U.S.-Pakistan
Centers for Advanced Studies in Water

Indus River Water Level Monitoring in Sindh using Satellite Radar Altimetry

Final Report 2019

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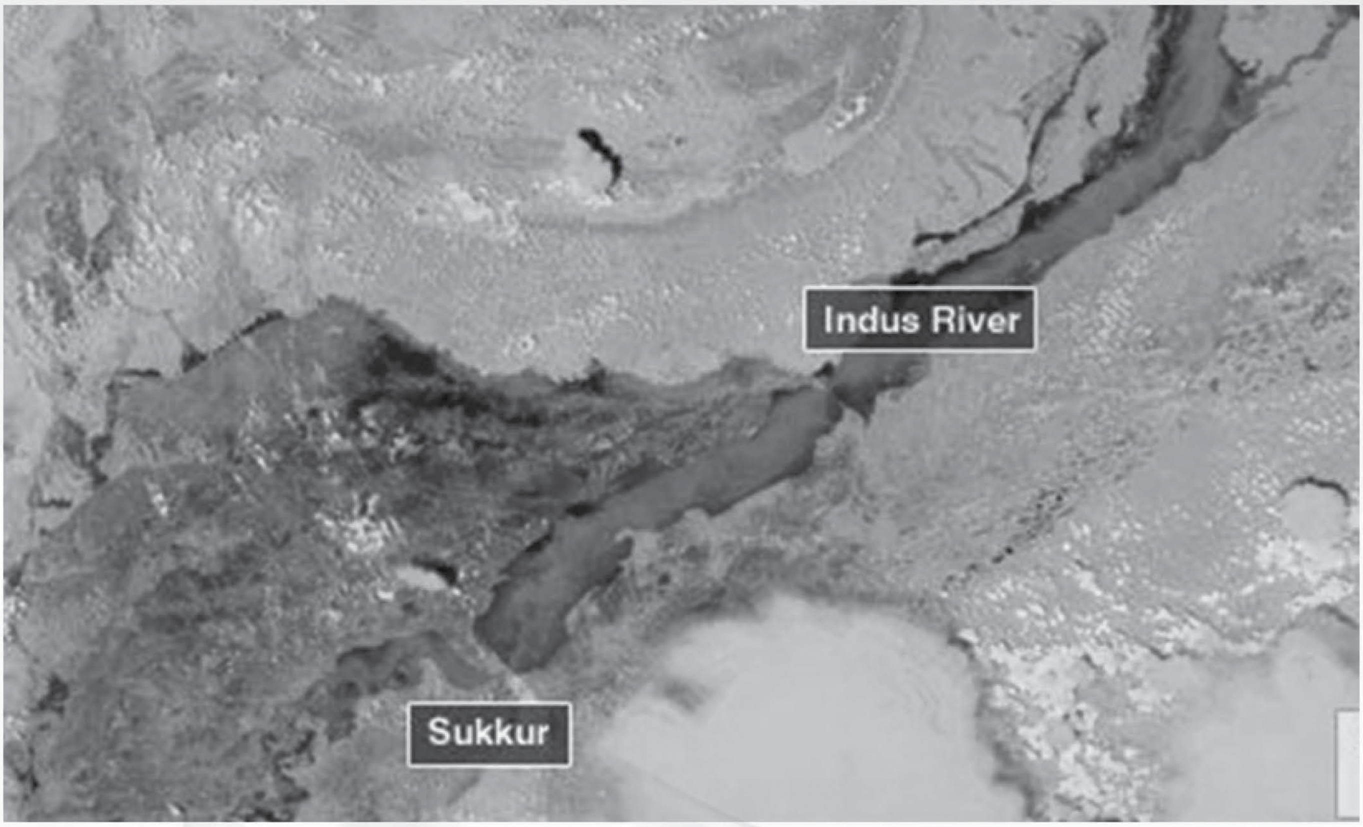

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ACRONYMS AND ABBREVIATIONS

2D	Two Dimensional
Alt	Altitude
CNR	Consiglio Nazionale Delle Ricerche
DEM	Digital Elevation Model
ESA	European Space Agency
G-POD	Grid Processing on Demand
HEC-RAS	Hydrologic Engineering Center's River Analysis System
Hz	Hertz
IoT	Internet of Things
IST	Institute of Space Technology
IWRM	Integrated Water Resources Management
km	Kilometer
m	Meter
NSE	Nash–Sutcliffe model efficiency coefficient
PDF	Portable Document Format
RMSD	Root Mean Square Difference
SID	Sindh Irrigation Department
SRTM	Shuttle Radar Topographic Mission
USPCAS-W	U.S.-Pakistan Center for Advanced Studies in Water
VSs	Virtual Stations

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EXECUTIVE SUMMARY

The Indus River system in Pakistan plays a vital role in the country's economy. The estimation and prediction of river flows are of great significance for the integrated management of water resources such as water allocation, reservoir operations, and forecasting and management of water-related hazards such as floods and droughts. In Pakistan, the supply-demand gap for water users is increasing, and without efficient and equitable allocations among users, this gap will further grow. Under the water stress scenario, therefore, it assumes added importance to manage the country's water resources sustainably. Regular monitoring of inland water bodies can reduce the uncertainties in the decision-making process based on reliable estimates of the hydrological budget of a watershed. Moreover, the monitoring of river surface-level changes is crucial for flood risk management to reduce water-stressed damages.

In recent years, satellite radar altimetry has demonstrated to be a significant source of information for monitoring inland water levels. The effectiveness of these remotely sensed data was evident in both real-time and long-term applications through various studies in the area of discharge modeling, flood mitigation, agriculture water management, and environmental assessment. In addition to the scientific and practical applications, this technique also offers a way of overcoming the difficulty of transboundary river management, which is frequently hindered by the governments that consider their hydrological data as sensitive information. Therefore, this technique can fill data gaps with multi-temporal and multi-spatial information pertinent to hydrological studies and modeling approaches. The main focus of this project was to develop a low-cost approach for national surface water level monitoring in Pakistan to support sustainable water management.

Indus River, the prime water resource of Pakistan, has a limited gauging network, especially at remote locations. The existing network is not sufficient for developing an integrated water resource management plan for the Indus River Basin. The river supports major agricultural activities of Sindh, Khyber Pakhtunkhwa, and Punjab provinces and fulfills major industrial and domestic demands of the country. A sustainable and optimal balance between supply and multipurpose demands can only be realized if the quantity of available water over a more extended period can reasonably be assessed.

Given these considerations as above, this project was planned with the primary goal of validating the utility of satellite radar altimetry in monitoring water levels along the Indus River. In this study, two locations were selected where Sentinel 3A ground tracks are available. These locations are near Guddu (downstream) and Sukkur (upstream) Barrages on the lower Indus River. Time-series data from gauges installed at the barrages were used to validate altimetry derived water heights. The results show an excellent fit of the two datasets with correlations higher than 0.9 and the root mean square difference (RMSD) less than 45 cm for both locations. This technique enabled us to observe river level changes on different segments of the river system where otherwise no measuring devices are installed. As a result, the low gauging frequency along the Indus River was enhanced by introducing the virtual stations (VSs) of radar altimetry.

The radar altimetry technique was found to be advantageous at ungauged locations where in-situ data were not available. Besides water level monitoring, satellite radar data can monitor flood extent as well. To reduce flood risks, usually, the spatial flood extent is mapped through optical satellite remote sensing. A problem of optical remote sensing during flood time is the presence of cloud cover that limits the use of satellite data. Whereas, satellite radar altimetry can facilitate flood forecasting in all weather conditions.

1. INTRODUCTION

1.1 Background

Satellite radar altimetry is a technique that is used to measure water levels in oceans and inland water bodies. Therefore, it contributes to observing continental waters, especially during floods and water-stressed seasons. The technique is particularly useful to monitor water level variations over lakes, rivers, and reservoirs, especially when in-situ information is sparse and non- existent (Berry *et al*., 2005; Brakenridge *et al*., 2012). The main focus of this study was to develop a low-cost approach for national surface water level monitoring in Pakistan to support sustainable water management.

In recent years, satellite radar altimetry has demonstrated to be a significant resource of information for monitoring water level over land. The effectiveness of these remotely sensed data was evident in both in real-time and long-term applications through various studies in the area of discharge modeling, flood mitigation, agriculture water management, and environmental assessment (Coe, 2004; Neal *et al*., 2009; Biancamaria *et al*., 2011; Michailovsky, Milzow, and Bauer-gottwein, 2013). In addition to the scientific and practical applications, satellite radar altimetry also offers a way of overcoming the difficulty of transboundary river management, which is frequently hindered by the governments that consider their hydrological data as sensitive information. Therefore, this technique can fill data gaps with multi-temporal and multi-spatial information pertinent to hydrological studies and modeling approaches.

In the Indus River water level monitoring project, we studied temporal changes in the water heights near Guddu and Sukkur Barrages on the Indus River using data collected from the Sentinel 3A mission (this satellite overflies at these locations). Sentinel 3A is part of the European Copernicus program that is expected to ensure continuity in the future about data availability. This study provides the first validation experiment of Sentinel 3A data over the Indus River, which means exploring a new area with new data, and hence with limited literature to support this study.

1.2 Satellite Radar Altimetry: How it Works

Satellite radar altimetry was designed primarily for the ocean domain, and the application to inland waters is relatively recent. The technique has the potential to provide a new dimension to inland water studies. The satellite radar altimetry concept is simple. A radar altimeter onboard satellite measures the round-trip time of pulses that are then converted in the distance between the satellite and the water surface (the so-called range). The basic principle of radar altimeter is shown in Fig. 1.1.

The range needs to be corrected for various effects (such as ionosphere and troposphere), and the position of the satellite from the earth's surface is necessary to determine the height of a water surface. Reservoir, lake, and river levels derived from satellite radar altimetry are cost-effective with less capital and no maintenance cost as compared to flow gauge acquired data (Klemas, 2010).

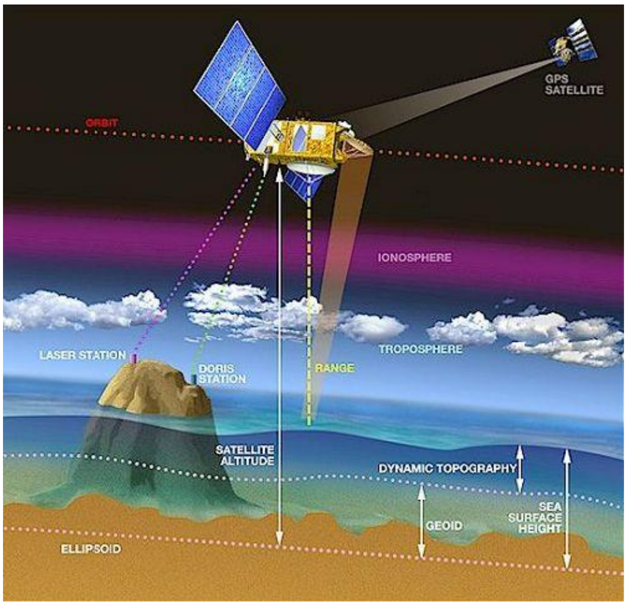


Fig. 1.1: The basic principle of radar altimeter (Credits CNES/ D. Ducros)

1.3 Objectives

The objectives of this study were:

1. To monitor variations in seasonal water levels at selected locations of the Indus River to identify spatial and temporal flow patterns of the lower Indus River through satellite radar altimetry.

2. To demonstrate the utility of altimetry data for calibrating flood model (2D HEC-RAS) for the recent (2019) medium flood in the lower Indus reach.

