An Image Processing Approach for Dynamic Monitoring of Reservoir Operation

Mohammad Amin Raoof[1], Mohammad Danesh-Yazdi[1,3], Majid Bayati[1,2],and Mostafa Fadaeifard[3]

1- Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

2- Remote Sensing Research Center, Sharif University of Technology, Tehran, Iran

3- UNESCO Chair for Water and Environment Management in Sustainable Cities, Sharif University of Technology, Tehran, Iran

3- Committee on Flood Assessment of Large Dams, ICOLD, Tehran, Iran

Email: danesh@sharif.edu

Abstract

Optimal dam operation before and during flood events is critical to flood control and mitigation of the risks threatening downstream regions. In this studywe present an approach for a dynamic monitoring of reservoir operation, leveraging satellite data and image processing techniques that were implemented within the Google Earth Engine platform. In particular, we examined the validity of the proposed approach to assess the performance of the Dez and Karkheh dams, i.e., two major dams in the Khuzestan Province, Iran, during the massive flash flood of Spring, 2019. Using Sentinel 2 high-resolution imagery, our results show a strong correlation between the observed and estimated times series of stored water volume for both dams, witnessing the efficiency of the proposed approach for monitoring dam operations in the absence of real-time ground data. Furthermore, although the above dams played a vital role in regulating a large portion of the so-called flood, the history of stored water volume in both reservoirs over at least a three-month period before the flood event proves that they could be operated more effectively to completely mitigate the devastating damages cause in the downstream regions.

Keywords: Khuzestan Flood of Spring 2019, Dez Dam, Karkheh Dam, Remote Sensing, Google Earth Engine

1. INTRODUCTION

Needless to mention, one of the long-term goals of dam construction in a region is to control flash floods during storm events. Nevertheless, inappropriate reservoir operation before and during flood events can cause catastrophic damages in the downstream areas due to an unanticipated release of a large volume of water within a short period of time. The Khuzestan Province (KP), located in southwest, Iran, encountered a massive amount of precipitation in Spring, 2019, that led to river flooding, loss of lives,and destructive damage to infrastructures, agriculture fields and livestock.Predictions prior to the flood event warned that approximately 6.7 BCM of water was anticipated to drain KPby the coming days. However, the input volume of water to merely the Karkheh dam has reached a value of 13 up to 14 BCM, surpassing the peak magnitude of 12.2 BCM ever recorded over the past 65 years.

Since the flood event, controversial debates have been circulating among experts and authorities discussing the possibility of a much more effective operation of the dams in this region to mitigate the flood damages. In particular, the performance of the Karkheh and Dez dams (i.e., the first and third largest reservoirs in the country with respect to storage capacity, respectively) has been of particular attention. While Karkheh, Dez, and Karoon Dams played a critical role in controlling a large portion of 2019 floods in the region, they could be operated with a more effective schedule to reduce the flood damages in KP.Indeed, water crisis in the country exacerbated by long periods of drought during the past two decades have forcedlocal authorities towards conservative decisions to store as much as water for drinking and agricultural purposes.As a result, gradual releases from these damsdid not lead to a complete control of the Spring 2019 flood.

In this study, we propose a computationally inexpensive approach that benefits remote sensing data and techniques todynamically estimate the change of stored water volume in reservoirs. The applicability of the approach wasdemonstrated for the Karkheh and Dez Dams. To this end, we firstdelineated the temporal change of surface area in these reservoirs by using the Xmeans classification method implemented on

Sentinel 2 high-resolution images. Then,the amount of stored water volume was estimated by using the area-volume-level curve of each reservoir, separately. The results werevalidated againstdata recordedfrom the gauging stations at both dams.

