primarily due to concerns that the local groundwater resources are being depleted severally in the area. This was based on recent findings that indicated the rapid depletion of water resources due to agricultural use [1]. The city of Al Ain holds a precious reserve of fresh water that is subjected to a growing demand for residential and industrial uses, as well as for agriculture given the considerable size of farms developed in the western part of the Al Ain municipality, on the road to Abu Dhabi. Therefore, understanding the water budget of the watershed is crucial to monitor the recharge mechanisms, which are very important for management and regulation purposes in a region where renewable water resources are scarce.

Lake Zakher has appeared in the desert within the study area as a result of treated wastewater discharge in 2010 (Figure 1). Since then, the lake size has been changing to indicate fluctuations in the total volume of treated water, which we believe should be in line with the change in water demand and consumption in the watershed and, therefore, a possible indicator of water storage variability. In this study this possible connection is examined.

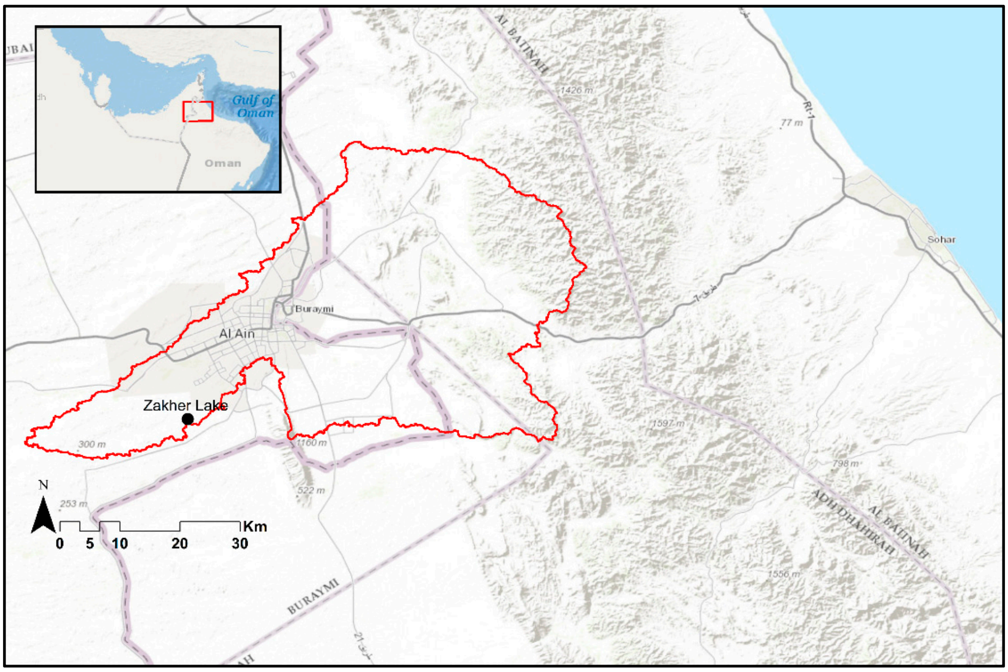


Figure 1. The city of Al Ain and its location on the Eastern United Arab Emirates (UAE) borders with Oman, and the red line shows the watershed boundary.

2.2. Dataset

2.2.1. GRACE Data

In this study, information on the total water storage variability was estimated from the Gravity recovery and climate experiment (GRACE), a mission by NASA Earth System Science Pathfinder that was launched in March 2002. GRACE consists of two identical satellites about 220 km apart and orbiting 500 km above the earth's surface. The main objective of NASA's GRACE mission is to monitor changes in the earth's mass by accurately measuring the change in distance between the satellites due to variation in gravitational force [12,28]. In this study, the level 3 gridded product from GRACE was used with 1-degree spatial resolution and approximately 1-month temporal resolution. The data was provided in anomaly relative to average values from January 2004 to December 2009, and was given in depth (cm) of water for each grid cell. The spatial resolution of the product is 100 km, which means the whole study area is enclosed in one pixel of the GRACE product. Moreover, water storage anomaly data was employed, starting from January 2005 up to December 2014 at an approximately 1-month temporal resolution.

2.2.2. Landsat Images

High resolution satellite images were used in this study to (a) delineate Lake Zhaker and monitor the change in its areal extent and (b) identify the green areas within the study domain to estimate the evapotranspiration losses. To this end, Landsat 8 imagery was used. The spatial resolution of Landsat images was 30 m with temporal resolution of 16 days. In this study, 38 cloud-free images of Landsat 7 and 8 were used covering the time period from 2010 up to 2014. Landsat images were used to capture the evolution of Lake Zhaker using the morphological gradient technique. The contour of the lake was then applied to a high-resolution 15 m Digital Elevation Model to calculate the total water storage in the lake that corresponds to each specific contour. Figure 2 shows examples of delineated lake boundary from Landsat images.