3. To install real-time water level sensors at the Sindh Barrages.

4. To organize a training course "Monitoring River Flows using Satellite Radar Altimetry" for the capacity building of the Sindh Agriculture Department, USPCAS-W, IST, and other relevant agencies.

5. To develop an economically viable and technologically robust sustainable Indus River management blueprint for Pakistan by demonstrating the potential of satellite radar altimetry to produce time-series of water heights at different locations of the Indus River.

1.4 The Research Gap

The main idea for the Indus River water level monitoring using satellite radar altimetry was to measure water heights, which are essential for achieving several integrated water resource management (IWRM) goals, among which the most important is to ascertain water availability for different purposes during different seasons of the year. Indus River, the prime water resource of Pakistan, has a limited gauging network, especially at remote locations (Bookhagen *et al*., 2010). The existing network is not sufficient for developing an IWRM plan for the Indus River Basin. The river supports major agricultural activities of Sindh, Khyber Pakhtunkhwa, and Punjab provinces and fulfills the industrial and domestic water demand of Pakistan (Economic Survey of Pakistan, 2016). A sustainable and optimal balance between the supply and multipurpose demands can only be realized if the quantity of available surface water over a more extended period can reasonably be predicted. At present, there are 89 weather stations/ observatories and 32 river gauging stations in Pakistan, with only three in the Sindh province at Guddu, Sukkur, and Kotri Barrages (FAO, 2016). In advanced countries, this count reaches more than a thousand gauges. In the United Kingdom (about 30% of Pakistan's size), there are around 1,500 flow measurement stations (Stream gauge, 2016). This study aims to fill this gap by providing an accurate and reliable flow monitoring system for managing reservoir operations including water releases and water allocation among various users, flood forecasting systems, calibration and validation of hydrologic and hydraulic models, and development of decision support tools for both real-time and long-term water resource management. Through this study, we expect that satellite radar altimetry will improve the gauge density of the Indus River by adding virtual stations at locations where tracks from Sentinel 3A and other satellite missions (e.g., Jason-3) are available.

1.5 Scope and Limitations of the Study

This study is first of its nature, which focuses only on the lower Indus reach, i.e., new area, new data, and no succinct literature carried out. Through satellite radar altimetry information, there is a possibility to build times series data of stages, discharges, and river altitude profiles (Calmant and Seyler, 2006). Moreover, the permanent water extent used in this study is of the year 2018. There is also a time difference between satellite and in-situ data acquisition —Sentinel 3A passes after 27 days over the study area at around 17:00 hrs at specific dates, whereas, in-situ gauge data is recorded manually at early morning every day.

2. MATERIALS AND METHODS

2.1 Study Area

The lower Indus River (flowing through the Sindh province) is selected as our study area for its proximity, easy reach, and insufficient data from gauges. Fig. 2.1 shows the map identifying satellite passages over the Indus River reach located in the study area. There are several points at which the satellite altimetry data can be acquired: two important locations being the Sukkur and Guddu Barrages (Fig. 2.1). Given the availability of altimetry data, measurements of temporal and spatial variations in the water levels using current and archived altimetry data were carried out. Altimetry data of Sentinel 3A and 3B satellites were used for this purpose.

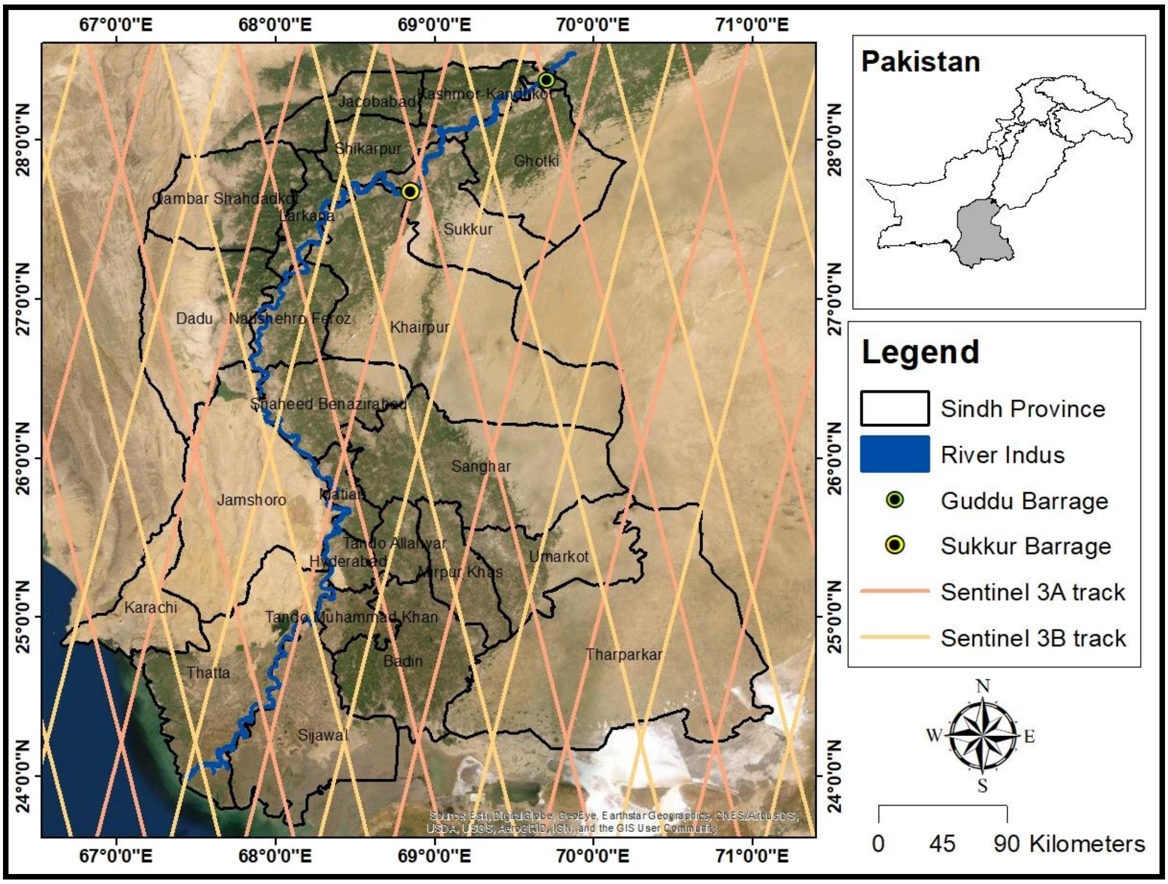


Fig. 2.1: Satellite passes over the lower Indus River

2.1.1 Guddu and Sukkur barrages

The Guddu Barrage is one of the prominent structures on the Indus River located near Kashmore in the Sindh province of Pakistan. The barrage was built after the creation of Pakistan. The main purpose of this barrage is to manage and administrate the River flows for irrigation and flood control. The Guddu Barrage is the fifth barrage of Pakistan, chronologically, that was built on Indus (Naqvi, 2012). Since Pakistan's economy largely depends on its agricultural products, this barrage has a vital role in the economic development of the country by managing the water demand of the agricultural sector.

Sukkur Barrage is considered as the pride of Pakistan's irrigation system, which was built on the Indus River downstream of the Guddu Barrage. This Barrage is the backbone of the country's economy through its network of canals, which provides irrigation water supplies to an area of about 7.63 million acres. One of the seven canals off taking from this Barrage is the Nara canal, which is the longest canal of the country and carries discharge almost equal to that of the Thames River in London (Sukkur Barrage, n.d). The bed width of Nara is 105.5m—one and a half (1 ½) times larger than the Suez Canal.

2.2 Datasets

2.2.1 Altimetry dataset

Sentinel 3A and 3B altimetry data for the period June 2016 to June 2019 and December 2018 to June 2019, respectively, were requested and obtained from the European Space Agency (ESA) Grid Processing on Demand (G-POD) web portal (// gpod.eo.esa.int/). The G-POD Service, SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation) for Sentinel 3 processes altimeter data in SAR mode (Dinardo *et al*., 2016). Sentinel 3A and 3B data are available on every 27th day. A total of 40 and 41 records were obtained during the study period for the Sukkur and Guddu Barrages, respectively, from Sentinel 3A. Moreover, around nine records were acquired from Sentinel 3B for other virtual stations. The detailed specifications of Sentinel 3A and 3B are given in Table 2.1.

Table 2.1: Technical specifications of Sentinel 3A and 3B Missions

Mission	Band (GHz)	Repeat ability (days)	Resolution	Data posting rate (Hz)	GPOD resolution	GPOD data posting rate (Hz)
Sentinel (3A- 3B)	Ku and C band	27	300 m	20 Hz	80m	80Hz

2.2.2 In-situ water levels (gauge data)

The Sindh Irrigation Department (SID) provided in-situ daily water levels data at Sukkur and Guddu Barrages. Gauged water levels recorded from June 2016 to December 2018 were used for comparison.

2.3 Methodology

2.3.1 Indus River water levels using satellite radar altimetry (Objective 1)

Temporal changes in water levels along the lower Indus River at two primary locations—downstream of Guddu Barrage and upstream of Sukkur Barrage— were studied using time-series data of Sentinel 3A. To achieve this objective, first, the altimetry-derived water levels were validated with the gauge data at the two barrages. Once we got a good compromise between the two datasets, the altimetry water levels were extracted from all virtual stations (VS) or locations along the Indus River, where satellite tracks were available.

2.3.1.1 Differences in the datasets

At Guddu and Sukkur Barrages, the satellite tracks and in-situ gauge locations are not exactly overlapping. The gauges are installed at the barrages, and the nearest satellite tracks are around 3.74 km downstream of the Guddu Barrage and 0.71 km upstream of the Sukkur Barrage (Fig. 2.2). Earlier it was thought that with this difference, the comparison might not be appropriate, but later literature has shown its acceptability by other researchers. Crétaux and Birkett (2006) measured river discharge of the Chari River at N'Djamena, Chad, which was about 500 km downstream of the altimetric measurements. Some comparisons of different inland products against ground truth in the selected sites were also found in the literature (Birkett *et al*., 2002; Ricko *et al*., 2012; Schwatke *et al*., 2015).