2. GEOGRAPHIC AND CLIMATIC CHARACTERISTICS OF THE KHUZESTAN PROVINCE

The 64057 km^2KP located in southwest, Iran (with longitudes between $47° 41'$E and $50° 39'$E and latitudes between $29° 58'$N and $33° 04'$N)is shared bymountainsin the East and Northeast, plains spanning from the south of Dezful to bounds of the Persian Gulf, and vegetation in the Northeast. The average annual precipitation fluctuates between 150 mm in the Southwest and 1000 mm in the Northeast. While KPownsonly a 4% of the total area of the country, it encompasses nearly33% of surface water resources [1].In recent decades, some large dams, namely the Dez, Karkheh, and Karoon dams have been constructed on the Dez, Karkheh, and KaroonRivers, respectively, to supply water for irrigation, produce hydro-electricity, and control seasonal floods.

Figure 1 depicts the geographical location ofthe Karkheh and Dezdams. Regarding a remarkable number of cities andpopulation residing in the downstream of these dams as well as high flow rate of Karkheh and Dez rivers draining into the corresponding dams signify the importance of appropriate reservoir operation in this region to mitigate the risk of devastating damages due to floods.

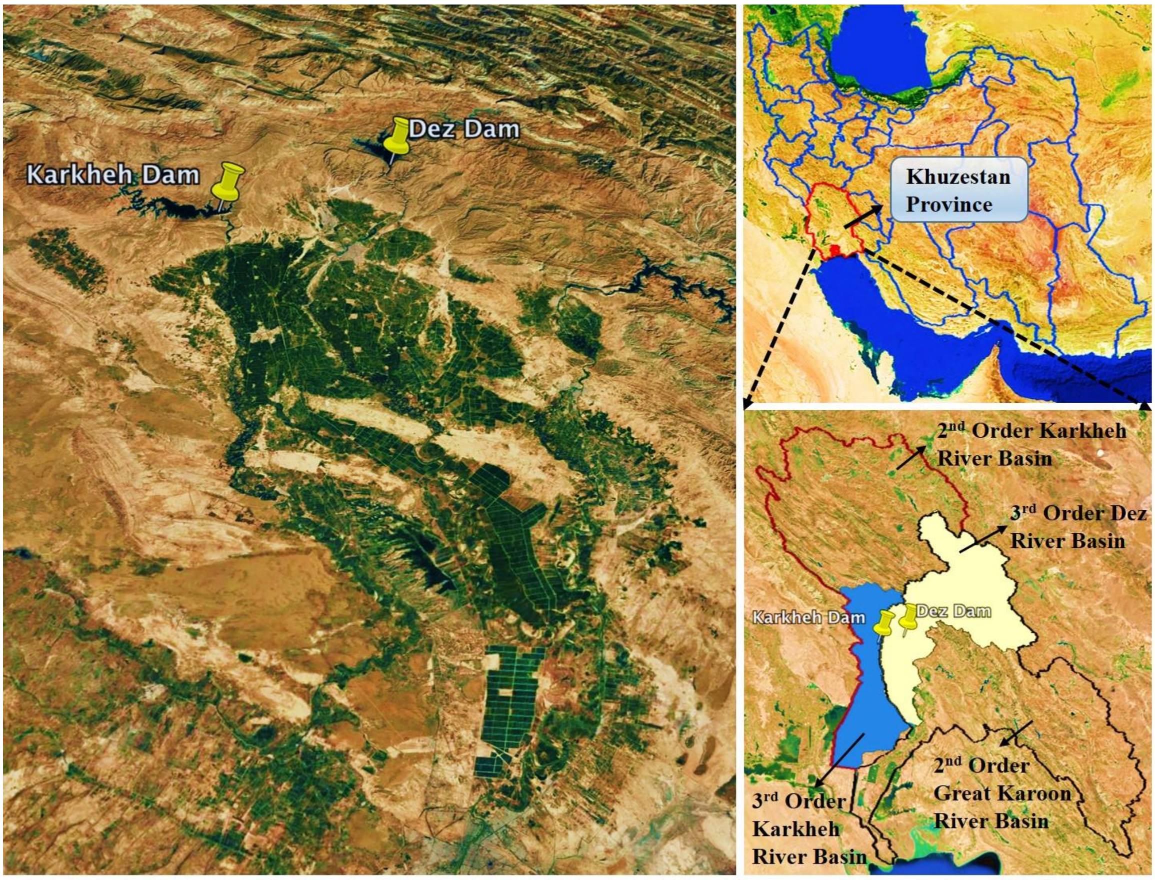

Fig. 1 Satellite image of the geographical location of the Dez and Karkheh Dams, and thedownstream cities (Image credit: Google Earth)

