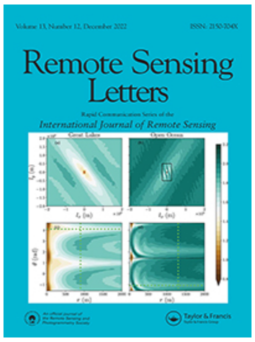

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Satellite-based agricultural water consumption assessment in the ungauged and transboundary Helmand Basin between Iran and Afghanistan

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ABSTRACT
Hamun Lake, the greatest (>8500 km^2) freshwater in the Iran plateau, has almost entirely dried over the last 20 years. The flow of the Hirmand (or Helmand) River, the most important feeding river, has decreased from 4.0 to 1.9 km^3 in the border of Iran-Afghanistan. In this river basin, the annual water consumption for irrigation is over 90% of the total consumed water. This study aims to calculate the increase in agricultural water consumption in the last two decades. Due to the lack of in-situ data across Afghanistan (including ~80% of the studied area), this research utilizes remote-sensing. Using Google Earth Engine, land use maps for the years 2002, 2008, 2013, 2017, and 2021 were developed by a supervised classification scheme. Since 2002, it was found that the cropland area has increased from 2008 to 5475 km^2. Most cropland has been developed around the Kajaki dam. Based on the Penman-Monteith-Leuning Evapotranspiration version 2 (PML V2) actual evapotranspiration (AET) data (our model assumes the irrigation efficiency equal to 0.3), the annual consumed water has increased from 2 to over 6 km^3 in the last two decades. The presented framework in this study can be recommended for other ungauged basins.

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1. Introduction

Managing water resources of large rivers flowing in a transboundary basin confront many challenges, and the main ones are expanding pressure from users, climate variability and change, and reconciling political borders and basin boundaries (Zeitoun, Goulden, and Tickner 2013). Moreover, data availability is crucial for managing water bodies shared among riparian countries (Skoulikaris and Zafirakou 2019). In many cases, for example, Indus (Akhter 2015), and Tigris and Euphrates (Haghighi et al. 2020), upstream river flow regulation and increased water consumption have changed the downstream flow regime, with effects on ecosystems, navigation, fisheries and agriculture.

Furthermore, due to population growth, the annual agricultural water demand increases from approximately 7,100 km^3 globally to between 8,500 and 11,000 km^3 to

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meet projected food requirements in 2050 (Fraiture, Charlotte, and Wichelns 2010). Threats of water consumption increase make estimation of agricultural development and water consumption variation decisive to develop policies that meet the present's needs without compromising the ability of future generations to meet their own needs (Omer 2008).

One way to mitigate the lack of in situ data in transboundary basins is to utilize global satellite remote-sensing data or reanalysis products (Rahimi, Tavakol-Davani, and Nasseri 2021; Ehsani et al. 2021; Zaki et al. 2019; Akbari et al. 2020; Bhattacharjee et al. 2021; Ghajarnia et al. 2022). Using remote sensing has been proven to be a reliable method of monitoring water consumption caused by evapotranspiration from croplands (Tan et al. 2018; Senay et al. 2016; Yongqiang et al. 2019).

Common legislative and technical frameworks are assets that foster the management of transboundary waters in an integrated and sustainable manner. For example, in Europe, a framework has been developed to incorporate cooperative and open access internet-based databases. This framework enhances cooperation and clarifies water-related conflicts among riparian countries (Skoulikaris and Zafirakou 2019). The Middle East, however, lacks such a framework. For example, Iran and Afghanistan share complex water bodies known as the Hamun Lake in the transboundary Helmand Basin which is the largest basin in Afghanistan (350,000 km^2). However, common legislation to facilitate the sharing of relevant data does not exist between the two countries.

The Hamun Lake desiccated completely in 2000 (Pekel et al. 2016) (Figure 1b and 1d). The most important river (70% of the total inflow) flowing to these lakes is the Hirmand (or Helmand) River which is very crucial for Afghan and Iranian farmers (Ahlers et al. 2014). However, the annual flow of the Hirmand around the border (gauge shown in Figure 1a) has decreased from 4.0 to 1.9 km^3 (Ministry of Energy (MoE) 2014) (more details in Figure S4 in supplementary materials). Afghanistan has suggested that a reduction in precipitation has led to a reduction in the quantity of water flowing into Iran from the Hirmand River (A. Mianabadi et al. 2020). However, studies have shown that anthropogenic activities are the leading causes of the downstream flow reduction (Akbari et al. 2022). Desiccation of the lakes has substantial environmental and economic impacts on the surrounding inhabitants and ecology (Rashki et al. 2012). For example, in 2012, Zabol (population 160,000 people) the neighbouring city to the lakes in Iran, had the worst polluted air in the world (WHO 2016). Iran and Afghanistan signed a treaty in 1973 and Afghanistan government-guaranteed that 0.820 km^3 of the Hirmand River inflow would enter Iran annually (Commission 1973). However, the treaty does not ensure the integrity of the downstream agro-ecological system (Thomas and Mahmoudzadeh Varzi 2015).