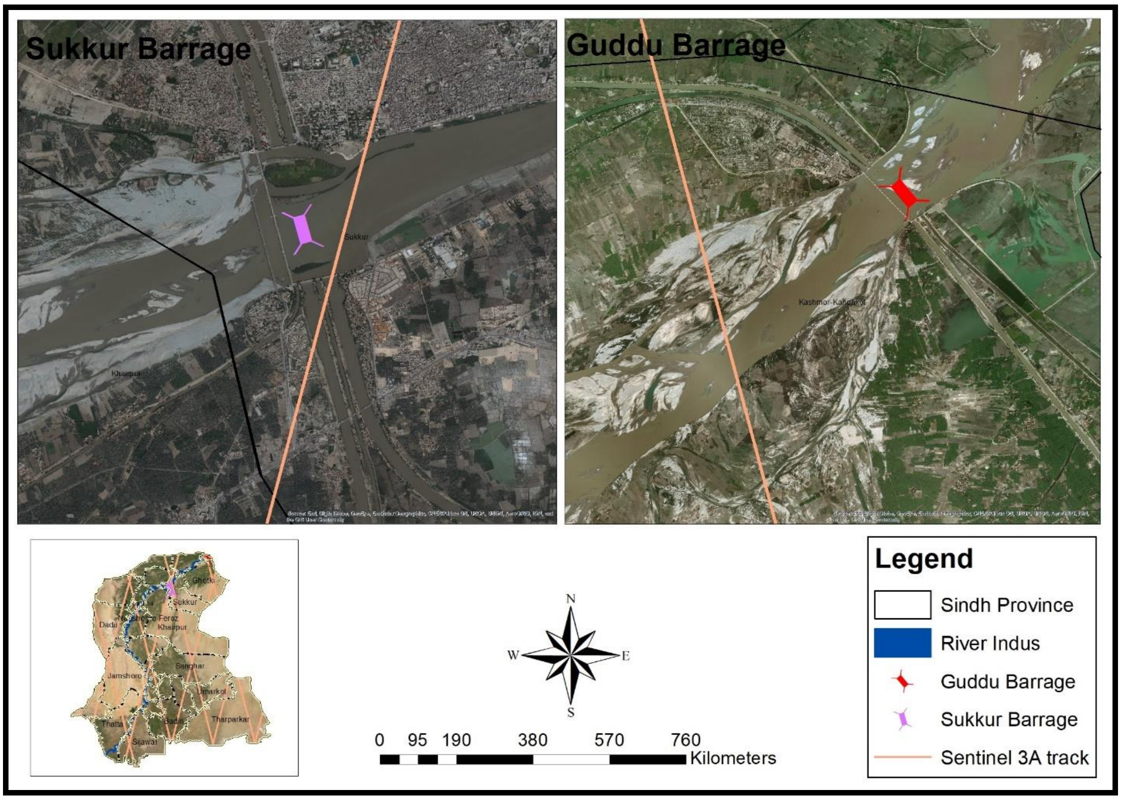


Fig. 2.2: The nearest satellite tracks from the Guddu and Sukkur Barrages

From both datasets, same date water levels should be compared, but there is a time difference between satellite and in-situ data acquisition—Sentinel 3A passes over the study area at around 17:00 hrs on specific dates, whereas, in-situ gauge data is recorded manually at early morning every day. Therefore, instead of selecting the same day gauge reading, three-day moving averages of the in-situ data were calculated and used for comparison to normalize any anomaly due to time difference. The three-day moving window allows us to average three days of water levels—on the satellite pass day, the day before, and the day later.

2.3.1.2 Permanent water surface

Over the width of the river, where a satellite track overlaps the water surface, many pulses are found for each pass. An average of eight to ten pulses of water heights in a single pass was considered as the water height for that pass. Due to seasonal changes in the river morphology, we included altimetry pulses in our analysis that overlapped with the permanent water surface and excluded those that were located outside the river water surface. The number of pulses varied because of river width and spatial displacement of satellite pass over the distance of approximately 2 km. For that, the permanent water surface was delineated from the seasonality image downloaded from the Global Surface Explorer (global-surface-water.appspot.com/) (Pekel et al., 2016). Hence, the altimetric data were processed and masked according to the permanent surface of the water. The Global Surface Explorer site computes water seasonality for every year and provides a global map of permanent and seasonal water surfaces having less than 1% error in detecting false water cover and a less than 5% chance of not detecting the 'true' water surface (Pekel et al., 2016). The class with value = 12 represents the permanent water surface or water extent throughout the year (water in all 12 months). The permanent water surface was extracted from the seasonal image of 2018 and converted into a vector format. Since only 2018 image was available at the website, we assumed that throughout the study period, the permanent water surface was the same as in 2018. The pulses within the permanent water surface were clipped by this vector shapefile. It is important to note that each cycle or pass of the track has a slight shift from its previous pass (Fig. 2.3 and Fig. 2.4). Due to this shift, the number of pulses intersecting the permeant water surface changes in each pass. As described earlier, the water levels at these pulses were averaged for each pass. The average water levels were used in this study to compare with the gauge data.

2.3.1.3 Data processing

The downloaded data were further processed to derive time-series of water levels using Eq. 2.1. The height (*H*) of the reflecting surface is the difference between the orbital altitude (*alt*) and the *range*. Various *corrections* were applied, including delays associated with the propagation through the atmosphere, interaction with the

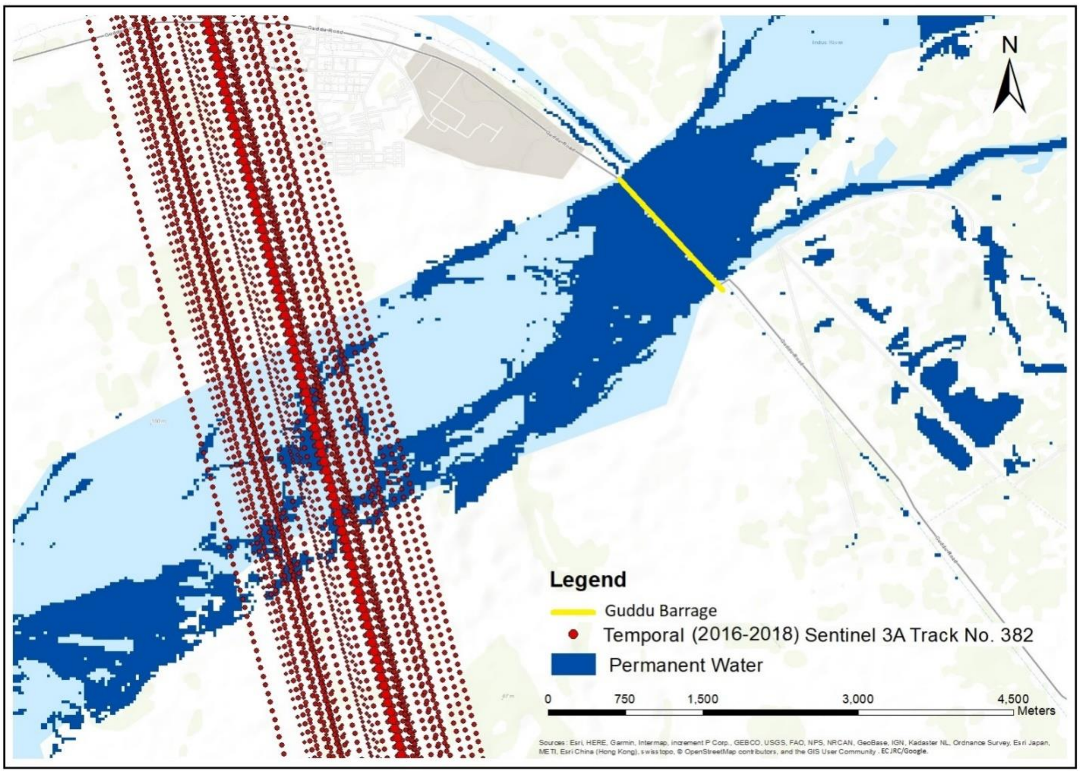


Fig. 2.3: Sentinel 3A temporal track (#382) paths near Guddu Barrage

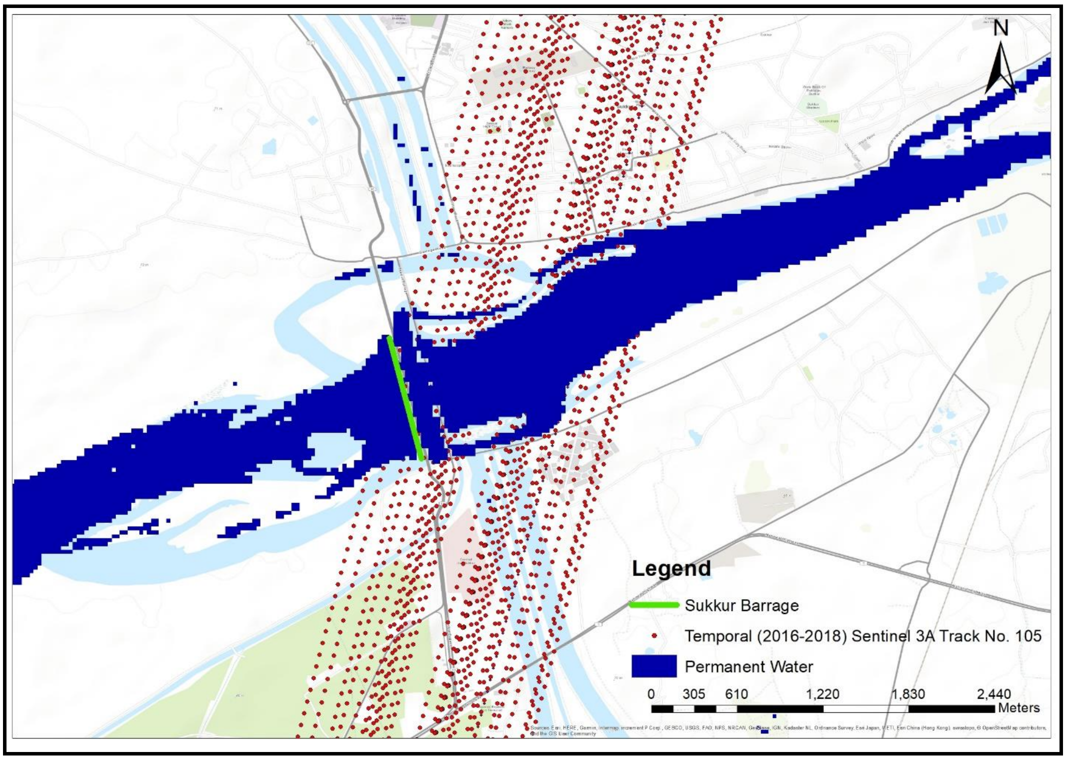


Fig. 2.4: Sentinel 3A temporal track (#105) paths near Sukkur Barrage

ionosphere, and correction for liquid and solid tidal effects on Earth. Table 2.2 presents the parameters and their details for calculating the water surface heights. A more detailed methodological framework is presented in Fig. 2.5.

$$H = alt - range - geiod - \sum corrections \qquad \text{(Eq.2.1)}$$

Table 2.2: **G-POD variables for estimating water heights**

Variables	G-POD parameter	Details
Alt	Altitude_20Hz	The distance of the satellite from the ellipsoid
Range	Range_Unc_20Hz	Re-tracked range with no geo-corrections
Geoid	EGM_2008_20Hz	Geoidal model
Correction	GEO_Corr_Land_20Hz	3D Dry Tropo, Wet Tropo, GimIono, Solid Earth Tide, Pole Tide

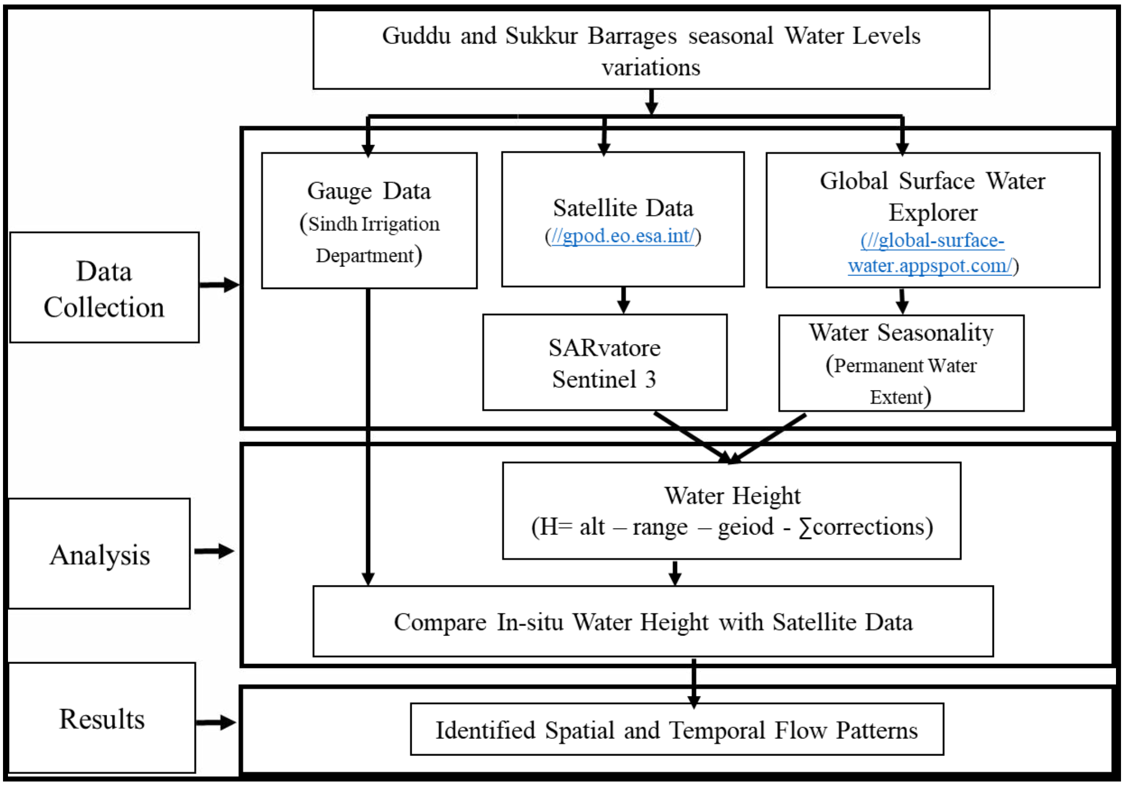


Fig. 2.5: Methodological framework

Water levels extracted from satellite radar altimetry were validated with gauge data. After validation, the virtual stations (VS) were identified, which are ungauged locations where altimetry tracks are available (Fig. 2.6). The same processing steps were applied to altimetry data to monitor water levels on a long-term basis at all VSs.