Figures 2 and 3 also compare average precipitation depth in four months of 2018-2019 water year (prior to the flood event) against the previous year, 50-year and, 11-year averages in the Great Karoon and Karkheh River Basins, respectively. It is seen that the precipitation depth in March-April 2019 was more than two times and four times greater than long-term averages in the Great Karoonand Karkheh River Basins, respectively.

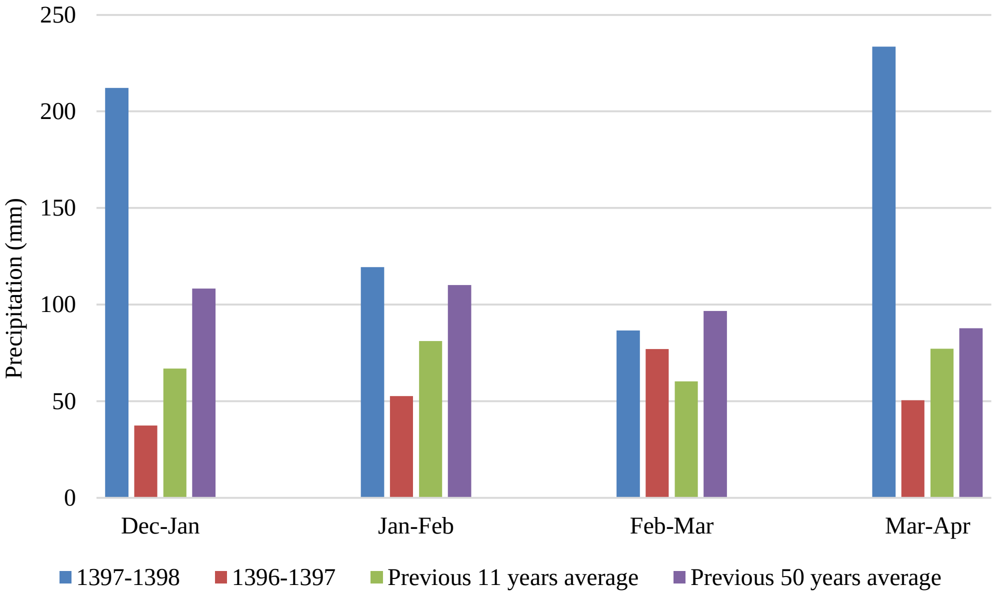

Fig 2. Total precipitation depth in the Great KaroonRiver Basin (Data source: IWRMC)