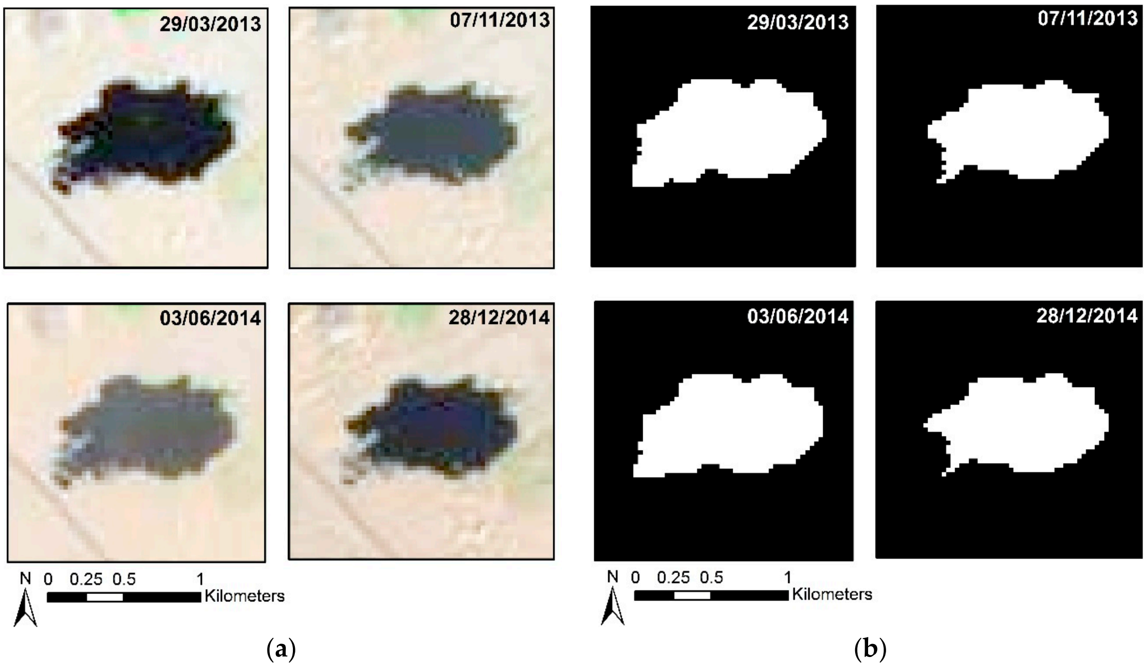


Figure 2. (**a**) Landsat 8 images at four different periods of Lake Zakher. (**b**) Extracted polygons using the morphological gradient from respective Landsat images.

2.2.3. NCEP/DOE Reanalysis II Data

We used the net incoming and net outgoing radiation data from National Center for Environmental Prediction/Department of Energy (NCEP/DOE) Reanalysis Project to determine evapotranspiration over agricultural and green areas [29]. The reanalysis information and selected outputs are available online (http://www.esrl.noaa.gov/psd/). The resolution of the data used in this study is $1.9^\circ \times 1.9^\circ$, with daily time step from 2005 up to 2013 at the surface of the earth. The resolution of the product is coarse with respect to the extent of the study area (13,000 km^2). We neglect the spatial variability of solar radiation and assumed homogenous solar radiation with the selected pixel over the study area.

2.2.4. Weather Station

In-situ observations from the weather station at the Al Ain Airport were used, starting from January 2005. Several variables were integrated into the simplified Penman-Monteith equation to estimate the evapotranspiration. The daily observations of wind speed, maximum and minimum temperature, atmospheric pressure, dew point temperature and atmospheric humidity were used on the simplified Penman-Monteith model. The precipitation data was also used as input flow in the water budget equation.

2.2.5. Water Supply, Demand, and Reuse Records

Records of water demand, consumption, recycled, and discharged water were obtained from Statistics Centre—Abu Dhabi (SCAD), which is a governmental entity responsible for the publication of official records in the Abu Dhabi Emirate [30]. Water consumption refers to the desalinated water supply, whereas recycled water denotes the treated water redistributed after treatment mostly for landscaping. However, the discharged water indicates the excess of treated water that is not reused but sent to Lake Zakher.

Records from SCAD were used along with satellite images to close the water budget in the study area. The monthly consumption of desalinated water, the annual inflow of wastewater, the annual treated water, and the annual quantity of reused water from the region of Al Ain were used.