2.3.2 Utility of altimetry data for calibrating the flood model (Objective 2)

2.3.2.1 Hydraulic modeling

The Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM), daily gauge data, Sentinel 3A altimetry data were used in this study for developing a flood model downstream Guddu Barrage. The US Hydrologic Engineering Center's

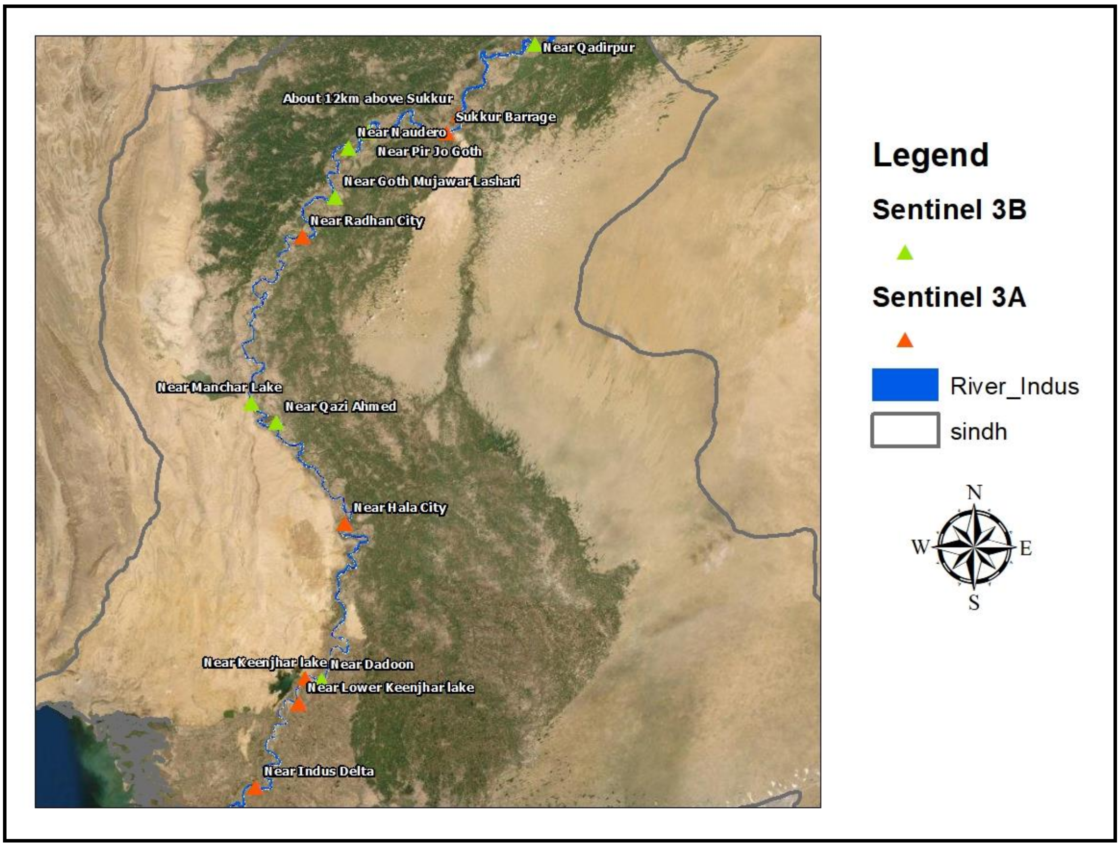


Fig. 2.6: Virtual stations are marked along the Indus River

River Analysis System (HEC-RAS) was used for 2-dimensional (2D) flood inundation mapping. The geometric data for hydraulic modeling were prepared in the RAS Mapper. The model was developed using DEM extracted geometry and recent time-series water flows at the Guddu Barrage. After executing the model, the model was calibrated and validated using altimetry data.

2.3.3 Installation of real-time water level sensors at the Sindh Barrages (Objective 3).

The use of IoT along data analysis can help in monitoring floods and provide useful information needed to forecast future floods. IoT can be used along with sensors and other technologies to improve data acquisition and real-time measurements for an effective monitoring system. Also, ultrasonic sensors and cellular transmission technologies can be deployed to ensure adequate transmission rates and to prevent data loss by implementing optimized telemetry methods and lightweight data structures to reduce the load of outcoming data.

Therefore, one sensor each at the downstream and upstream sides was installed at the Guddu and Sukkur Barrages (Fig. 2.7). These sensors were purchased and installed by a local vendor (Linked Thing Pvt. Ltd.). They provided measuring systems that remotely and automatically monitor water levels. The sensors acquire real-time water heights at 15-minute intervals continually. The data frequency can be adjusted as per requirements. The detailed specifications of the sensors are given in Table 2.3.

Table 2.3: Sensor specification

Sensor	Range (cm)	Connectivity	Power	Casing
Ultrasonic	20-600	3G	Grid Power	IP68

Fig. 2.7: Real-time water level sensor

2.3.4 Organization of a training course (Objective 4)

A custom-made training course, *"Hydrology and Satellite Radar Altimetry,"* was developed and delivered by Dr. Stefano Vignudelli, an expert on the subject with more than 25 years of experience in satellite radar altimetry. The aim of this course was the capacity building of the project team, the Sindh Agriculture Department, educational institutions, and other relevant agencies.

2.3.5 Indus River management blueprint for Pakistan (Objective 5)

This report will serve as a blueprint for sustainable management of the Indus River in Pakistan by demonstrating the potential of satellite radar altimetry to produce time-series of water heights at different locations of Indus River. The proposed methodology will enable the Indus River management in an economically viable and technologically feasible manner.

3. RESULTS AND DISCUSSIONS

This chapter presents the results derived from the Indus River water level monitoring in Sindh using satellite radar altimetry. The water resource monitoring and management play a significant role in the sustainable development of a country. Water resource management is becoming a political and societal issue across the world in many countries. The following sections discussed the objective-wise results.

3.1 Time-Series of Altimetric Water Levels

The altimetric water levels, from the period of June 2016 to August 2019 at the Guddu Barrage and July 2016 to August 2019 at the Sukkur Barrage, were processed in this study, matching with the available gauge data at the two stations. To utilize altimetric data for water level monitoring, it is necessary to first validate altimetric data with in-situ datasets (assuming gauge data to be reliable). For this purpose, the altimetry water levels were derived from a reference ellipsoid and compared with in-situ gauge data measured from the mean sea level.

As described in the methodology chapter, three-day moving averages of the daily gauge data were calculated, and the satellite pulses that were exclusively found on the permanent water surface at the Guddu and Sukkur Barrages (Fig. 3.1 and Fig. 3.2) were included in the analysis. Table 3.1 and Table 3.2 present the number of pulses found for each pass over the permanent water surface.