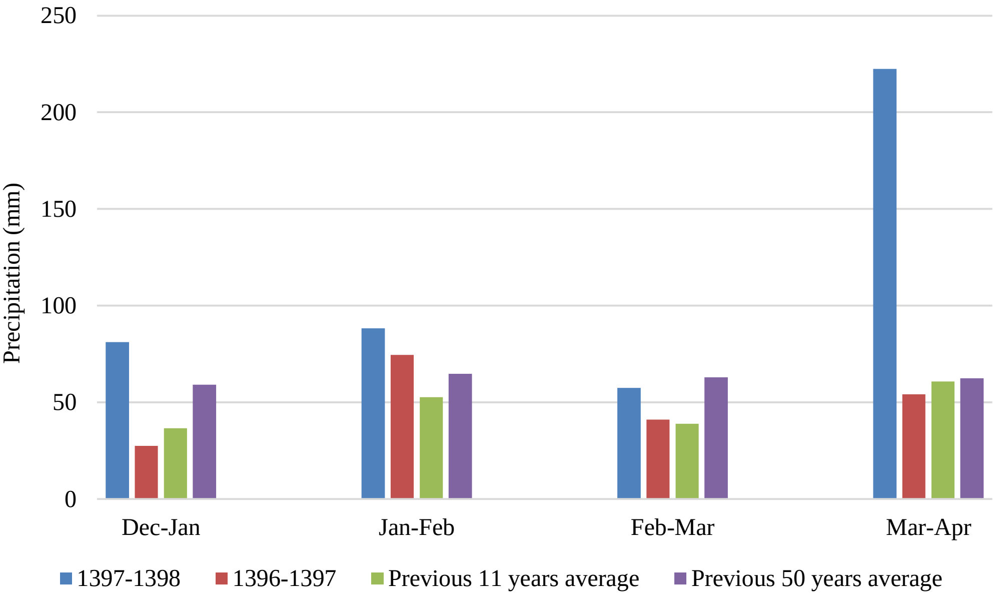

Fig 3. Total precipitationdepth in the Karkheh River Basin (Data source: IWRMC)

3. METHODAND DATA

In this study,Sentinel 2 satellite imagery with a 5-day temporal resolutionand 10-meter spatial resolutionwere used within the Google Earth Engine platform [2] to delineate the surface area of water stored in the Karkheh and Dez dams. To this end,only cloud-free images at multiples instances between January $11^{th}$and May 16^{th} of 2019 were used.Having implemented atmospheric and geometric corrections, anunsupervised image classification technique, i.e., Xmeans algorithm [3],was employed to extract water storage boundary of dams. In this algorithm, the number of classes are not fixed but can be optimizedby the Bayesian Information Criterion (BIC), which is forced bySoil-Adjusted Vegetation Index (SAVI) and Normalized Difference Water Index (NDWI)for clustering purposes. A low-pass filter was alsoimplemented to remove the spot noise in the classification.Finally, the computed water surface areasfrom all images of a damweresubstituted into the area-volume-level curve of therelatingdam to estimate the time series of stored water volume.

4. RESULTS

Figures 4 and 5 illustrate the classified images of Dez and Karkheh dams, respectively, where the history of water surface area change is presented between January 11th and May 16th, 2019. Tables 1 and 2 also compare the water surface area and volume estimated from the image processing approach in section 3, to those obtained from the area-volume-height relationships using the measured height of water in the Dez and Karkheh dams, respectively. The average relative error of surface area between two approaches is equal to 1.12% and 3.25% for the Dez dam and Karkheh dam, respectively. The same metric for the estimated water volume is 1.23% and 4.13% for the Dez dam and Karkheh dam, respectively. The small difference between the results derived from image processing and observed data highlights the reliability of the proposed remote sensingbased approach for a continuous monitoring of reservoir operation. Nevertheless, the estimations suffer some inevitable errors due to the quality of satellite images, classification error, measurement of dam water level, accuracy of area-volume-level relationships for each dam, and ignoring the temporal change of these relationships due to the subsidence sediments in the reservoir. As an example of such errors is found in the satellite image of January 26th, 2019, which is noised by high humidity.

Table 1- Time Series of Water Surface Area and Volume in the Dez Dam

Date	Surface Area (Km^2)		Relative Error (%)	Volume ($\times 10^6$ m^3)		Relative Error (%)
	Remotely- Sensed Estimation	Observed		Remotely-Sensed Estimation	Observed	
Jan 11	52.96	52.69	-0.5	2060.70	2044.00	-0.8
Jan 26	48.45	52.72	8.1	1784.24	2045.60	12.8
Feb 05	56.65	55.69	-1.7	2295.93	2234.80	-2.7
Feb 20	52.75	52.17	-1.1	2047.08	2010.40	-1.8
Feb 25	51.74	51.25	-1.0	1984.20	1952.50	-1.6
Mar 02	51.72	50.83	-1.8	1982.96	1926.50	-2.9
Mar 07	51.01	50.74	-0.5	1938.52	1920.90	-0.9
Mar 12	51.15	50.88	-0.5	1947.36	1929.50	-0.9
Mar 22	51.37	52.08	1.4	1960.83	2004.70	2.2
Apr 21	56.77	59.31	4.3	2303.31	2451.20	6.0
Apr 26	58.04	58.9	1.5	2385.19	2429.90	1.8
May 06	58.95	61.31	3.8	2443.92	2554.40	4.3
May 11	61.05	62.39	2.1	2580.08	2612.50	1.2
May 16	61.47	62.52	1.7	2607.53	2619.40	0.5