2.3. Water Balance

A general water balance equation, $I - O = \Delta S$, where I is inflow, O is outflow, and ΔS is change in storage, was rewritten in this study as:

$$DS + P + R - Et = \Delta S \tag{1}$$

where DS is desalinated water input to the system (watershed) , P is precipitation input to the system, R is reused water input to the system, Et is evapotranspiration from the vegetation and the lake, and ΔS is change in storage.

Inflow to the system is mainly governed by the desalinated water supply, which is common in arid regions. In Al Ain, most of the desalinated water is delivered from the desalination plant Qidfa' in the Emirate of Al Fujairah. The hybrid plant that is run by Abu Dhabi Water and Electricity Authority (ADWEA) produces 760 MW and 455,000 m^3 of water per day. Another component of the inflow to the system is precipitation, which is not as significant as the desalination water supply. The last component of the inflow is the recycled water, also known as reused water.

The main loss from the system is evapotranspiration, which includes the evaporation from Lake Zakher and the evapotranspiration from the agricultural areas within the system. Evapotranspiration was calculated using the simplified Penman equation [31] written as:

$$ET = (0.015 + 0.00042 \times T + 10 \times 10^{-6} \times z) \times (0.8 \times R - 40 + 2.5 \times F \times U \times (T - Td)) \tag{2}$$

where T is mean temperature, Td is dew temperature, U is wind speed, z is elevation, R is radiation in W/m^2, $F = (1.0 - 8.7 \times 10^{-5} \times z)$, and ET evapotranspiration mm/day.

The Penman equation combines the energy balance and mass transfer equations to estimate the evapotranspiration from an agricultural area. The modified Penman method was found to be the best approach, with minimum uncertainty compared to other methods [32]. This method has been tested in a wide range of locations and different climatic conditions. The main advantage of Penman method is its applicability in data-scarce situations. Above all, the Food and Agriculture Organization (FAO) strongly recommends the use of the Penman method where possible [33]. It is recommended to validate the outcome of the Penman method with in situ readings. Due to the absence of in situ data, the validation of evapotranspiration was not performed in this study.

The change in water storage in the study area was assessed using two approaches, the first using the determined ΔS according to Equation (1), and the second using GRACE mass anomaly values. The agreement between both approaches should corroborate the assessment of the variability of water storage variability in the area. To this end, a trend analysis was carried out using the water storage change obtained from the water balance equation and the GRACE mass change anomalies. The Mann-Kendal test was performed on both time series data at a 95% confidence level. We expected a consistency between both water storage indicators, ΔS and GRACE anomalies.

It is worth noting that in the water balance equation, the sub-surface water movement was not accounted for because of the lack of data. This will not affect the water balance model outputs as the average permeability is reported to be very small [22]. In addition, in the region and particularly in agricultural areas, deep well pumping is common as treated wastewater is not used for irrigation and desalination water that is not available in remote farms is not a cost-effective alternative. In this study, we do not account for the deep well pumping because of the lack of data. The water volumes from deep well pumping used in the irrigation could have augmented the amount of evapotranspiration. Accounting for deep well pumping would have made the estimated ΔS more accurate. However, neglecting it makes the estimation more conservative by underestimating the evapotranspiration.

3. Results

3.1. Surface Water Monitoring

Zhaker Lake started to expand in late 2009, reaching 1 Mm^3 capacity in the first quarter of 2010. Then, the volume rapidly increased to reach the capacity of 4.5 Mm^3 by the year 2012. Finally, it plunged to reach a plateau of approximately 2 Mm^3 in 2013 and 2014. The increase of the lake volume in 2009 suggests the existence of an excess of recycled water that continued at least until 2012. The lake did not completely disappear after 2012; it only lost around 50% of its total volume, which may indicate that the excess of recycled water continued after 2012, perhaps at a lower magnitude.

A variability in extent can be noticed throughout the year because in 2013 and 2014 the lake size was larger in March and June than in November and December. In the region, temperature and solar radiation and, therefore, evaporation in March and June, when the lake size is larger, tend to be higher than those in November and December. This suggests that the variation in the lake size is not only sensitive to meteorological conditions but also driven by wastewater discharge.

3.2. Water Consumption

Changes in water consumption in Al Ain are shown in Figure 3. Water consumption increased with a relatively small amount, only a 30 Mm^3 increase in a four-year period between 2005 and 2009 (Figure 3). Then, water consumption started to soar in 2009 and continued, reaching 300 Mm^3 in 2013, which corresponds to an approximately 100 Mm^3 increase for the same duration (four years), a threefold increase recorded between 2005 and 2009. These records corroborate the increase in Lake Zakher volume-to-water consumption.