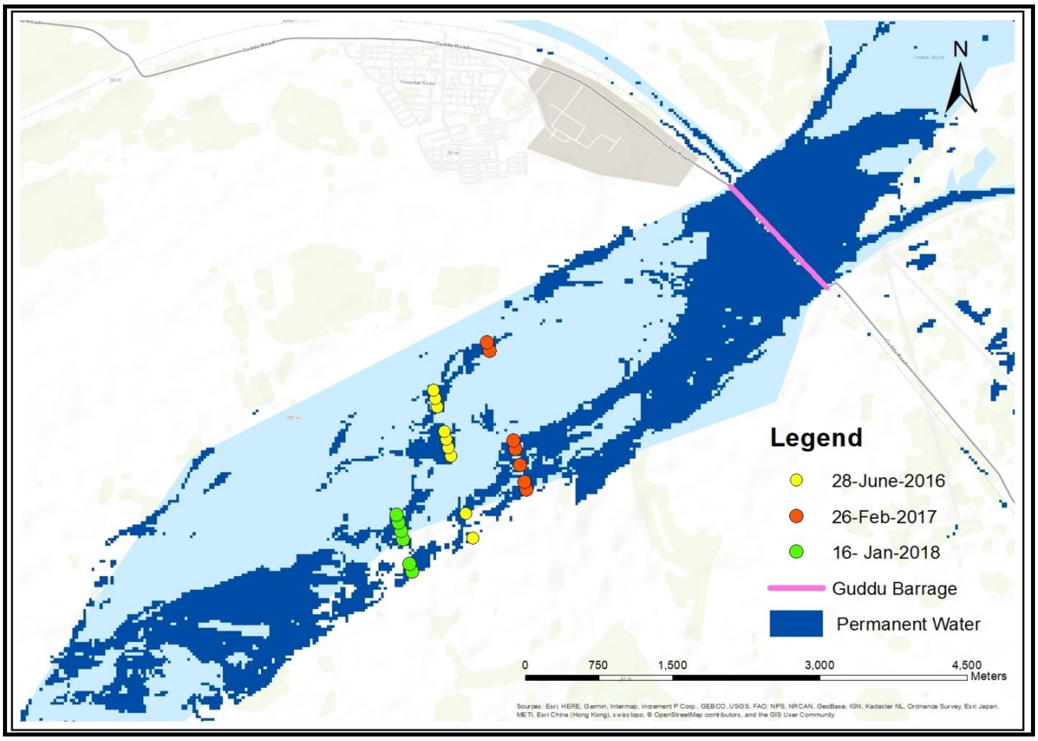


Fig. 3.1: Guddu Barrage satellite pulses over the permanent water surface

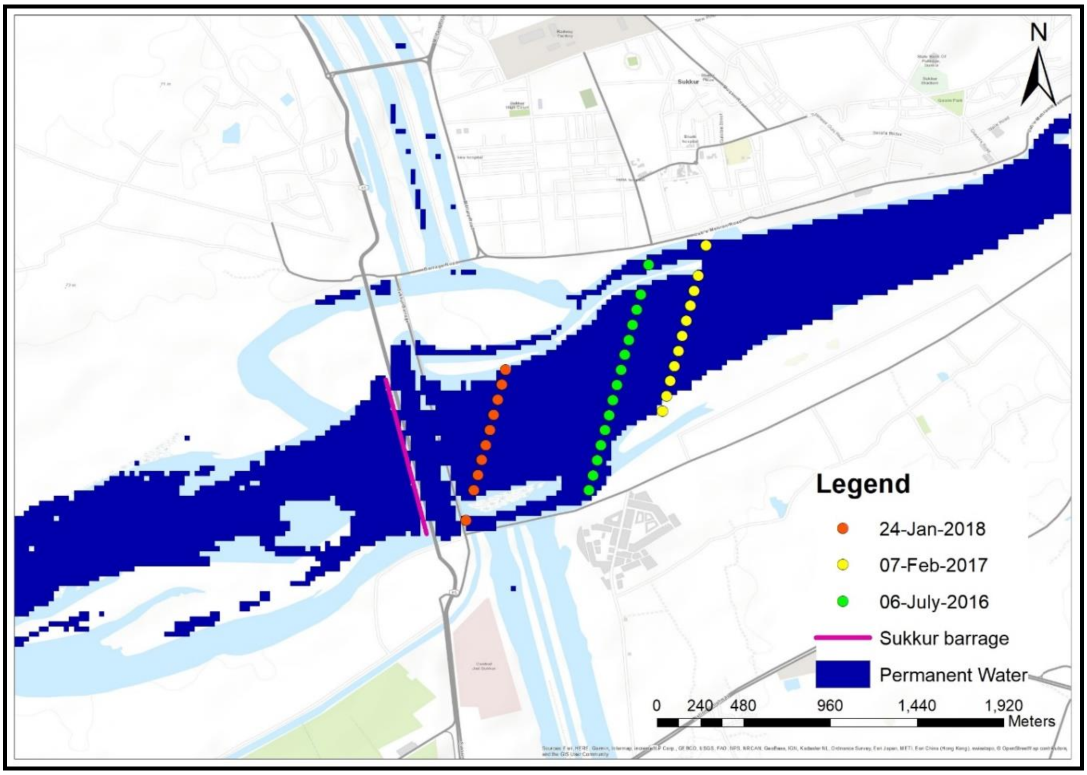


Fig. 3.2: Sukkur Barrage satellite pulses over the permanent water surface

Table 3.1: Guddu Barrage radar pulses on the permanent water surface and their average values

S. No.	Satellite pass date	Average height (m)
1	June 26, 2016	76.00
2	July 23, 2016	76.00
3	August 19, 2016	76.00
4	September 15, 2016	75.25
5	October 12, 2016	75.00
6	November 08, 2016	74.33
7	December 05, 2016	74.50
8	January 01, 2017	73.50
9	January 28, 2017	75.00
10	February 24, 2017	74.28
11	March 23, 2017	73.00
12	April 19, 2017	74.16
13	May 16, 2017	75.00
14	June 12, 2017	76.00
15	July 09, 2017	76.00
16	August 05, 2017	77.00
17	September 01, 2017	76.00
18	September 28, 2017	75.00

19	October 25, 2017	74.25
20	November 21, 2017	73.60
21	December 18, 2017	74.00
22	January 14, 2018	72.50
23	February 10, 2018	73.80
24	March 09, 2018	72.57
25	April 05, 2018	73.00
26	May 02, 2018	73.10
27	May 29, 2018	73.33
28	June 25, 2018	76.00
29	July 22, 2018	76.00
30	August 18, 2018	76.00
31	September 14, 2018	75.00
32	October 11, 2018	74.00
33	November 07, 2018	74.00
34	December 04, 2018	74.00
35	December 31, 2018	72.94
36	January 27, 2019	73.02
37	February 23, 2019	73.87
38	March 22, 2019	73.44
39	April 18, 2019	74.50
40	May 15, 2019	74.76
41	June 11, 2019	75.22
42	July 08, 2019	76.00
43	August 04, 2019	76.55

Table 3.2: Sukkur Barrage radar pulses on the permanent water surface and their average values

S. No.	Satellite pass date	Average height (m)
1	July 06, 2016	61.54
2	August 02, 2016	61.52
3	August 29, 2016	61.35
4	September 25, 2016	61.02
5	October 22, 2016	60.25
6	November 18, 2016	60.41
7	December 15, 2016	60.16
8	January 11, 2017	56.27

9	February 07, 2017	60.21
10	March 06, 2017	60.01
11	April 02, 2017	60.01
12	April 29, 2017	59.09
13	May 26, 2017	60.38
14	June 22, 2017	60.38
15	July 19, 2017	61.53
16	August 15, 2017	61.83
17	September 11, 2017	61.39
18	October 08, 2017	60.51
19	November 04, 2017	60.48
20	December 01, 2017	60.09
21	December 28, 2017	60.32
22	January 24, 2018	59.14
23	February 20, 2018	59.37
24	March 19, 2018	59.17
25	April 15, 2018	59.06
26	May 12, 2018	59.94
27	June 08, 2018	59.46
28	July 05, 2018	60.92
29	August 01, 2018	61.33
30	August 28, 2018	61.42
31	September 24, 2018	61.25
32	October 21, 2018	60.40
33	November 17, 2018	60.28
34	December 14, 2018	59.74
35	January 10, 2019	56.57
36	February 06, 2019	59.44
37	March 05, 2019	60.48
38	April 01, 2019	59.44
39	April 28, 2019	60.63
40	May 25, 2019	60.63
41	June 21, 2019	61.05
42	July 18, 2019	61.72
43	August 14, 2019	61.61

3.1.1 Comparison between gauge and altimetric data

The processed water heights and in-situ gauge datasets were plotted on the same graph for comparison. The plots of both the datasets for the Guddu (June 2016 to August 2019) and Sukkur Barrages (July 2016 to August 2019) are shown in Fig. 3.3 and 3.4, respectively. These plots show a good agreement between the datasets except at some dates where the water heights are not matching.

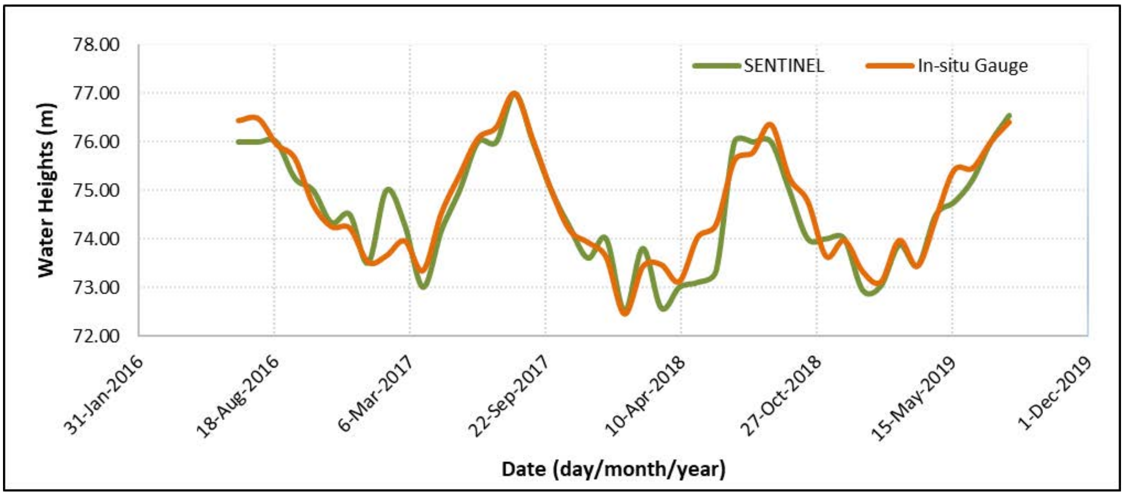


Fig. 3.3: Time-series plots of water heights from altimetry (Sentinel 3A) versus in-situ gauge data at the Guddu Barrage

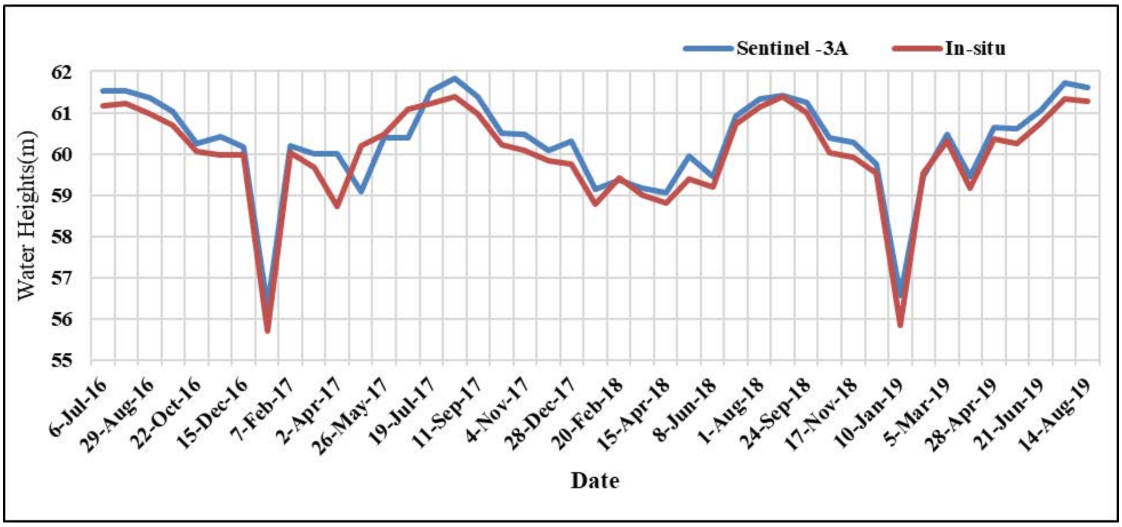


Fig. 3.4: Time-series plots of water heights from altimetry (Sentinel 3A) versus in-situ gauge data at the Sukkur Barrage

3.1.2 Statistical analysis

Statistically significant results were found for Guddu and Sukkur Barrages among two datasets—R= 0.937 and RMSD= 43 cm for Guddu Barrage and R= 0.941 and RMSD = 44.9 cm at the Sukkur Barrage. Thus, the altimetry water levels and gauge data validation exercise revealed the typical accuracy of the satellite measurements. Generally, the RMSD estimates can vary from few centimeters until about a meter (e.g., Zambesi River). The characteristics of the water target mainly influence the resulting accuracy. However, the inland water altimetry products are processed by various research groups that adopt different algorithms (e.g., re-tracking, corrections, editing). Therefore, the water heights in the various products might have different resolutions, accuracies, and errors. For estimating the acceptable performance of the satellite data concerning the observed in-situ measurements, the Nash–Sutcliffe model efficiency coefficient (NSE) was calculated. The NSE coefficients for Guddu and Sukkur Barrages were found to be 0.898 and 0.833, respectively. The NSE values > 0 indicated the acceptable performance of the two datasets. A summary table of all relevant validation experiments is provided in Vignudelli et al. (2019).

3.1.3 Other virtual stations

After validation of the altimetric data for reasonably representing the 3-day average water heights at two locations of the Indus River, the applicability of altimetric data for other virtual station (VSs) was also inferred reasonably. The data from Sentinel 3A, together with Sentinel 3B, were used for calculating the time-series of water levels at different VS. Other than Guddu and Sukkur Barrages, there are 16 more VSs (for both Sentinel 3A and 3B) over the Indus river from Guddu to Indus Delta as listed in Table 3.3. The same processing was applied to calculate water levels as presented in the methodology chapter. Few locations allow the use of more than one track in case of a crossover point between different altimeter tracks. Fig. 3.5 represents the results of selective VSs with comparatively longer time-series data.