Table 2- Time Series of Water Surface Area and Volume in the Karkheh Dam

Date	Surface Area (Km^2)		Relative Error (%)	Volume ($\times 10^6$ m^3)		Relative Error (%)
	Remotely-Sensed Estimation	Observed		Remotely-Sensed Estimation	Observed	
Jan 11	121.36	122.91	1.3	3435.57	3515.58	2.3
Jan 26	120.17	130.74	8.1	3380.38	3897.19	13.3
Feb 05	141.69	146.26	3.1	4392.19	4601.15	4.5
Feb 20	145.62	150.24	3.1	4567.64	4782.99	4.5
Feb 25	145.74	149.98	2.8	4573.20	4771.40	4.2
Mar 02	145.83	149.81	2.7	4577.09	4763.47	3.9
Mar 07	144.67	149.38	3.2	4523.92	4743.78	4.6
Mar 12	144.56	148.97	3.0	4519.08	4725.33	4.4
Mar 22	144.50	148.99	3.0	4516.47	4725.94	4.4
Mar 27	149.94	158.07	5.1	4770.70	5141.03	7.2
Apr 21	167.08	173.11	3.5	5596.17	5815.24	3.8
Apr 26	168.01	171.33	1.9	5640.26	5735.31	1.7
May 01	163.63	168.85	3.1	5431.61	5625.21	3.4
May 06	164.67	167.59	1.7	5481.32	5568.96	1.6
May 11	165.55	167.59	1.2	5523.48	5568.96	0.8
May 16	165.27	168.29	1.8	5509.98	5599.81	1.6