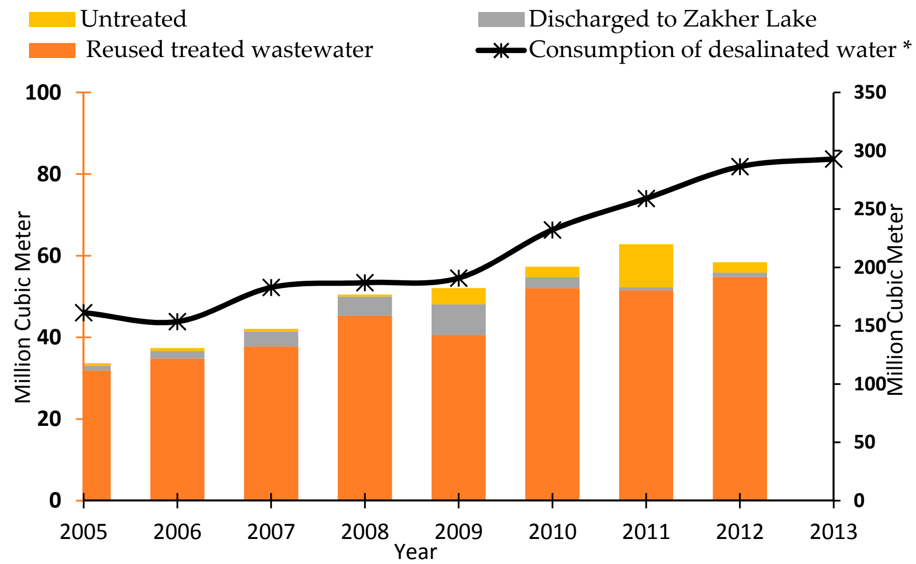


Figure 3. Desalinated water and wastewater figures from Statistics Centre—Abu Dhabi (SCAD) [30] (*Consumption of desalinated water is referred to on the right axis).

Out of 160 Mm^3 in consumed water in 2005, only 33.7 Mm^3 was sent to the wastewater treatment plants, which corresponds to 21% of the total supplied. As late as 2009, the ratio remained somehow similar, with 27% out of the total consumed reaching wastewater treatment plants, which corresponds to 52.1 Mm^3 out of the 190.9 Mm^3 in water consumed. Starting from 2009, wastewater inflow did not increase at the same rate as water consumption. Wastewater inflow increased only by 12% with the rise of more than 50% of the consumption from 2009 to 2012. This means that the increase of the wastewater inflow to the treatment plant was less than 10 Mm^3, while water consumption soared by almost 100 Mm^3. The difference between wastewater inflow and treated water was relatively small from 2005 to 2008. Increased differences were observed after 2008, with the highest difference of 10.53 Mm^3 observed in 2011.

3.3. Water Storage Monitoring

3.3.1. Water Storage from Satellite

Time series results of GRACE anomalies were used to monitor changes in water storage in the Al Ain watershed (Figure 4). Recall that we assumed that there are no other activities within the watershed involving mass movement that may impact GRACE readings, such as excessive mining or oil production activities in Al Ain watershed. It is worth noting that the spatial footprint of GRACE reading is large, with a pixel size ranging from 300–400 km. However, the main urban area, with a significant agricultural and landscaping extent within the study area, is Al Ain city, with no surface water processes elsewhere. So, we assume that anomalies in the CRACE reading should reflect fluctuations of the water storage within the city area and the agricultural areas around it. Moreover, the gridded data of level 3 (110 km × 110 km at the equator) were resampled and modified to reduce noise in the signal. The de-striping and filtering applied are essential in reducing the random measurement errors, but the methods also alter the original signal needed. This modification should affect the interpretation of the readings in the local settings (small scales) [34]. In addition, the study objective was to monitor the change in time and assess the validity of the inferred trend of storage not to quantify the actual amount of change in groundwater. So, in such contexts, discrepancies in the spatial extent should not impact the inferred trends.