Agricultural development and dam operation in upstream of the Helmand Basin is perceived by Iran as significant security threat to water resources and the environment. Accelerating water scarcity and environmental degradation could result in further tension. However, the lack of information and data is a severe barrier to Afghanistan's engagement with riparian neighbours on transboundary issues (e.g., Iran with the Hirmand River). Since 1979, Afghanistan has published no hydrologic data publicly (Ahlers et al. 2014; Williams-Sether 2008). Also, there is a lack of data with a proper spatial and temporal coverage/resolution of water consumption in the agricultural sector in Iran (Akbari et al. 2019).

Due to the importance of the Hamun Lake and the consequences of its desiccation, it is essential to address the lake's decreasing inflow. The annual water consumption for irrigation in Afghanistan and Iran is 99 (Qureshi 2002) and 93% (Keshavarz et al. 2005) of the total available water, respectively; therefore, variation in the amount of water used for irrigation may be the main reason for the drying of water bodies. This study, using remote sensing, aimed to estimate the agricultural water consumption within the Helmand Basin which can benefit both countries to update the 1973 bilateral treaty and consider new users and environmental flow to the lakes as the symbol of sustainable developments in the region.

2. Material and methods

In this study, we used Google Earth Engine (GEE) Java Script API (Gorelick et al. 2017) to access satellite images. We 1) determined croplands change using Random Forest classifier in GEE to address agricultural development in the upstream section of the Hamun Lake; 2) quantified actual evapotranspiration (AET) over croplands of the basin to estimate water consumption in the agricultural sector by considering irrigation efficiency, and 3) calculated the variation of potential evapotranspiration (PET) to answer whether the climatic condition is responsible for AET change or not. All links for the JavaScript codes to the online platform of GEE are provided in the 'Data availability' section at the end of manuscript.

2.1. Study area

The Hamun Lake, consisting of four connected water bodies, was the greatest (>8500 km^2) freshwater bodies in Iran plateau (Figure 1a). To estimate spatio-temporal water consumption in the studied area, the basin area was divided into 11 sub-basins (Figure 1a). The sub-basins were chosen based on: i) political border: IRB (known as the Sistan region), i.e., Iran part of the basin, ii) main rivers' sub-basin: ADR (Adraskhan River), FRH (Farah River), KHSP (Khospas River), and KHS (Khash River), iii) location of main dams: KAJU, (upstream of Kajaki dam), ARGU (upstream of Arghandab dam), and HM (Helmand mid-basin, the area downstream of Kajaki and Arghandab Dam before Iran-Afghanistan border), and iv) other features: EU (eastern part of the basin upstream), HMD, (Helmand mid dry region, an area with ephemeral stream), and HEN (an isolated closed sub-basin in the high elevation of the Hindukesh mountain range).

2.2. Cropland change

In this study, Random Forest algorithm was used to produce land use maps to detect croplands in 2002, 2008, 2013, 2017 and 2021. We selected Random Forest, because this classifier had the most accurate results among others available classifiers in GEE. This method was first introduced by (Breiman 2001) as a supervised learning algorithm. This method is based on random combinations of tree predictors such that each tree depends on the values of a random vector sampled independently and with the same distribution for all trees in the forest. In supervised machine-learning-based method for land use classification, at least 50–100 samples per class (as a good rule of thumb) are needed. The

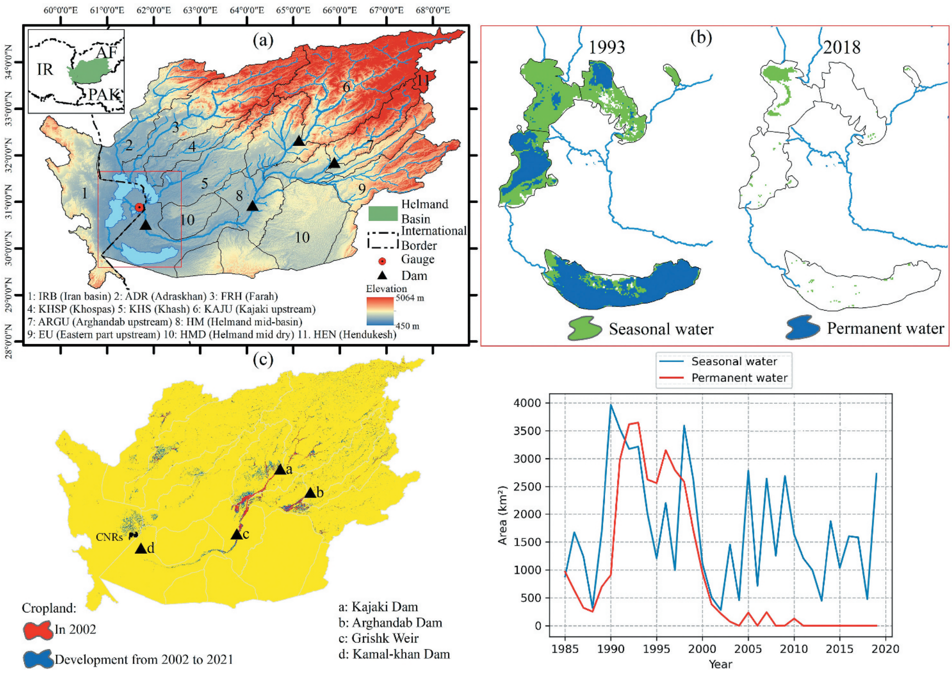

Figure 1. Study area: a) location of dams, Chah-nimeh Reservoirs (CNRs), rivers and gauge on the Hirmand River in Iran after the border; b) maps of annual permanent and seasonal water for the Hamun Lake based on JRC Global Surface Water Mapping (Pekel et al. 2016) in 1993 (maximum area in 1988–2018) and 2018; c) changes in croplands of the Helmand Basin from 2002 to 2021 developed by Random Forest supervised classification; d) annual time series of permanent and seasonal water in the Hamun Lake, calculated based on JRC.