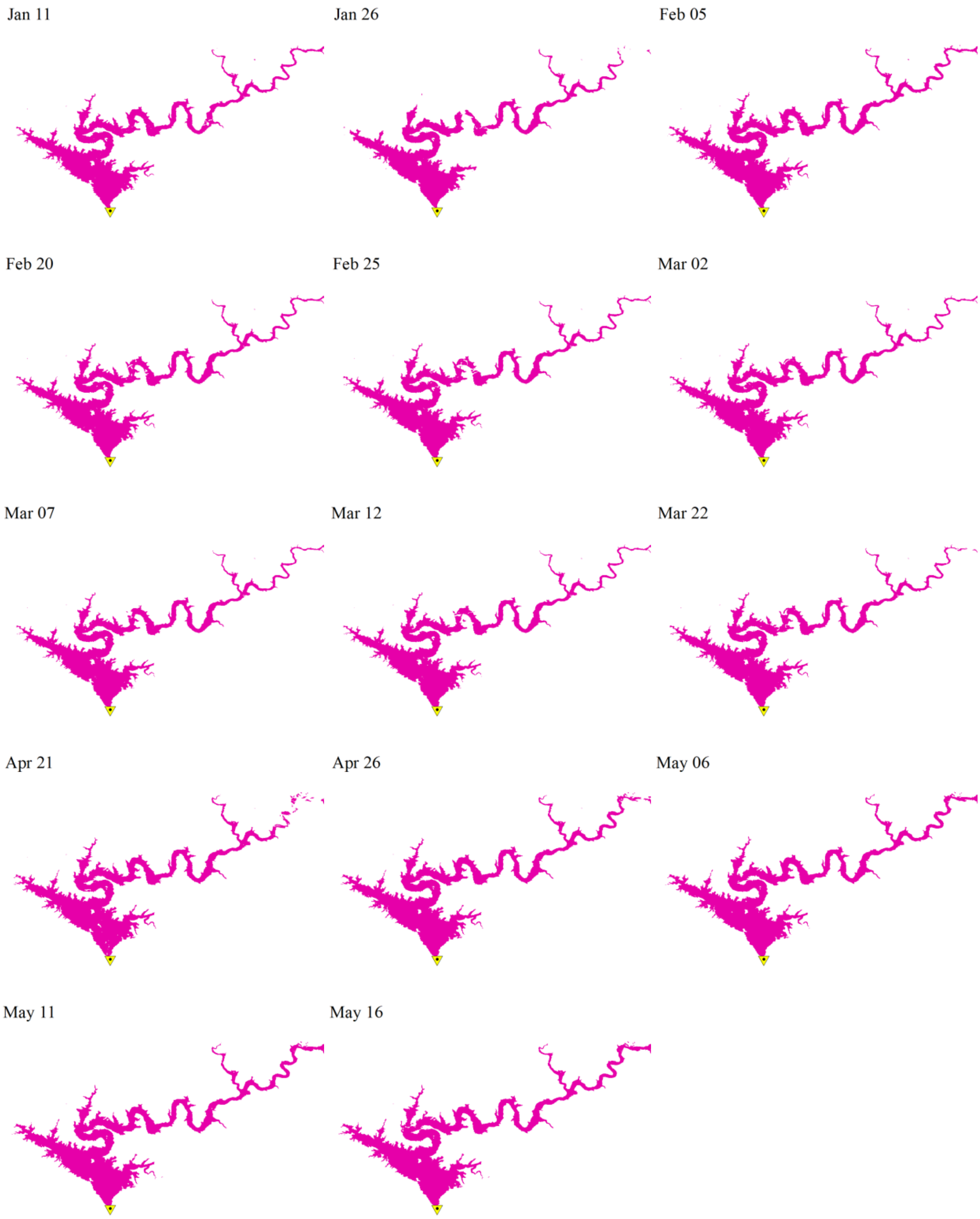

Fig 4. Schematic of water surface area in the Dez Dam between January 11th and May 16th, 2019, derived from Sentinel 2 imagery