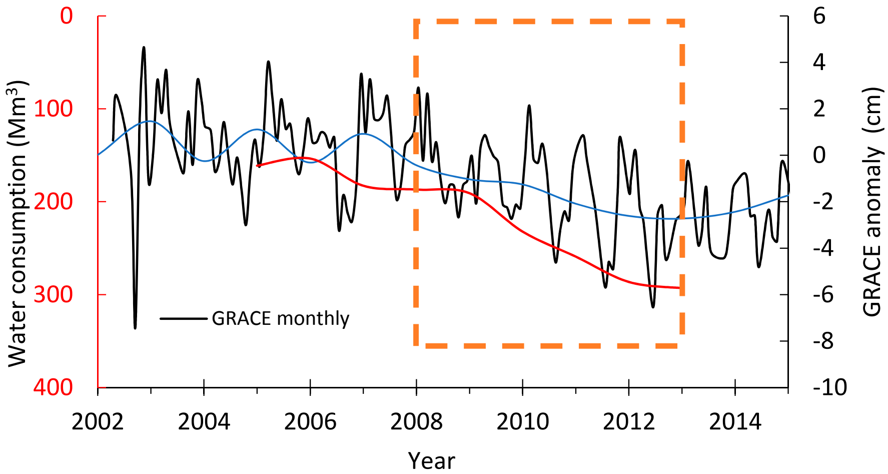


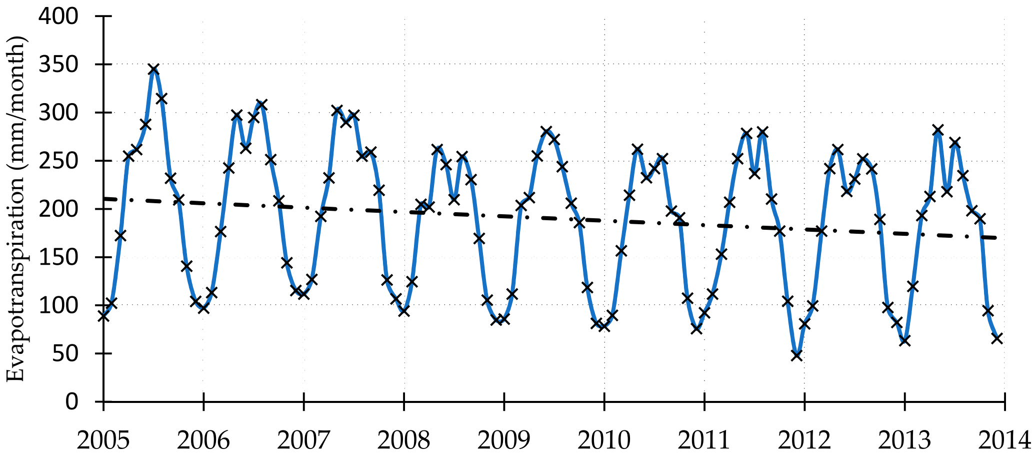
Figure 4. Grace Anomaly of Al Ain and the water consumption for the city from Abu Dhabi Water and Electricity Authority (ADWEA).

GRACE anomalies for the city of Al Ain showed a clear biannual cycle (Figure 4). Most of the positive anomalies were observed before 2008. Peak anomalies were observed during winter months of the year (December–March), while relatively low anomalies were recorded during summer months (June–October).

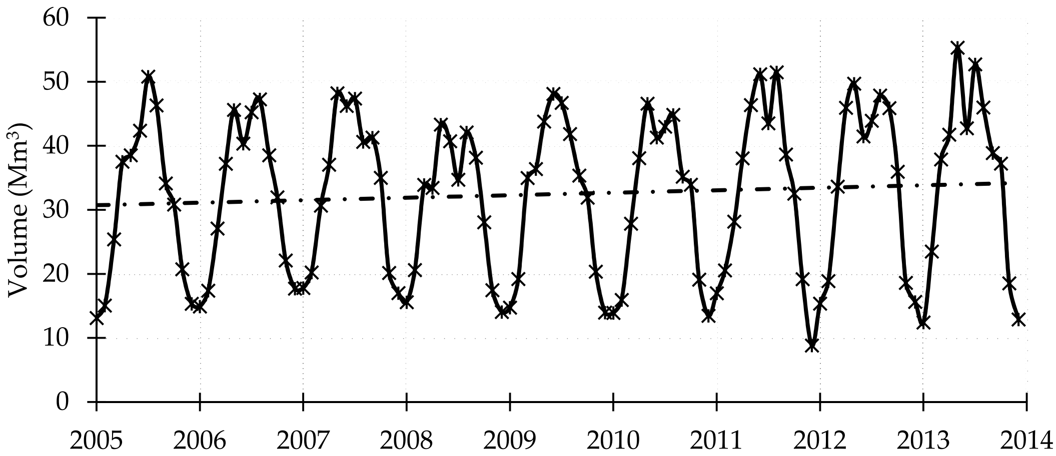
Water storage within the study area started to significantly decline from 2008 onwards, as the values of GRACE anomalies were persistently negative (Figure 4). The negative gradient continued and reached its lowest level (−2.7 cm) in 2013 (Figure 3). This depletion coincided with the increase in the area of Lake Zakher, which could result in the loss of a significant quantity of water to evaporation. This also indicates that groundwater resources in the area were excessively exploited in the last decade. GRACE results showed a substantial decline in the rate of depletion as the monthly and annual values flattened in 2013 and 2014. The overall rate of change of storage obtained from the GRACE readings showed a decreasing trend of 0.35 cm water depth annually. The trend analysis of the GRACE reading indicated a significant negative trend based on the Mann-Kendal test ($p < 0.05$). In agreement with observed depletion of water storage, water consumption in the city increased by 100 Mm^3 in six years (2009–2015). Water consumption reached 190.90 Mm^3 in 2009 from 161.2 Mm^3 in 2005. Then, consumption dramatically increased and reached 293 Mm^3 in 2013. The main factor for increased water demand was the expansion of the city and the growth in industrial and agricultural sectors. Figure 4 shows the increase in the water consumption throughout the period of 2005–2013 versus the depletion of the groundwater resource with the GRACE results.