sample size can be less if a specific class area is small in studied area (Jensen 2015). To build training and test set of Random Forest classifier, we utilized true-colour images of Landsat 5 and 8 Surface Reflectance in each year. Also, Digital Elevation Model (DEM), surface reflectance bands, land surface temperature, Leaf Area Index (LAI), and Normalized Difference Vegetation Index (NDVI) from Landsat were used as features of classification.

Furthermore, NDVI is recommended in the literature to estimate seasonal changes of crop and the amount of surface vegetation and growth activity (Ray and Dadhwal 2001; Hunsaker et al. 2003). NDVI varied from −1.0 to 1.0 and is generated from the Near-Infrared (NIR) and Red bands of each scene as $(NIR - Red)/(NIR + Red)$. The croplands area can be estimated by examining different thresholds $(NDVI > threshold)$. This method is simple and does not require high computational skill. Therefore, we compared Random Forest (as a machine learning-based) with NDVI to determine how the performance of these two different approaches are comparable over the studied area. This study suggested the most appropriate threshold for cropland detection by NDVI based on comparing the estimated area with Random Forest and literature (more detail in the result and discussion section). It should be considered that MOD12Q1 landcover product of MODIS underestimates cropland area in the studied area (more detail in Appendix E).

2.3. Evapotranspiration

Evapotranspiration is liquid water from soil and plants transferring to vapour into the atmosphere, it can either be expressed as PET or AET (a.k.a. ET_a). PET is defined as the amount of evaporation that would occur if a sufficient water source were available (on a surface), while AET is considered the net result of atmospheric demand (i.e., PET) and moisture availability. PET is often simplified to a reference ET (ET_0), which provides a PET estimate for a standard condition, e.g., green grass of 12 cm (Allen et al. 1998). To calculate maximum experienced evapotranspiration for other crops (e.g., wheat, rice, etc.), k_c coefficient must be multiplied to ET_0. Finally, AET is calculated based on equation (1):

$$\mathrm{AET} = \alpha(k_c \mathrm{ET}_0) \quad (1)$$

where α is a fraction based on the prevailing land surface temperature to reduce the PET to AET. Many studies have applied satellite images to estimate actual evaporation (Jalilvand et al. 2019; Rezaei et al. 2021; Rahimpour and Rahimzadegan 2021; Sima, Ahmadalipour, and Tajrishy 2013; Ghahreman and Rahimzadegan 2022; Bhattacharjee et al. 2021). We utilized MOD16 product to estimate PET over the studied area. The MOD16 algorithm uses satellite data from MODIS and uses the Penman-Monteith approach described in the literature (Qiaozhen et al. 2007; Qiaozhen, Zhao, and Running 2011). Among of available global AET products (Table-S1 in the Supplementary Material), we chose Penman-Monteith-Leuning Evapotranspiration version 2 (PML V2) available from 2002; since PML V2 i) has good spatial (500 metre) and temporal (8-day) resolution (Yongqiang et al. 2019), ii) separates AET into three components as evapotranspiration from vegetation (E_c), direct evaporation from the soil (E_s) and vaporization of intercepted rainfall from vegetation (E_i), and iii) performed well against observations at 95 flux sites across the globe (Yongqiang et al. 2019). As shown in Figure S2 (details in Appendix A), comparison between AET from PML V2 (E_c) and the reported values by FAO (FAO 2015) for the Helmand River Basin showed high correspondence (RMSE = 13 mm and correlation = 78%).

2.4. Water consumption in the agricultural sector

Calculated E_c from PML V2 is the actual amount of water consumed by crops. A significant portion of the allocated water for irrigation is not directly utilized for crop growth due to losses such as seepage through the bunds of canals (Rai, Singh, and Upadhyay 2017). Thus, the Irrigation efficiency should be considered to estimate the actual volume of delivered water for agricultural activities from the source. Irrigation system efficiency in the most developed countries is about 70–90% (FAO 2016). The irrigation efficiency is about 25–30% for Afghanistan (Qureshi 2002) and about 35% for Iran (Madani 2014). The annual volume of consumed water (CW_i) for agricultural activities in km^3 is estimated by:

$$\mathrm{CW}_i = (E_{ci}/e) * \mathrm{A}_{ci} * 10^{-6} \quad (2)$$

where A_{ci} is the annual croplands area (km^2) in the year i (2002, 2008, 2013, 2017 and 2021 detected by Random Forest classifier). In Equation (2), e is irrigation efficiency (assumed 0.3) and E_{ci} is annual evapotranspiration from vegetation (by PML V2 in mm).