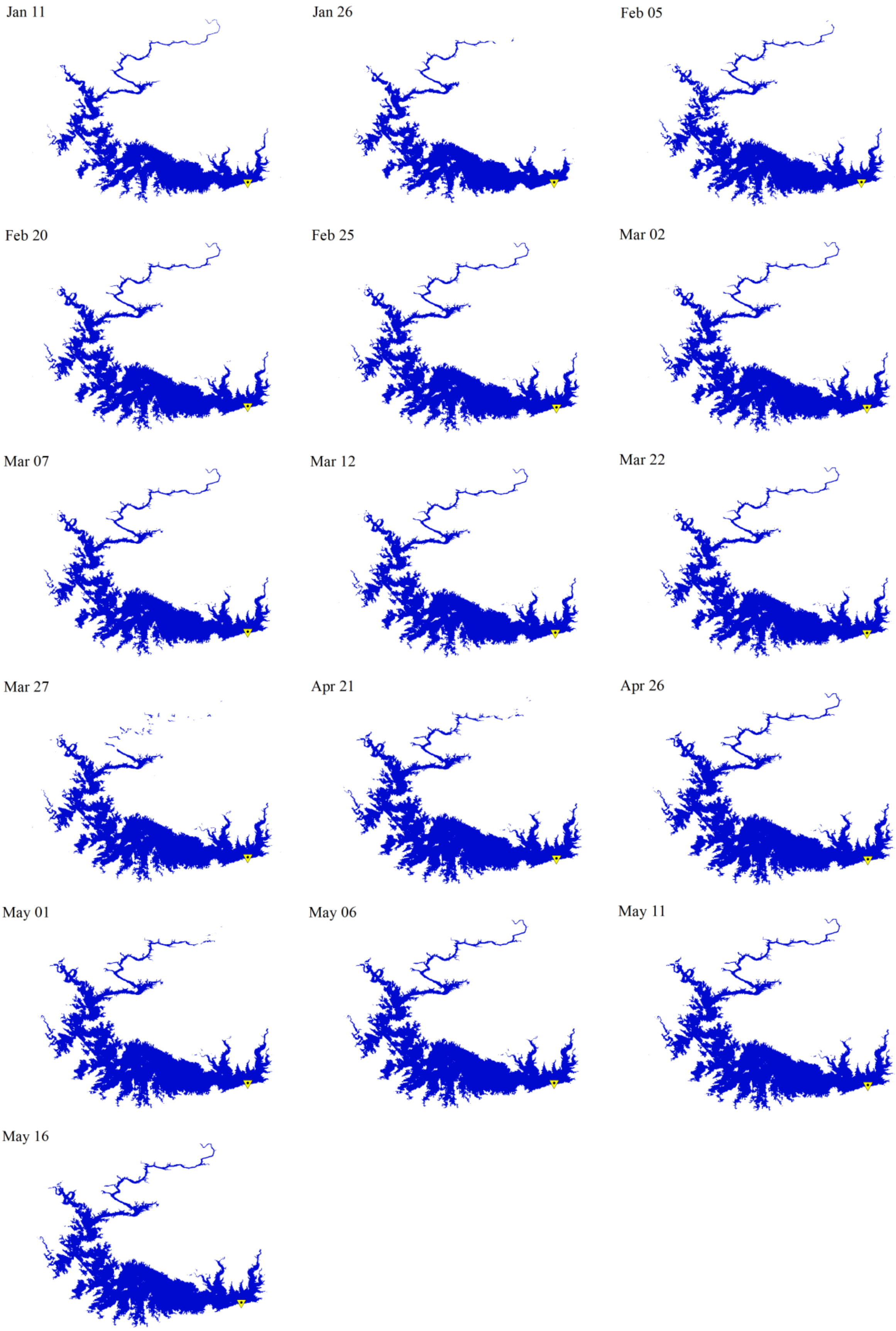

Fig 5. Schematic of water surface area in the Karkheh Dam between January 11th and May 16th, 2019, derived from Sentinel 2 imagery

5. DISCUSSION

Figures 6 and 7 indicate the time series of stored water volume in the Dez and Karkheh dams, respectively. For both dams, the stored water volume changes slightly within a month period before the flood events of 25th and 31st of March, 2019. Also, the storage volume changes by -14% and +8% betweenFebruary 5th and March 22nd, i.e., during a period of two weeks before the flood eventin the Dez and Karkheh dams, respectively. This observation witnesses that in spite of the warningsannounced by the Iran Meteorological Organization on theoccurrence of a possible flashy flood, sufficient capacity was not available toboth dams to fully control the Spring flood of 2019.Two points are noteworthy here. First, the country has been suffering from water crisis over the past two decades due to mainly extensive development in agriculture, overexploitation of groundwater sources, and long-term drought periods. This critical condition has forced water management authorities to operate reservoirs in a manner that ensures required supply for drinking and agriculture demands. As a result, the Dez and Karkheh could effectively control a large portion of the so-called flood, their operation long enough before the flood event could be less conservative to minimize the caused damages. Second, violation of protocols on respecting a buffer distance between the river floodplain and residential areas has limited the capacity of rivers such that a required rate of release from reservoirs during flood events cannot be achieved. This is of particular importance downstream of the Karkheh Dam, that is, although the corresponding river should have the carrying capacity of 4000 m^3/s, only a release of 400 m^3/s from the Karkheh Dam during the recent flood resulted in damages downstream [4].The integrated effects of the above limitations partly explain the reason for the implemented reservoir operation in the flood event of Spring, 2019, in this region.