3.3.2. Water Balance Equation

Evapotranspiration is the main output from the system. It depends on meteorological variables, the expansion in agricultural areas and change in their extent, as well as the change in the discharged treated water and landscaping activities. In this study, the extent of agricultural area was obtained from Landsat images. Using a linear regression, the estimated annual areal increase in agricultural areas from the images was approximately 6 km^2. The estimate of the evapotranspiration of the area ranges from 50 to 350 mm/month, with an annual average of 2264 mm (based on data from 2005 to 2014). Monthly evapotranspiration data is shown in Figure 5, from 2005 to 2014. The results show the existence of two peaks of evapotranspiration over a year, in the months of April and July. The lowest evapotranspiration was recorded in the month of January, reaching as low as 50 mm/month.



(**a**)



(**b**)

Figure 5. Time series of the monthly evapotranspiration (**a**) in mm/month over agricultural and landscaping area and (**b**) total evapotranspiration volume loss over the watershed (Mm^3/month).

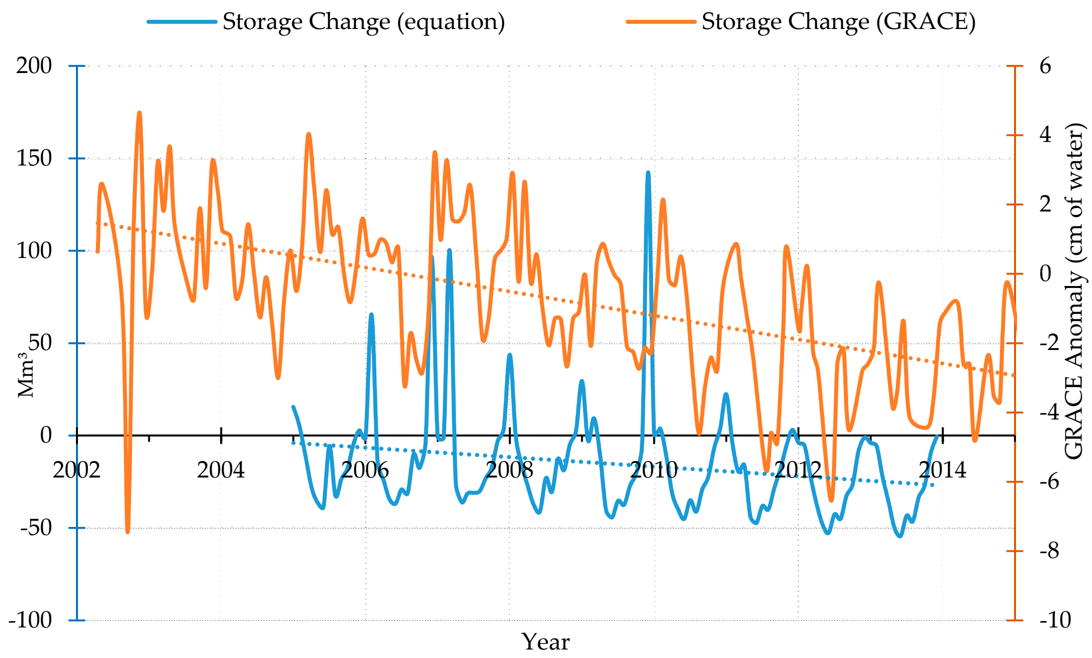


Figure 6. Variability of estimated water storage compared to gravity recovery and climate experiment (GRACE) anomalies (GRACE right axis).

Total evapotranspiration within the study area is presented in Figure 5. Unlike the monthly evapotranspiration, total evapotranspiration showed an increasing trend mainly controlled by the increase of the agricultural areas and green spaces delineated by Landsat. This suggests that expansion of irrigated areas clearly caused the increase in total evapotranspiration. As shown in Equation (1), total evapotranspiration is the major water loss from the study area. It is, therefore, expectable that the noticed increase in evapotranspiration corresponds to a depletion of water reserves in the area.