3. Results and discussion

3.1. Land-use change

The accuracy of training and testing in the classification by Random Forest were 99% and 95%, respectively (by Cohen's Kappa score- more detail is presented GEE Java Script codes section). Based on average values of croplands area in 2002–2021 (Figure 2), the majority (over 60%) of the total croplands of the basin are in HM. As shown in pie chart of Figure 2, 14, 7 and 7% of croplands are in KAJU, FRH and IRB, respectively. ARGU, ADR, EU and KHS include about 10% of the total cropland area. Due to a low contribution to the total cropland area, HEN, HMD and KHP are excluded from the water consumption calculation. The cropland area of the basin has increased about 3500 km^2 (i.e., 273% from 2008 to 5475 km^2) since 2002. As shown in Figure 1c, the most of cropland development has occurred near reservoirs and close to rivers of the basin because of easy access to surface water. In HM, KAJU and FRH, croplands have increased 1456 (203% increase), 786 km^2 (400% increase) and 263 km^2 (425% increase). Also, the most of increase has been detected in IRB, i.e., croplands area in 2021 is 25 times higher than 2002 (23 to 603 km^2). This is very important to consider that in the beginning of the 2000s (e.g., in 2002), due to extremely dry condition, farming activity was almost completely zero in IRB (a.k.a. the Sistan). However, before this dry period, the Sistan region was one of the most important centres of agricultural activities in Iran and the Hamun Lake was in normal condition (Iran Ministry of Agriculture 2018). Therefore, IRB farming activities cannot be the main reason of desiccation, because only 7% of the total cropland area is in this sub-basin.

The United Nations has reported that Opium cultivation in Afghanistan has increased from 900 km^2 (in 2000) to over 3300 km^2 (in 2017). The major opium centres of the country ($\approx$ 75%) are found in the provinces located in the Helmand Basin (Figure S5) (UNODC 2020). In 2017, about 2500 km^2 (75% of the total) of opium farmlands could be found in the Helmand Basin. The studied area's crop pattern in Afghanistan comprises chiefly irrigated wheat and vegetables (FAO 2015). Also, in IRB sub-basin, 53 and 42% of croplands are allocated to wheat and vegetables cultivation, respectively (Chehrenegar and Bayati 2022).

In Figure 2, different thresholds for the Landsat NDVI used to estimate cropland area are compared with the Random Forest algorithm results and the literature. A study by (Hajihosseini et al. 2020) used supervised machine learning techniques in remotely sensed data to estimate that the croplands areas in HM covered 1030 km^2, 1220 km^2, and 1670 km^2 in 1990, 2001, and 2011, respectively (shown in Figure 2 for HM). Based on our comparison, the best corresponding threshold for cropland estimation in each sub-basin is suggested in Figure 2. For the whole basin (Figure 2 labelled as 'All'), results comply with the detected area by applying a threshold of 0.4–0.5. The NDVI method is a simple method for detecting croplands. Using recommended thresholds of NDVI in this study makes this simple method more reliable in the studied area. However, in some years (e.g., 2021 in IRB), the NDVI thresholding method ended to considerable difference compared to Random Forest results. Also, some other studies reported different values for cropland area of the Helmand Basin, which are overestimation based on the basins' water resources (more detail in Appendix D).

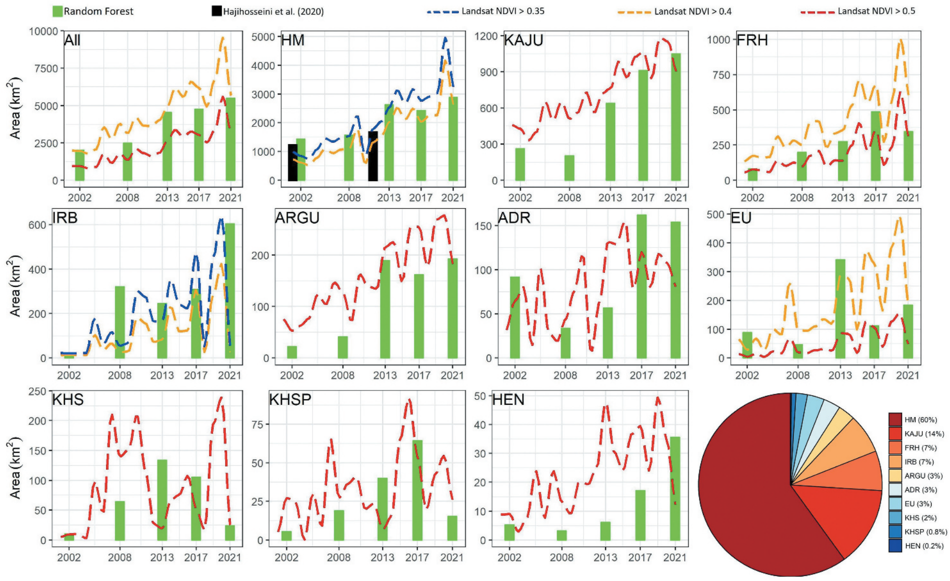

Figure 2. Annual cropland area in the different sub-basins of the Helmand Basin as determined by Random Forest and NDVI thresholding.