Table 3.3: Virtual stations and their details

SN	VS	Track No.	Location	No. of Records	Satellite	Date Range	
1	VS1	track#211	Indus Delta	4	S3B	December 4, 2018	February 23, 2019
2	VS2	track#211	Near Indus Delta	43	S3B	June 16, 2016	June 28, 2019
3	VS3	track#105	Near Lower Keenjhar Lake	40	S3B	August 29, 2016	June 21, 2019
4	VS4	track#105	Near Keenjhar Lake	40	S3A	August 29, 2016	June 21, 2019
5	VS5	track#268	Near Banoo City	4	S3B	December 08, 2018	February 27, 2019
6	VS6	track#105	Unarpur City	40	S3A	August 29, 2016	June 21, 2019
7	VS7	track#105	Khando City	40	S3A	August 29, 2016	June 21, 2019
8	VS8	track#105	Old Hala City	40	S3A	August 29, 2016	June 21, 2019
9	VS9	track#105	Near Qazi Ahmed City	5	S3B	November 27, 2018	July 18, 2019
10	VS10	track#268	Near Manchar Lake	4	S3B	December 08, 2018	February 27, 2019
11	VS11	track#268	Near Radhan City	43	S3A	June 20, 2016	July 02, 2019
12	VS12	track#105	Near Naudero	5	S3B	November 27, 2018	July 29, 2019
13	VS13	track#268	Near Pir Jo Goth	4	S3B	December 12, 2018	March 03, 2019
14	VS14	track#325	12km Above Sukkar	42	S3A	June 24, 2016	June 09, 2019
15	VS15	track#382	Near Qadirpur	8	S3B	December 16, 2018	June 23,2019
16	VS16	track#162	28km D/s Guddu	9	S3B	December 01, 2018	July 05, 2019

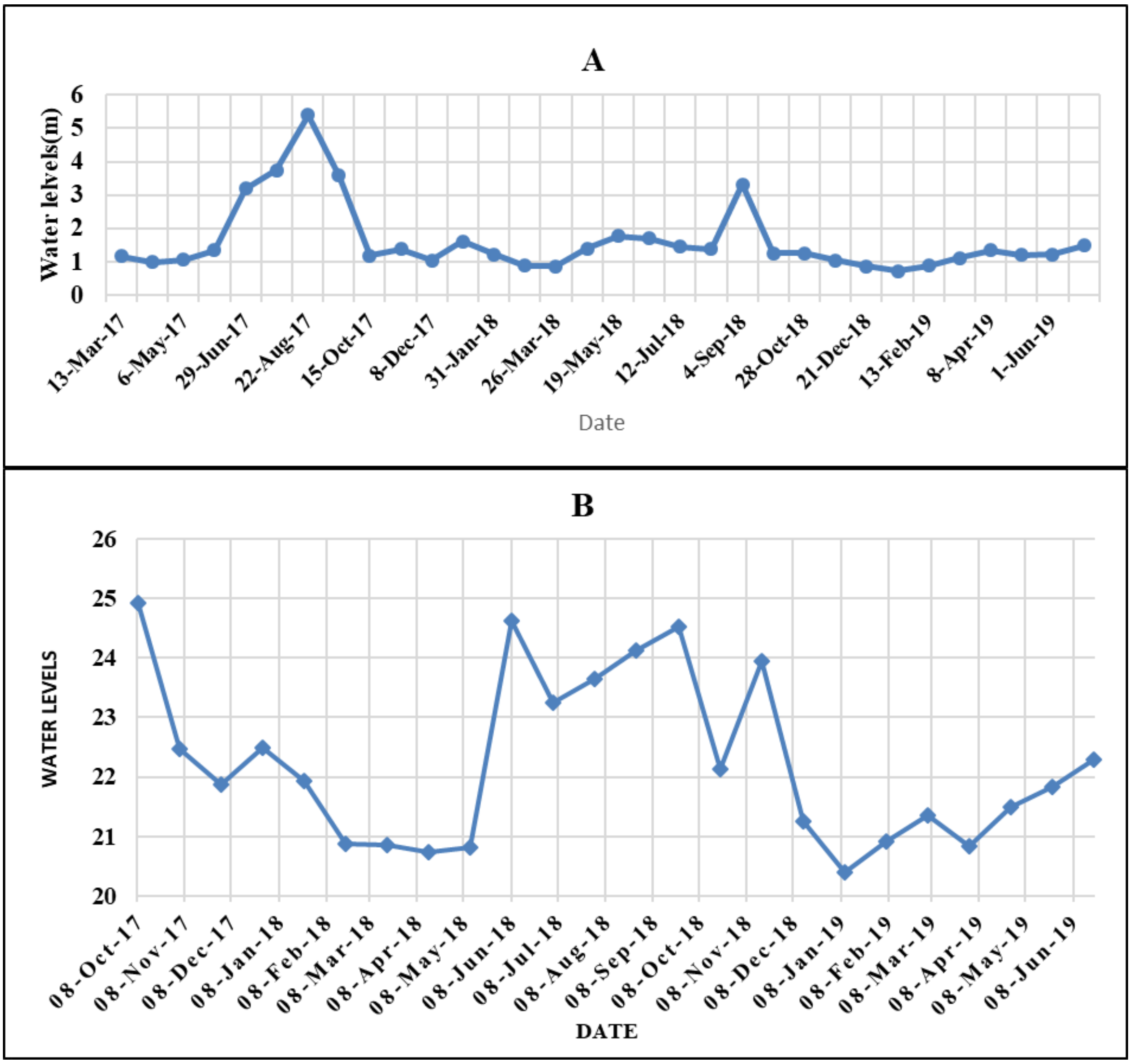
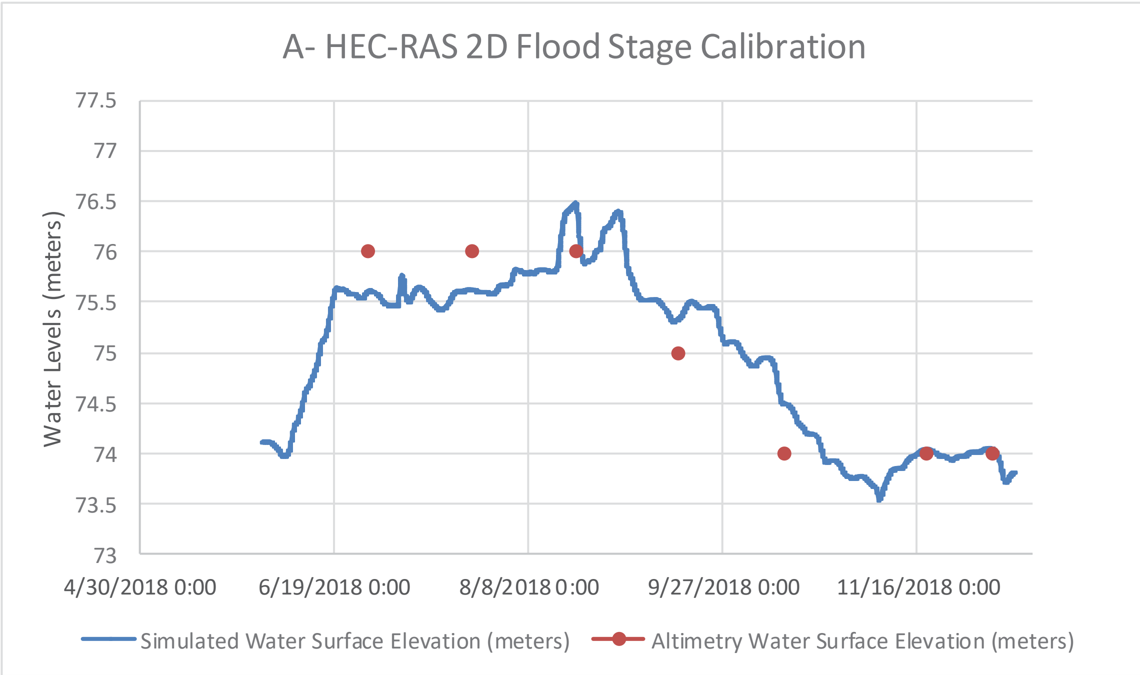


Fig. 3.5: Water level time-series at: A) VS2- Near Indus Delta B) VS6- Near Unarpur city

3.2 Flood Model (2D HEC-RAS) in the Lower Indus reach Using Satellite Altimetry

After the estimation of water levels from the altimeter and its validation, the water levels from the VS at the Guddu Barrage were compared with the results obtained from flood modeling (2D HEC-RAS). The year 2018 was selected to calibrate the model and 2019 for model validation. Fig. 3.6 (A) presents the 2D HEC-RAS simulated water levels in 2018 (calibrated) at the main river channel along the altimetry track, and Fig. 3.6 (B) shows the temporal results of 2019 (validated) at the same location. The difference between the altimetric derived vs. 2D HEC-RAS simulated water levels was found to be in the range from +0.338 m to -0.858 m in the calibrated model and 0.134 m to +0.413 in the validated model.



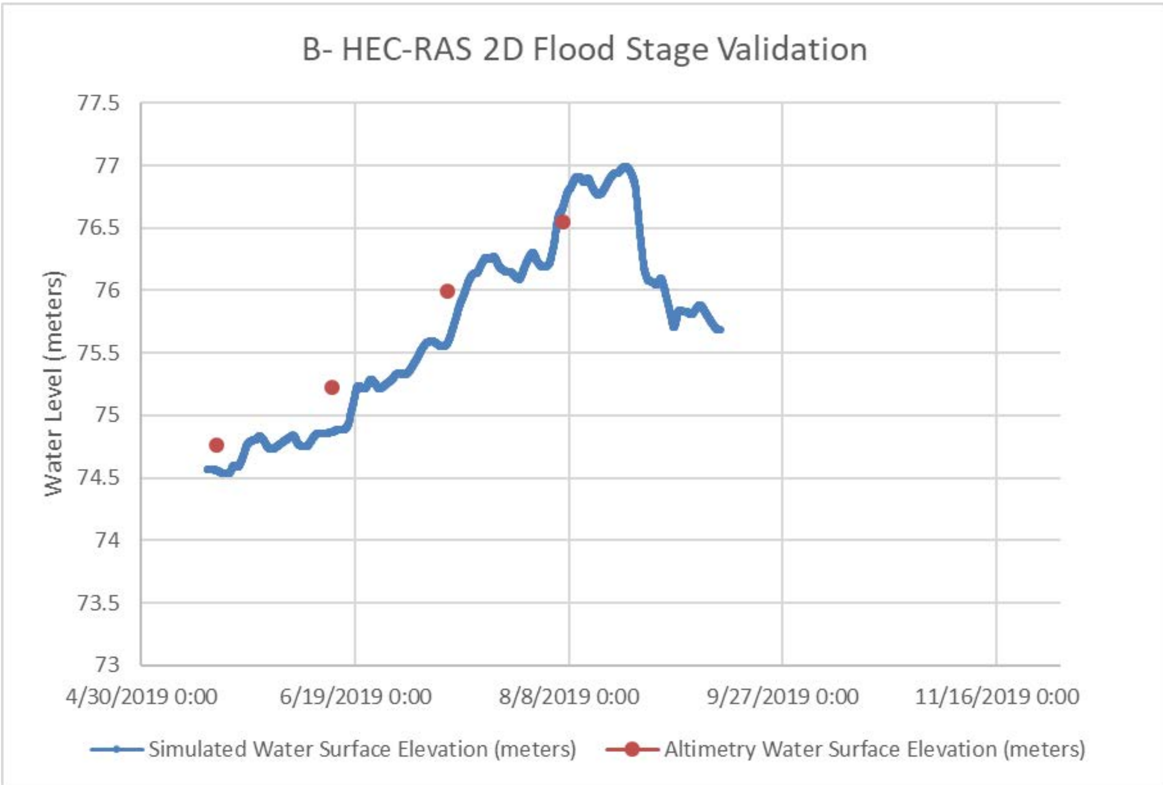


Fig. 3.6: 2D flood model calibration and validation results

3.3 Real-time Water Level Sensors at the Sindh Barrages

Our sensor device employs an ultrasonic sensor, which measures water levels (shown in Fig. 3.7). Data from the downstream and upstream sides of the Guddu and Sukkur Barrages were collected at continually at 15 minutes intervals. The web platform is provided, which integrates a dashboard to display retrieved data from all the nodes, where sensors are placed. The dashboard includes all the latest notifications and statistics which can be visualized or hid depending on the sensors that are connected to the devices. Markers (Fig. 3.8) also show a map where sensors are placed.