Change in water storage (ΔS) showed a strong seasonality mainly due to the variability of evapotranspiration. The rainy months (December–February) had the peak change in storage due to the relatively greater precipitation in the system compared to other months. Moreover, the evapotranspiration (loss) is low. The 2006/07 season had two extreme peaks due to unprecedented high precipitation in December 2006 (50 mm) and March 2007 (61 mm). Another noticeable increase was recorded in December 2009, with a precipitation of 74 mm/month. Generally, ΔS showed a significant negative trend at a 5% significance level using Mann-Kendal test, even though the inputs (desalinated and recycled water) showed an increase during the study period. The overall change of storage inferred from Water Budget Equation showed a decreasing trend at an average rate of 2.57 Mm^3 annually. Figure 6 represents the time series of the both the remotely sensed data and the estimated storage from the water balance equation.

3.4. Correlation between Results from Remote Sensing and Water Balance Equation

There is a clear agreement between the changes in storage calculated using the two datasets. They both show a significant negative trend when tested with the non-parametric Mann-Kendal test at a confidence level of 95%. The statistically significant negative trends in ΔS and GRACE readings corroborates the assumption of severe water depletion in the region.

A two-month lag was noticed between GRACE and water balance results. The phase lag between GRACE and water storage time series could be attributed to the difference in sampling time as GRACE data products were monthly, whereas the data used for the estimated of water storage was daily, which was then aggregated to a monthly time interval. This could also be due the fact that groundwater movement is slow to react to external sway. The correlation between GRACE anomalies and water storage estimates reaches 0.54 when a two-month lag is considered. Additionally, neglecting groundwater movement from the mountains in Oman towards the Gulf in UAE, especially during rainy periods, may have contributed to this discrepancy between both time series. However, despite the phase lag, both estimates of water storage variability from the two datasets showed significant negative trends, which corroborates the assumption of water depletion in the area.

The analysis of GRACE time series indicated two change points, 2008 and 2013, which marked a severe depletion between those specific years (Figure 7). The change point in 2008 was detected using the cumulative sum (CUMSUM) change point detection method. The CUMSUM method is a nonparametric statistical technique that can be used for detecting changes in time series [35]. The change point in 2013 was only visually identified and was not detected in the procedure mainly because of the short record after 2013. However, visually there was an existent plateau on the time series starting in 2013. The first period (2002–2008) has a gentle slope with very small slope, indicating that the water storage was relatively constant. The second period (2008–2013) indicates significant depletion of the storage followed by a period (2013–2015) of stabilization of the storage. However, this needs to be confirmed using additional years of observations.