3.2. Evapotranspiration change

The annual PET of the sub-basins (Figure S1-a) has had a decreasing trend since 2001, meaning climatic conditions cannot be the leading cause of the increasing trend of AET (Figure S1-b). The range of PET change in different sub-basins represents the various climatic condition in the studied area. For example, HMD with a desert climate has the highest PET values in the basin. On the other hand, HEN, with snow climate and dry summers, has the lowest PET values (<2000 mm/year) (more detail on climatic condition of the studies area provides in Figure S3). Also, AET in the basin's main agricultural centres (i.e., HM and KAJU) has increased. After 2010, the mean of AET has significantly grown all over these sub-basins, which means more water is available for crops. In HM, after 2004, the mean of annual AET has jumped from 310 mm to 350 mm. In KAJU, we can observe the constant increase of annual AET in croplands from less than 300 mm to over 400 mm annually. The croplands area of the basin has increased, and more water availability for crops (captured by an increasing trend of AET) intensifies the volume of consumed water in the agriculture sector (see Equation (2).

3.3. Water consumption in the agriculture sector

The Agricultural Water consumption of the basin has increased more than three times from 2 to 6.2 km^3 since 2002 (shown in Figure 3). Most growth has been observed in four sub-basins, i.e., 1.9, 1.1, 0.6 and 0.3 km^3 in HM, KAJU, IRB and FRH, respectively. A long severe drought period between 1998 and 2004 in the Helmand basin has caused a considerable decrease in the amount of water flowing through the Hirmand River in the

Figure 3. Annual water consumption in croplands for the main centres of agriculture activities in the studied area.

location of international border (Akbari et al. 2022). Also, there has been a rapid expansion of agricultural activities in Afghanistan in the last two decades coincident with the relative political stability in the country between the two periods of Taliban governance (Shroder and Jan Ahmadzai 2016). Passing dry condition of the basin and the Afghanistan war in the beginning of the 2000s, from 2002 to 2008 (6 years), water consumption increased by 0.4 km^3. These changes intensified between 2008 to 2013 (5 years) to more than 2.7 km^3 (about seven times faster than 2002–2008). From 2013 to 2017, the increasing variation declined to about 0.2 km^3, which should be attributed to reaching the capacity of cropland development in the basin based on the available infrastructures in Afghanistan. After 2013, water consumption in Afghanistan sub-basins fluctuates (e.g., HM, FRH, and EU) or converges (compare 2008–2013 and 2017–2021 in KAJU). We estimated that water consumption is IRB is between 0.4–0.7 km^3 (excluding extremely dry years in the beginning of 2000s). The Department of Environment of Iran (DOE) has estimated the agricultural water consumption in IRB sub-basin equal to 0.78 km^3, 85% from surface water and the rest from aquifers (Iran Department of Environment 2014). Also, Ministry of Agriculture of Iran reported that annually 0.385 km^3 water is being consumed for irrigation in the Sistan region where water deficiency led to farmers unemployment and migration. In 2013, Iran investigated 850 million U.S. dollar to increase efficiency of irrigation in the Sistan to solve the water stress in irrigation (Iran Ministry of Agriculture 2018). As shown in Figure 1c, Iran regulates water by Chah-nimeh Reservoirs (CNRs) to meet the water need of the Sistan as a very dry region. The capacity of CNRs was 0.630 km^3, but this capacity increased to 1450 km^3 after 2008 providing opportunities for more water regulation across this country to meet needs. This increase in CNRs capacity is potential to intensify negative effect of anthropogenic regulations on the lakes downstream. However, about 90% of agricultural water consumption is happening in Afghanistan. This country has more control over the surface water resources in the basin, which has a huge impact on the lakes downstream. For example, the inauguration of Kamal-Khan dam (close to Iran-Afghanistan international border) in 2021 adds another control on the magnitude and timing of flow deliveries to Iran, which could increase downstream stress and aggravate the condition of the lakes (Akbari et al. 2022). More than 1700 km^2 of cropland development is planned to be irrigated by the Kamal-Khan Dam in the future (H. Mianabadi, Alioghli, and Morid 2021). Bilateral negotiation between both countries is urgent to obtain an optimal policy which can meet the needs and minimize the negative impacts.

4. Conclusion

In this study, we investigated spatio-temporal changes in agricultural consumed water over the Helmand Basin, the largest basin in Afghanistan (covering almost half of the country). In Afghanistan, the lack of hydrologic data is a very crucial problem (Ahlers et al. 2014; Williams-Sether 2008); thus, to solve this issue, we utilized remote sensing data. We found that the croplands of the basin and consumed water in the agriculture sector have increased, respectively, more than 273% (about 3500 km^2) and 310% (4.2 km^3) since 2002. This phenomenon has consequences on the Hamun Lake, water bodies located downstream. Recent studies have shown that anthropogenic activities (e.g., damming) are the leading causes of flow reduction downstream and desiccation of the lakes (Akbari et al. 2022). Therefore, this study helps policymakers for restoring the Hamun Lake by quantifying spatio-temporal water consumption changes in last two decades across all sub-basins of the Helmand Basin. The results of this study highlights the urgency of bilateral negotiation between Iran and Afghanistan to provide environmental flow of the Hamun Lake.

5. Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. Data availability and GEE java script codes

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Links for Java Script codes to the online platform of GEE (https://earthengine.google.com/) are presented separately below for each section of this study:

- Estimation of croplands using Random Forest:

https://code.earthengine.google.com/547ce4bb2c0afada05c8a5373c20658a

- Estimation of croplands using Landsat NDVI:

https://code.earthengine.google.com/193543fd0894fbc2f5004537d3045a1e

- Estimation of land use classes using MODIS (Friedl and Sulla-Menashe 2019):

https://code.earthengine.google.com/c59f97bd84d654d51993bab39f24a3d4

- Estimation of PET from MODIS and AET from PML V2 (Zhang et al. 2019):

https://code.earthengine.google.com/a6bfad5405b1aa62b1b0ae0a008c8b53

- Estimation of seasonal and permanent water body from JRC (Pekel et al. 2016):

https://code.earthengine.google.com/4b5caedfc205ce0a0ebe690e9fce1ba5

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Ahlers, R., L. Brandimarte, I. Kleemans, and S. Hashmat Sadat. 2014. "Ambitious Development on Fragile Foundations: Criticalities of Current Large Dam Construction in Afghanistan." *Geoforum* 54: 49–58. July 2014 Elsevier Ltd. doi:10.1016/j.geoforum.2014.03.004.

Akbari, M., A. Baubekova, A. Roozbahani, A. Gafurov, A. Shiklomanov, K. Rasouli, N. Ivkina, B. Kløve, and A. Torabi Haghighi. 2020. "Vulnerability of the Caspian Sea Shoreline to Changes in Hydrology and Climate." *Environmental Research Letters*. doi:10.1088/1748-9326/abaad8.

Akbari, M., A. Mirchi, A. Roozbahani, A. Gafurov, B. Kløve, and A. Torabi Haghighi. 2022. "Desiccation of the Transboundary Hamun Lakes Between Iran and Afghanistan in Response to Hydro-Climatic Droughts and Anthropogenic Activities." *Journal of Great Lakes Research*. doi:10.1016/J.JGLR.2022.05.004.

Akbari, M., A. Torabi Haghighi, M. Mahdi Aghayi, M. Javadian, M. Tajrishy, and B. Kløve. 2019. "Assimilation of Satellite-Based Data for Hydrological Mapping of Precipitation and Direct Runoff Coefficient for the Lake Urmia Basin in Iran." *Water* 11: (8): 1624. Multidisciplinary Digital Publishing Institute.

Akhter, M. 2015. "The Hydropolitical Cold War: The Indus Waters Treaty and State Formation in Pakistan." *Political Geography* 46: 65–75. doi:10.1016/j.polgeo.2014.12.002, Elsevier.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. "Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56." *Fao, Rome* 300 (9): D05109. (and others).

Bhattacharjee, J., M. Rabbil, N. Fazel, H. Darabi, B. Choubin, M. Motiur Rahman Khan, H. Marttila, and A. Torabi Haghighi. 2021. "Accuracy Assessment of Remotely Sensed Data to Analyze Lake Water Balance in Semi-Arid Region." *The Science of the Total Environment* 797: 149034. November. Elsevier. doi:10.1016/J.SCITOTENV.2021.149034.

Breiman, L. 2001. "Random Forests." *Machine Learning* 45 (1): 5–32. doi:10.1023/A:1010933404324.

Chehrenegar, B., and M. Bayati. 2022. *Develop a Participatory Plan for Sustainable and Integrated Land Use Planning with an Emphasis on the Development of Sustainable Livelihoods*. Iran: International Plan for Comprehensive Management of Natural Resources and Socio-Economic Development of Sistan.

Commission, H. 1973. "The 1973 Helmand River Treaty." https://www.internationalwaterlaw.org/documents/regionaldocs/1973_Helmand_River_Water_Treaty-Afghanistan-Iran.pdf.

Ehsani, M. R., A. Behrangi, A. Adhikari, Y. Song, G. J. Huffman, R. F. Adler, D. T. Bolvin, and E. J. Nelkin. 2021. "Assessment of the Advanced Very High-Resolution Radiometer (AVHRR) for Snowfall Retrieval in High Latitudes Using CloudSat and Machine Learning." *Journal of Hydrometeorology* 22: 1591–1608.

FAO. 2015. "Analysis on Water Availability and Uses in Afghanistan River Basins: Water Accounting Through Remote Sensing (WA+) in Helmand River Basin." FAO Project TCP/AFG/ TCP/AFG/ *TCP/AFG/* 3402 (March): 50.

FAO. 2016. "Country Water Report." Rome. http://www.fao.org.

Fraiture, D., D. M. Charlotte, and D. Wichelns. 2010. "Investing in Water for Food, Ecosystems, and Livelihoods: An Overview of the Comprehensive Assessment of Water Management in Agriculture." *Agricultural Water Management* 97 (4): 495–501. (Elsevier).

Friedl, M., and D. Sulla-Menashe. 2019. "MCD12Q1 MODIS/Terra+aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data Set]." doi:10.5067/MODIS/MCD12Q1.006.