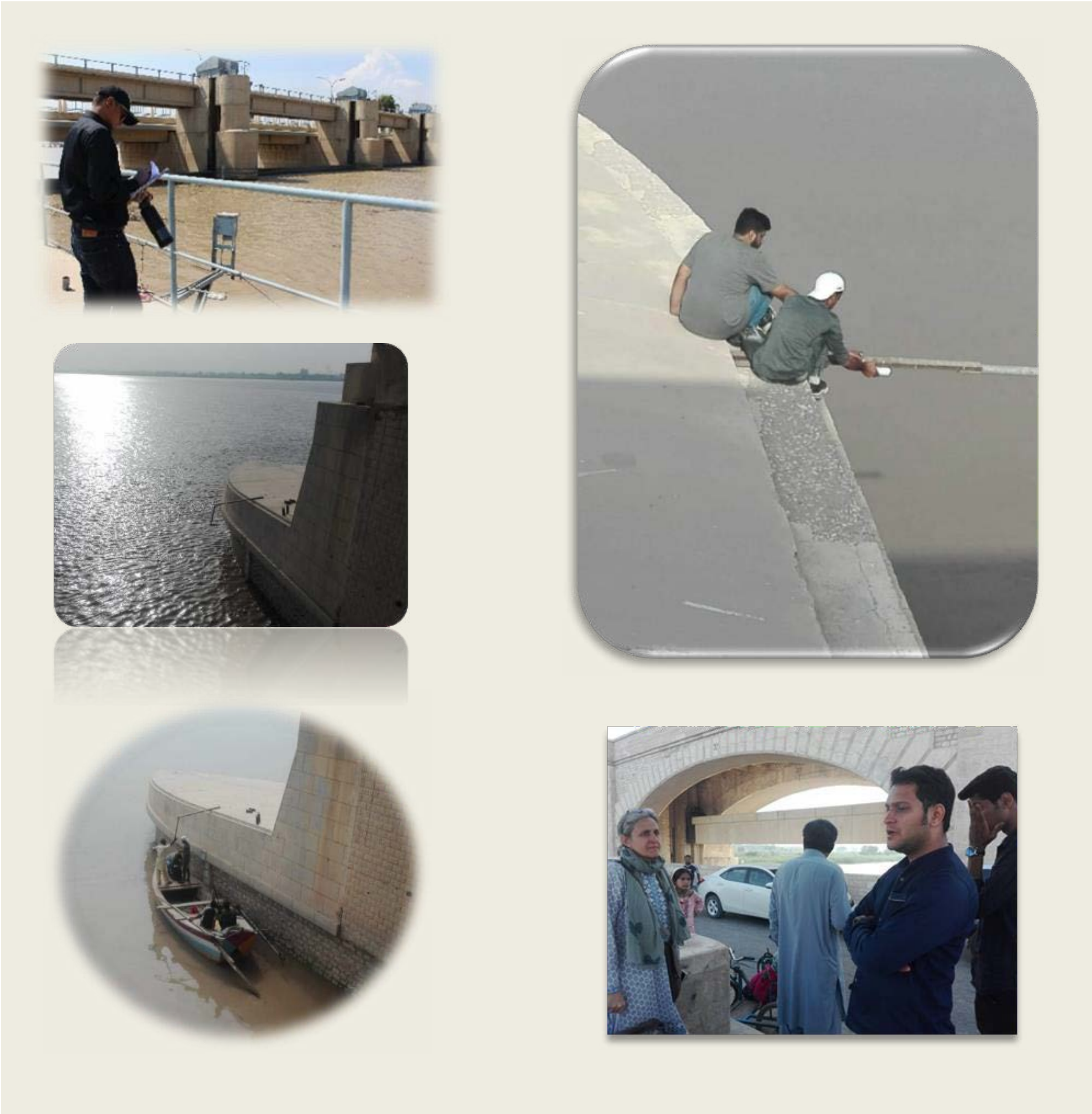


Fig. 3.7: Water level sensors' installation at the Sukkur Barrage

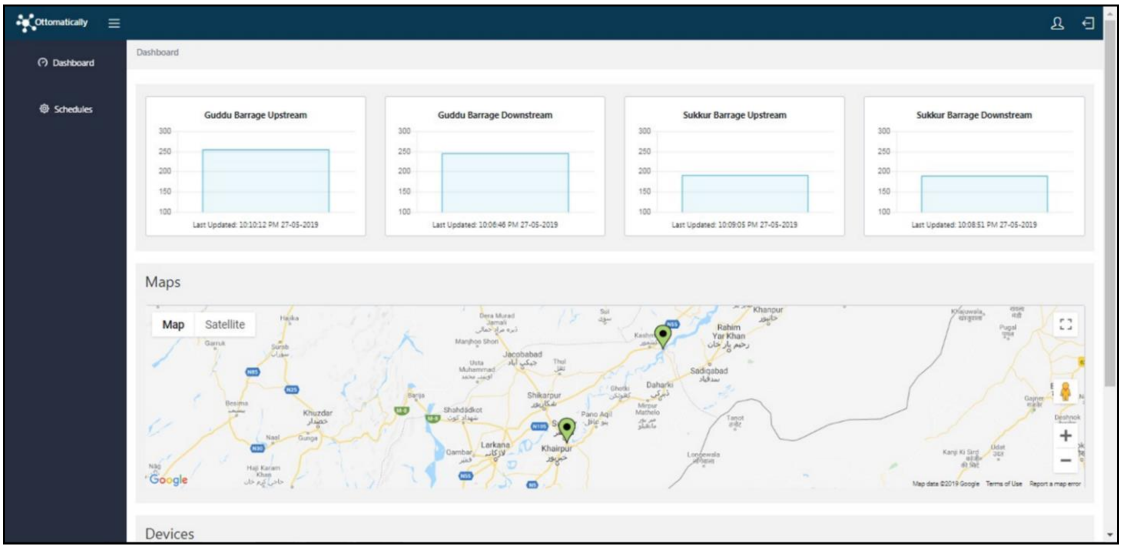


Fig. 3.8: Web platform- Dashboard

The retrieved data from all sensors can be downloaded as a report, PDF, EXCEL, or CSV files, and its application can be further used in flood forecast systems. Moreover, data can be filtered by inbuilt queries such as dates, as it is shown in Figure 3.9.

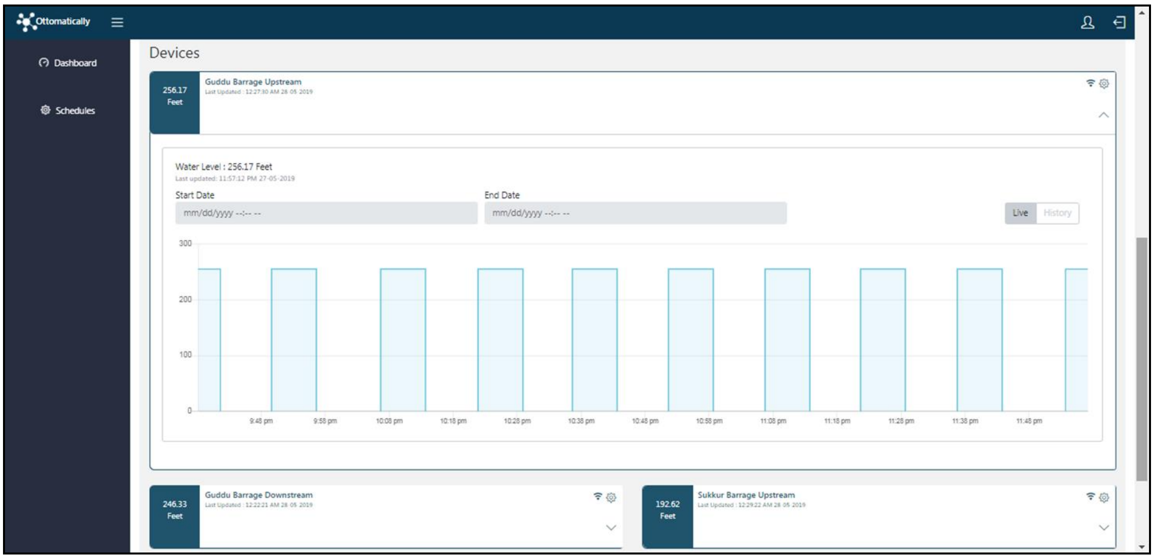


Fig. 3.9: Statistical view of sensor reading

Fig. 3.10 presents the results of these four different sources, where sensors were installed. The data were collected at continually at 15 minutes intervals over a controlled water source.