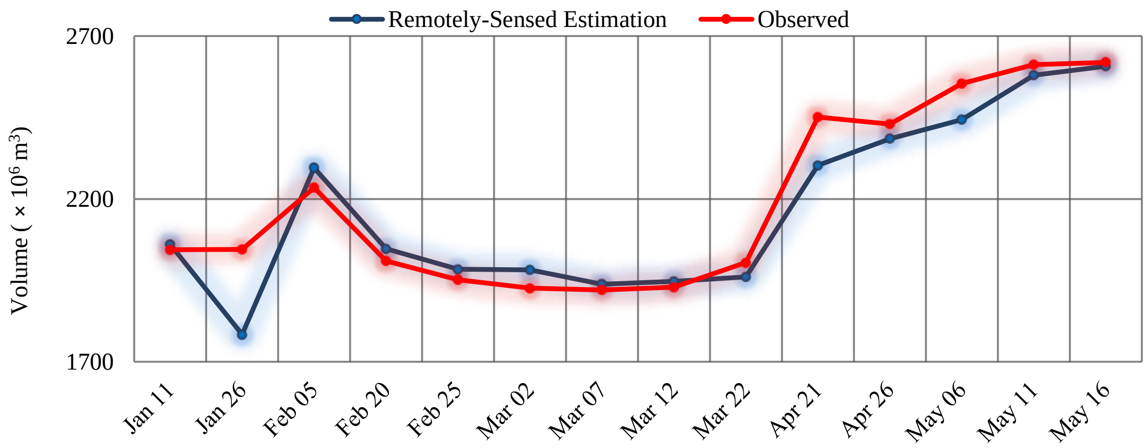

Fig 6. Times Series of Stored Water Volume in the Dez Dam

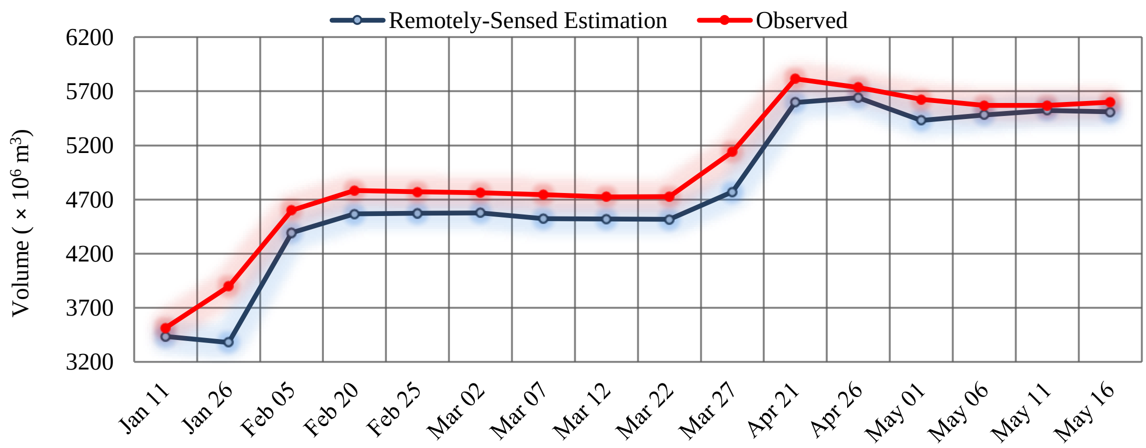

Fig 7. Times Series of Stored Water Volume in the Karkheh Dam

6. CONCLUSION

The goal of this study was to propose an approach for an online monitoring of reservoir operation using high-resolution remote sensing data and efficient classification tools. We examined the reliability of this approach in the Dez and Karkheh dams in the KhuzestanProvince, Iran, wherein a devastating flood took place in Spring, 2019. The accuracy of the results proves the validity of the presented method to estimate the time series of stored water volume in reservoirs, which is strongly critical for a dynamic monitoring of reservoirs with the purpose of flood control and mitigation of damages. Furthermore,the results show that even though the Karkheh and Dez dams contributed significantly in mitigating a large portion of the so-called flood, they could be operatedwith a more effective schedule to completely prevent damages caused in the downstream areas. This was not followed mainly because ofthe limited carrying capacity of streams together with theconservative policies on reservoir operation to ensuring required supply for drinking and irrigation demands. Regarding the observed changes in the precipitation pattern with respect to intensity and duration, as well as increase in the extreme runoff ratesover the recent years, models of reservoir operation should be revisited to guarantee the most efficient schemeunder the condition of climate change.

7. REFERENCES

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