Ghahreman, R., and M. Rahimzadegan. 2022. "Calculating Net Radiation of Freshwater Reservoir to Estimate Spatial Distribution of Evaporation Using Satellite Images." *Journal of Hydrology* 605 (February): 127392. Elsevier. doi:10.1016/J.JHYDROL.2021.127392.

Ghajarnia, N., M. Akbari, P. Saemian, M. Reza Ehsani, S.-M. Hosseini-Moghari, A. Azizian, Z. Kalantari, et al. 2022. "Evaluating the Evolution of ECMWF Precipitation Products Using Observational Data for Iran: From ERA40 to ERA5." *Earth and Space Science* John Wiley & Sons, Ltd 9 (10): e2022EA002352. 10.1029/2022EA002352

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore. 2017. "*Google Earth Engine: Planetary-Scale Geospatial Analysis for Everyone*". *Remote Sensing of Environment* 202: 18–27.

Haghighi, T., M. S. Ali, J. Bhattacharjee, M. Emin Sönmez, M. Noury, N. Yilmaz, R. Noori, and B. Kløve. 2020. "The Impact of River Regulation in the Tigris and Euphrates on the Arvandroud Estuary." *Progress in Physical Geography* 44 (6): 948–970. doi:10.1177/0309133320938676.

Hajihosseini, M., H. Hajihosseini, S. Morid, M. Delavar, and M. J. Booij. 2020. "Impacts of Land Use Changes and Climate Variability on Transboundary Hirmand River Using SWAT." *Journal of Water and Climate Change* 11 (4): 1695–1711. (IWA Publishing).

Hunsaker, D. J., P. J. Pinter, E. M. Barnes, and B. A. Kimball. 2003. "Estimating Cotton Evapotranspiration Crop Coefficients with a Multispectral Vegetation Index." *Irrigation Science* 22 (2): 95–104. (Springer).

Iran Department of Environment. 2014. "Determining the Environmental Flow Needs of the Hamun Lakes." https://crw.doe.ir/portal/file/?1249740/اهون.pdf .

Iran Ministry of Agriculture. 2018. *Cultivation Pattern of Agricultural and Horticultural Crops in Sistan Plain*. Iran: Iran Ministry of Agriculture.

Jalilvand, E., M. Tajrishy, S. Alsadat Ghazi Zadeh Hashemi, and L. Brocca. 2019. "Quantification of Irrigation Water Using Remote Sensing of Soil Moisture in a Semi-Arid Region." *Remote Sensing of Environment* 231 (September): 111226. Elsevier. doi:10.1016/J.RSE.2019.111226.

Jensen, J. R. 2015. *Introductory Digital Image Processing: A Remote Sensing Perspective*. 4th ed. United States of America: Pearson Education, Inc.

Keshavarz, A., S. Ashrafi, N. Hydari, M. Pouran, and E. Farzaneh. 2005. "Water Allocation and Pricing in Agriculture of Iran". In *Water Conservation, Reuse, and Recycling: Proceeding of an Iranian American Workshop*. 153–172. *Washington, DC*: *The National Academies Press*.

Madani, K. 2014. "Water Management in Iran: What is Causing the Looming Crisis?" *Journal of Environmental Studies and Sciences* 4 (4): 315–328. Springer. doi:10.1007/s13412-014-0182-z.

Mianabadi, H., S. Alioghli, and S. Morid. 2021. "Quantitative Evaluation of 'No-Harm' Rule in International Transboundary Water Law in the Helmand River Basin." *Journal of Hydrology* 599 (August): 126368. Elsevier. doi:10.1016/J.JHYDROL.2021.126368.

Mianabadi, A., K. Davary, H. Mianabadi, and P. Karimi. 2020. "International Environmental Conflict Management in Transboundary River Basins." *Water Resources Management* 34 (11): 3445–3464. doi:10.1007/s11269-020-02576-7.

Ministry of Energy (MoE). 2014. *Studies of the Second Phase of Water Supply in Sistan Plain*. Tehran: Ministry of Energy.

Omer, A. M. 2008. "Energy, Environment and Sustainable Development." *Renewable and Sustainable Energy Reviews* 12 (9): 2265–2300. doi:10.1016/j.rser.2007.05.001.

Pekel, J. F., A. Cottam, N. Gorelick, and A. S. Belward. 2016. "High-Resolution Mapping of Global Surface Water and Its Long-Term Changes." *Nature* 540 (7633): 418–422. Nature Publishing Group. doi:10.1038/nature20584.

Qiaozhen, M., F. Ann Heinsch, M. Zhao, and S. W. Running. 2007. "Development of a Global Evapotranspiration Algorithm Based on MODIS and Global Meteorology Data." *Remote Sensing of Environment* 111 (4): 519–536. (Elsevier).

Qiaozhen, M., M. Zhao, and S. W. Running. 2011. "Improvements to a MODIS Global Terrestrial Evapotranspiration Algorithm." *Remote Sensing of Environment* 115 (8): 1781–1800. (Elsevier).

Qureshi, A. S. 2002. Water Resources Management in Afghanistan. *Internation Water Management Institute*, no. 14: 30. http://www.afghaneic.net/library/hydrologicalsurveys/wor49.pdf.