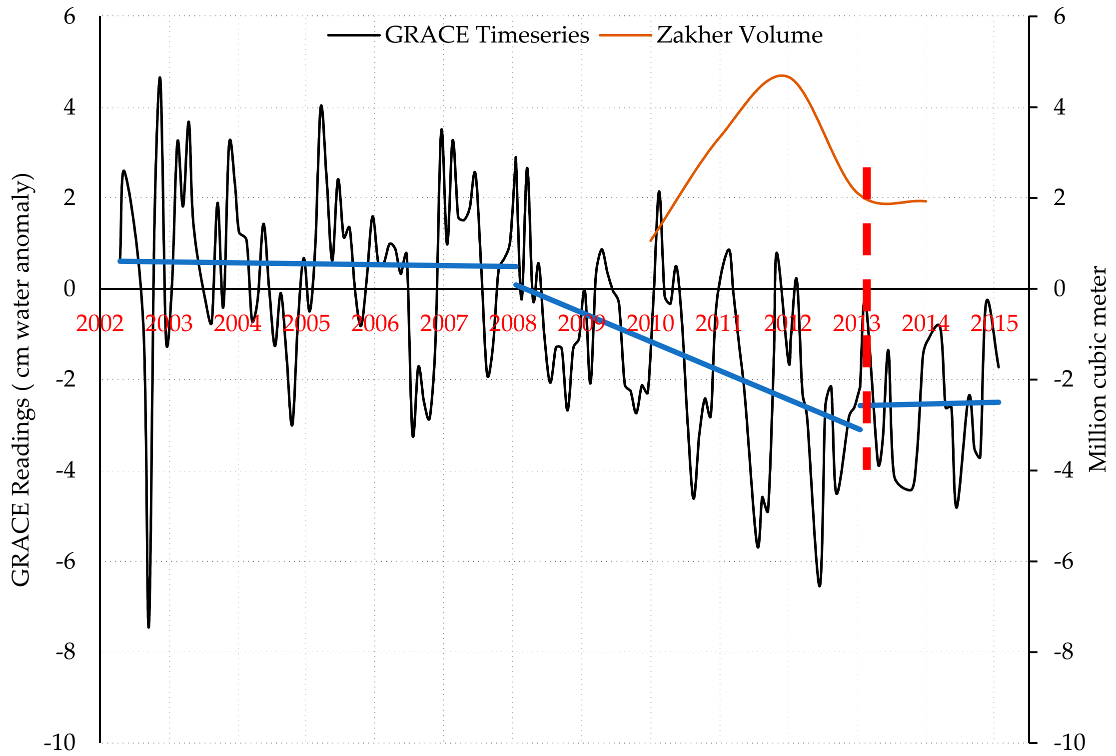


Figure 7. The Lake Zakher Volume (Mm^3) versus the GRACE time series anomalies (left axis); the dashed vertical line shows the timing of the second change point in the time series that coincides with the stabilization of the Lake Zakher water volume (Right axis).

The change points detected in Figure 7 are in line with the variability of the water consumption reported in Figure 4, where an increase in water demand coincided with the 2008–2013 time period that corresponds to a severe depletion of the water storage based on the GRACE results. Water consumption records seem to stabilize starting from the end of 2013. More recent records are needed to confirm this trend.

On the other hand, the start of the depletion was followed by an increase in Lake Zakher water volume. The volume in the lake peaked in late 2011, followed by a sharp decrease in 2012 and 2013. This was in agreement with the second change point of the GRACE results. This indicates that there is a relationship between the lake's water volume and total water storage. The period of water storage increase in the lake between 2008 and 2011 corresponds to the steeper decline of water storage. The decline of water storage in the lake coincides with a slower water storage decrease between 2011 and 2013. Finally, the flattening of the water storage in the lake after 2013 corresponds to a plateau in the GRACE results. The variability of water storage in Figure 6 confirmed the depletion between 2008 and 2013. However, the record was not enough to come to a conclusion regarding the stabilization of the water depletion after 2013.

The depletion and, therefore, excess water in Lake Zakher could be also explained by the conducted infrastructure projects in the city which require draining of considerable volumes of water from the shallow water table. The drained water is usually sent to the storm water drainage network to get to the city's flood control channels or infiltrate to the domestic water network to eventually get to the wastewater treatment plant. The impact of these practices was reflected in the variability of water storage in Lake Zakher which suggests that the lake can be used as a water storage gauge that could be monitored from space.

The agricultural lands and green spaces within the study area are irrigated from desalinated and deep well pumping in the case of the former and reused water in the case of the latter. The consumption of the desalinated water is expected to increase by 22% in 2030 according to the Abu Dhabi Water and Electricity Company (ADWEC) reports. This will increase the input to the system significantly. However, the output from the system will also continue to increase if the continuous expansion of green areas (agricultural and landscaping) as reflected in the Landsat images is maintained. This suggests the need to adapt an optimized water resources management strategy in the region which would help to make informed decisions on infrastructure development. This should allow for more water reuse and advancing wastewater treatment technologies to reach a level where treated water can be used for irrigation of crops and, therefore, reduce the need for deep well water pumping.

4. Conclusions

The main goal of this study was to use satellite images to monitor water storage variability in an arid watershed. Results showed that water storage, especially groundwater, in Al Ain was depleted throughout the period of the study. This was clearly demonstrated in this study through the analysis of GRACE readings. This finding was in agreement with the previous study by [36], which indicated the increased depletion of groundwater across the UAE. Murad et al. [36] suggested that the only solution is to implement an integrated water resource management strategy. The implementation of maximum pumping regulation and controlling the expansion of the agricultural areas could be some of the initiatives to mitigate the rapid depletion of water storage in the region. Promoting other water efficient agricultural practices should contribute to the control of the water depletion in the region.

Findings from this study demonstrated that remote sensing could be effectively used for monitoring water resources in an arid watershed. Water resources can be reasonably estimated using remote sensing techniques, which can also complement in situ measurements, especially in arid and semi-arid areas where the main water input (gain) to the study area was from the desalination plant. Furthermore, the main output (loss) from the watershed was from evapotranspiration. A significant fraction of the treated water ends up in Lake Zakher, which was monitored from space to infer changes in water storage. GRACE and estimated water storage using other remotely sensed information show good agreement in showing a decreasing trend in the study area.

Overall, this study showed that remote sensing could be a useful tool in monitoring water resources in arid regions. This could be enhanced by using satellite imagery to monitor land use and vegetation health. Therefore, satellite imagery should be an important component of any comprehensive water resource management strategy that should be implemented in the UAE to achieve water and food security.

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