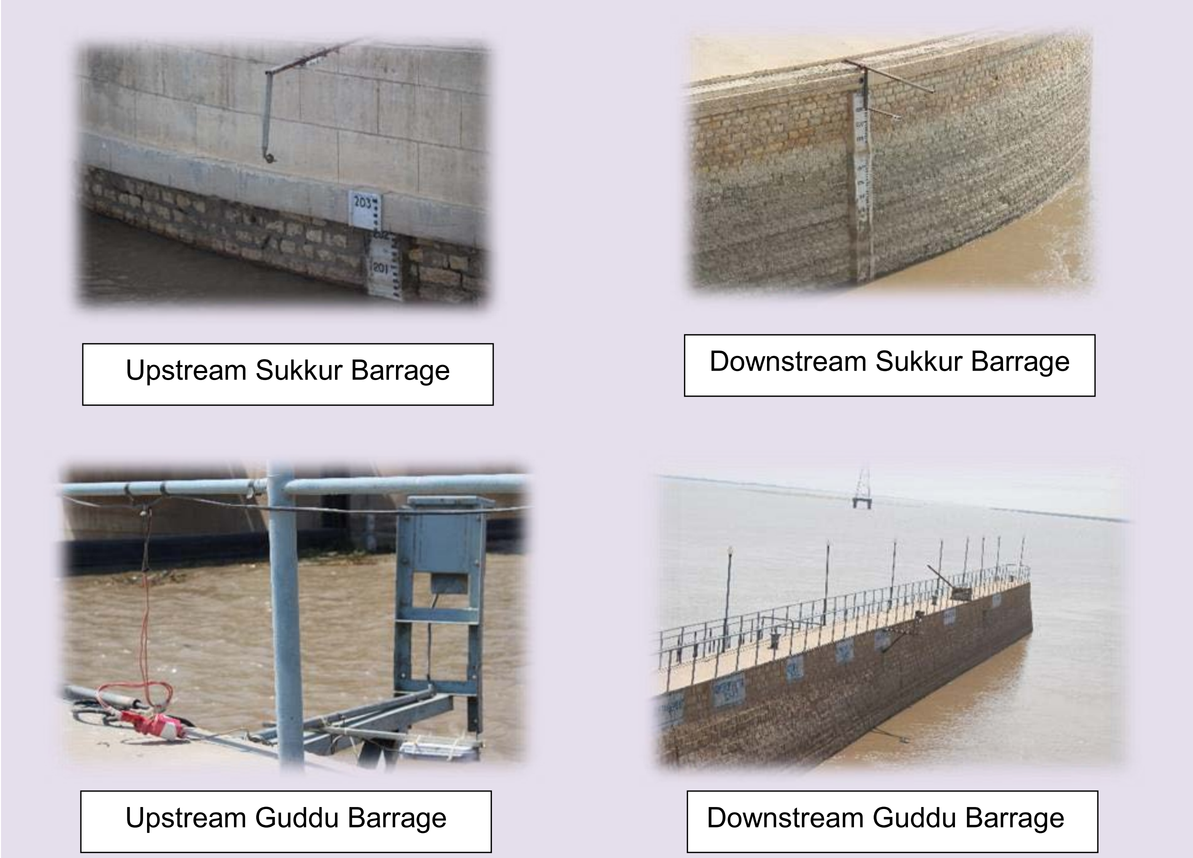


Fig. 3.10: Installed sensors at the barrages

3.4 Training Course – "Hydrology and Satellite Radar Altimetry"

In November 2018, a four-day training workshop on "Satellite Altimetry and its Hydrological Applications" was arranged with the support of the U.S.-Pakistan Center for Advanced Studies in Water (USPCAS-W), MUET Jamshoro, and the Institute of Space Technology (IST), Karachi. The primary purpose of this workshop was to provide a forum to share knowledge of Altimetry satellite remote sensing and image processing techniques amongst researchers and scientists of various national departments and academia. Dr. Stefano Vignudelli, an expert in satellite radar altimetry conducted the workshop from CNR – Consiglio Nazionale Delle Ricerche, Pisa, Italy. The workshop was attended by different stakeholders from government and non-government organizations, academia, researchers, and students. The photographs of the workshop are provided in Annex 1.

3.5 Research Output

The research outputs are presented below in terms of research papers presented/submitted in national and international conferences and research journals, M.Sc. thesis research of two students supported under this project, a training workshop and a project completion seminar for dissemination of research results.

3.5.1 Papers and posters presented in conferences (Annex-2)

1. Jamro, S., Naseer, T., Zaidi, A., and Vignudelli, S. (2019). A comparative analysis of altimetry derived water levels with in-situ guage data on river Indus. Presented in *International Geoscience and Remote Sensing Symposium* (IGARSS 2019) held on July 28 – August 2, 209, Yokohama, Japan.

2. Muzaffer, R., Zaidi, A., and Zafar, S. (2019). Volumetric variations of inland water body: A case study of Manchar Lake. Presented in *International Geoscience and Remote Sensing Symposium* (IGARSS 2019) held on July 28 – August 2, 2019, Yokohama, Japan.

3. Jamro, S., Haq, ul. S., and Zaidi, A. (2018). Indus River water level monitoring in Sindh using satellite radar altimetry. Presented poster on *Committee on Space Research (COSPAR) Conference* held on July 14-22, 2018, Pasadena, California, USA.

3.5.2 Papers to be presented in 12th Coastal Altimetry Workshop

Two papers are planned to be presented in the 12th Coastal Altimetry Workshop:

1. Zaidi, A., Muzaffer, R., Panhwar, V., Zafar, S., and Vignudelli, S. Indus River level monitoring using Sentinel 3A data. *12th Coastal Altimetry Workshop*. To be held on February 4-7, 2020, Frascati (Rome), Italy.

2. Panhwar, V., Zaidi, A., Vignudelli, S., and Naeem, B. 2D flood model validation in the lower Indus reach using satellite altimetry. *12th Coastal Altimetry Workshop*. To be held on February 4-7, 2020, Frascati (Rome), Italy.

3.5.3 Papers submitted for publications in research journals

1. Zaidi, A., Vignudelli, S., Khero, Z., Ghauri, B. M. K., Muzzafer, R., Naeem, B., Panhwar, V., and Zafar, S. River water level monitoring using satellite radar altimetry. *Advances in Space Research* (accepted).

2. Muzaffer, R., Zaidi, A., and Panhwar, V. Lake measurements using remote sensing: A review. *Advances in Space Research* (under 2nd review).

3.5.4 MS thesis produced

1. Ramsha Muzaffer: Lake measurements using remote sensing.

2. Talal Naseer: Monitoring sea level rise and its impacts along Pakistan coast using satellite radar altimetry and tidal gauge data.

3.5.5 Training workshop on satellite radar altimetry

A one-day hands-on training to demonstrate the process of *Indus River Monitoring in Sindh Using Satellite Radar Altimetry* was conducted in the USPACSW at the end of the project on October 15, 2019. Officials from the Sindh Irrigation department, students of USPCASW, and faculty from other institutions participated in the workshop. Ms. Sophia Hasnain (Founder & CEO - Linked Things) also presented the advantages of the Internet of Things (IoT) and salient features of the automatic waters sensors installed at the Guddu and Sukkur Barrages. A picture of the event is given in Annex 3.

3.5.6 Project results dissemination seminar

The project results were disseminated by organizing a seminar on November 22, 2019 at the Pak-US Center for Advanced Studies in Water (USPCAS-W), MUET Jamshoro. The seminar was attended by different stakeholders from government and non-government organizations, water experts, officials from Sindh Irrigation Department, academia, researchers, and students. The pictures of the event are given in Annex 4.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The primary aim of this project was to develop a low-cost approach for national surface water level monitoring in Pakistan to support sustainable water management. Satellite altimetry-based monitoring of water bodies is an advanced and cost-effective approach that was initially designed to study oceans. Radar altimetry for inland waters is a relatively new approach that was utilized for measuring water levels at two critical locations along the Indus River—near Guddu and Sukkur Barrages. This study found a good agreement between the satellite altimetry data of Sentinel 3A and the water levels measured at the Guddu (downstream side) and Sukkur (upstream side) Barrages. The limitation of this technique lies in not acquiring continuous data due to the satellites' longer revisit times that can be resolved by considering a combination of different altimetric missions (such as Jason series, ENVISAT series, CryoSat-2, TP—TopexPoseidon, Saral), which may provide higher temporal and spatial resolutions (CryoSat-2 takes observations according to a geographical mode mask that does not cover our study region). The irregular shoreline of the Indus River results in noisy waveforms with a narrow width. The along-track width (the width as seen by the satellite flying along the water body) varies over the area due to the drifting of satellite tacks up to certain km, which resulted in limited clean waveforms over the study area.

This technique enabled us to observe river level changes on different segments of the river system where otherwise no measuring devices are installed. As a result, the low gauging frequency along the Indus River can be enhanced by introducing the virtual stations (VSs) of Radar altimetry. There are 18 satellite tracks or VSs over the Indus River within the Sindh Province only. This study shows that building a reliable water level monitoring system can be achieved using technologies of satellite radar altimetry and new monitoring developments such Internet of Things (IoT). In comparison to the limited or restricted availability of gauge data, the present study found the satellite observations advantageous.

4.2 Recommendations

The excellent agreement between the water levels at the Guddu and Sukkur Barrages and altimetry data provided an opportunity to utilize the satellite radar altimetry to supplement the lean network of gauges at the Indus River. Considering all the VSs over the Indus River within and upstream, Pakistan, these can be utilized for the Indus River system monitoring and management. The transboundary and inter-provincial water flows can also be monitored, which are needed in many strategic decisions.

Although this study covered only two sites, the results of this study are promising with nearly the *'best'* fit between the in-situ gauge and the satellite data. The inclusion of more temporal and spatial data (Tarbela Reservoir gauge records) can lead to more authentic and improved results tested at different locations with varying topographies.

The accessibility of altimetry data and their spatial coverages across the Indus River can be exploited to predict, as much 1-2 months in advance, for the downstream water availability. Therefore, it is recommended that this technique for water resource management and monitoring from satellite altimetry data may be utilized at all decision levels related to water resource allocations and reservoirs operations. It is also essential to develop an economically viable and technologically robust sustainable Indus River management system for Pakistan utilizing satellite, and wireless sensors derived water levels along with gauge data.

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Annex-1: Training Course on "Hydrology and Satellite Radar Altimetry"

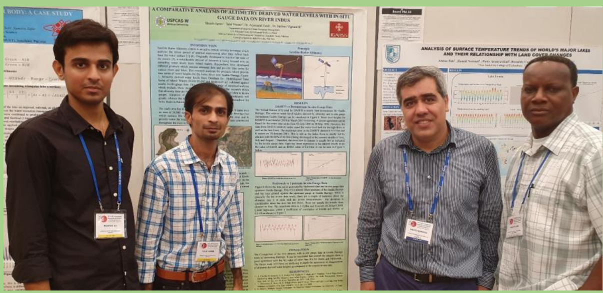


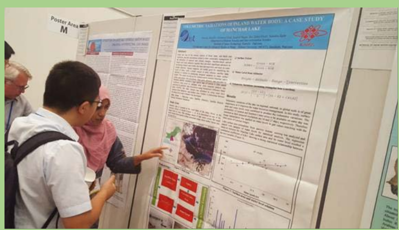







Annex-2: Presentation of Posters





Annex-3: Workshop on Indus River Monitoring in Sindh Using Satellite Radar Altimetry









Annex-4: Project Completion Seminar

About the Authors

Dr. Arjumand Zaidi did her Ph.D. from George Mason University, Virginia, USA in Environmental Engineering. Dr. Zaidi is currently working as a Senior Research Fellow in the U.S.-Pakistan Center for Advanced Studies in Water (USPCASW), Mehran University of Engineering and Technology, Jamshoro, Pakistan. Her professional experience is in the field of environmental evaluation and water resources management, aided by geospatial technologies. Recently her research is focused on the integration of satellite radar altimetry data with hydraulic and hydrologic modeling and geographical information system. The long-term goal of this study is to utilize satellite-estimated data in planning and policy-making for monitoring and managing of the Indus River.

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Engr. Zarif Iqbal Khero is currently working as Superintendent Engineer/Project Director of Chotiari Reservoir Project Circle in Sindh Irrigation Department, Government of Pakistan. He has more than 25 years of experience in the field of irrigation. He earned his BE degree in Civil Engineering and MS in Irrigation and Drainage Engineering from the Mehran University of Engineering and Technology, Jamshoro. Mr. Khero has received various trainings in the field of water resources management from different national and international water experts. His field of interest includes water resources and drainage engineering and the application of GIS and remote sensing for water resources management. He has published several peer reviewed research articles in national and international journals.

Dr. Badar Munir Khan Ghauri has done Ph.D. in Environmental Engineering from Institut National Des Sciences Appliquees, Toulouse, France and Postdoc from USA. Dr. Ghauri joined SUPARCO as a Senior Engineer in 1985 and served it till 2012 as Director. In 2012, Dr. Ghauri joined the Institute of Space Technology, Karachi as a Professor from where he retired in 2018. He has more than 25 years of experience in the field of research. His research interests include atmospheric aerosols studies, atmospheric trace gases and aerosol chemistry, terrestrial carbon and biospheric studies, land use, land cover dynamics and ecosystem studies and glacier and snow monitoring. More specifically, his research work involves environmental monitoring using satellite and in-situ data, atmospheric trace gases and aerosols such as atmospheric brown clouds, and climate change, the optical properties of aerosols related to their scattering coefficient and chemical composition, transport and transformation, cytotoxicity of urban aerosols.

Main thrust of Applied Research component of the Water Center is to stimulate an environment that promotes multi-disciplinary research within the broader context of water-development nexus to support evidence-based policy making in the water sector. This is pursued using the framework provided by the six targets of the Sustainable Development Goal on Water i.e., SDG-6.

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