Rahimi, R., H. Tavakol-Davani, and M. Nasseri. 2021. "An Uncertainty-Based Regional Comparative Analysis on the Performance of Different Bias Correction Methods in Statistical Downscaling of Precipitation."*Water Resources Management*, 1–16. Springer.

Rahimpour, M., and M. Rahimzadegan. 2021. "Assessment of Surface Energy Balance Algorithm for Land and Operational Simplified Surface Energy Balance Algorithm Over Freshwater and Saline Water Bodies in Urmia Lake Basin." *Theoretical and Applied Climatology* 143 (3–4): 1457–1472. Springer. doi:10.1007/S00704-020-03472-1/FIGURES/8.

Rai, R. K., V. P. Singh, and A. Upadhyay. 2017. "Chapter 18 - Scheme Irrigation Efficiency". In *Planning and Evaluation of Irrigation Projects*, In edited by R. K. Rai, V. P. Singh, and A. Upadhyay, 525–538. Academic Press. doi:https://doi.org/10.1016/B978-0-12-811748-4.00018-2

Rashki, A., D. G. Kaskaoutis, C. J. D. W. Rautenbach, P. G. Eriksson, M. Qiang, and P. Gupta. 2012. "Dust Storms and Their Horizontal Dust Loading in the Sistan Region, Iran." *Aeolian Research* 5: 51–62. doi:10.1016/j.aeolia.2011.12.001, Elsevier B.V.

Ray, S. S., and V. K. Dadhwal. 2001. "Estimation of Crop Evapotranspiration of Irrigation Command Area Using Remote Sensing and GIS." *Agricultural Water Management* 49 (3): 239–249. Elsevier. doi:10.1016/S0378-3774(00)00147-5.

Rezaei, E. E., G. Ghazaryan, R. Moradi, O. Dubovyk, and S. Siebert. 2021. "Crop Harvested Area, Not Yield, Drives Variability in Crop Production in Iran." *Environmental Research Letters* 16 (6): 064058. IOP Publishing. doi:10.1088/1748-9326/ABFE29.

Senay, G. B., M. Friedrichs, R. K. Singh, and N. Manohar Velpuri. 2016. "Evaluating Landsat 8 Evapotranspiration for Water Use Mapping in the Colorado River Basin." *Remote Sensing of Environment* 185: 171–185. Elsevier.

Shroder, J. F., and S. Jan Ahmadzai. 2016. *Transboundary Water Resources in Afghanistan: Climate Change and Land-Use Implications*. Cambridge: Elsevier.

Sima, S., A. Ahmadalipour, and M. Tajrishy. 2013. "Mapping Surface Temperature in a Hyper-Saline Lake and Investigating the Effect of Temperature Distribution on the Lake Evaporation." *Remote Sensing of Environment* 136 (September): 374–385. doi:10.1016/J.RSE.2013.05.014.

Skoulikaris, C., and A. Zafirakou. 2019. "River Basin Management Plans as a Tool for Sustainable Transboundary River Basins' Management." *Environmental Science and Pollution Research* 26 (15): 14835–14848. doi:10.1007/s11356-019-04122-4.

Tan, S., B. Wu, N. Yan, and H. Zeng. 2018. "Satellite-Based Water Consumption Dynamics Monitoring in an Extremely Arid Area." *Remote Sensing* 10 (9). doi:10.3390/rs10091399.

Thomas, V., and M. Mahmoudzadeh Varzi. 2015. "A Legal Licence for an Ecological Disaster: The Inadequacies of the 1973 Helmand/Hirmand Water Treaty for Sustainable Transboundary Water Resources Development." *International Journal of Water Resources Development* 31 (4): 499–518. Routledge. doi:10.1080/07900627.2014.1003346.

UNODC. 2020. "Afghanistan Opium Survey 2020." https://www.unodc.org/unodc/en/crop-monitoring/index.html?tag=Afghanistan.

WHO . 2016. "Global Health Observatory Data Repository." *World Health Organization* . https://apps.who.int/gho/data/view.main.AMBIENTCITY2016?lang=en

Williams-Sether, T. 2008. *Streamflow Characteristics of Streams in the Helmand Basin, Afghanistan*. United States of America: US Department of the Interior, US Geological Survey.

Yongqiang, Z., D. Kong, R. Gan, H. S. C. Francis, T. R. McVicar, Q. Zhang, and Y. Yang. 2019. "Coupled Estimation of 500 M and 8-Day Resolution Global Evapotranspiration and Gross Primary Production in 2002–2017." *Remote Sensing of Environment* 222: 165–182. Elsevier.

Zaki, A., A. T. H. Nizar, P. M. Rossi, M. J. Tourian, and B. Kløve. 2019. "Monitoring Groundwater Storage Depletion Using Gravity Recovery and Climate Experiment (GRACE) Data in Bakhtegan Catchment, Iran." *Water* 11: 7. Multidisciplinary Digital Publishing Institute: 1456.

Zeitoun, M., M. Goulden, and D. Tickner. 2013. "Current and Future Challenges Facing Transboundary River Basin Management." *Wiley Interdisciplinary Reviews: Climate Change* 4 (5): 331–349. doi:10.1002/wcc.228.