ASSESSMENT OF SPATIO-TEMPORAL WATERLINE CHANGES OF A RESERVOIR: A CASE STUDY OF UJJANI WETLAND, MAHARASHTRA, INDIA

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Abstract
The Ujjani reservoir is an artificial inland wetland and a potential Ramsar site in Maharashtra, India. The present study investigates the changes in the surface water area over time using remote sensing imageries (LANDSAT, LISS-III, Sentinel 2 series) for four decades (1981 to 2021) and the normalized difference water index (NDWI). The study reveals that the overall mean amount and rate of decrease in the surface water area are estimated at 20.50% (44.31 + 30.38 sq. km) and 0.75% year-1 (1.62 + 1.36 sq. km year-1), respectively. Furthermore, multiple correlation matrix analysis shows a strong positive correlation between surface water area and rainfall while a weak negative correlation with mean annual temperature (T_{MAX}). Thus, indicating rainfall as the principal factor in inducing changes to the surface water area of the Ujjani wetland. However, the study also finds that the impact of the dramatic rise in population growth and anthropogenic activities in the form of overexploitation of water and land encroachments for agriculture are gradual but significant cursors to wetland degradation. Hence, the study recommends periodic monitoring, management, and conservation of wetlands, by employing stringent policies and effective technological measures.

Keywords: India; Maharashtra; Ujjani Wetland; Remote sensing & GIS; Normalized Difference Water Index (NDWI); Spatio-temporal monitoring; Rainfall; Wetland Management

1. Introduction

Wetlands are unique, productive, and ignored ecosystems of the world (Ramsar Convention, 2016). A comprehensive study by World Wildlife Fund (WWF) on 89 wetlands globally reported, that the wetland area of 63 m ha generates around $3.4 billion per year, with wetlands in Asia contributing $1.8 billion (Schuyt & Brander, 2004). Nevertheless, the deterioration of wetlands has accelerated worldwide in the last 50 years (Bridgewater & Kim, 2021), with marine and inland wetlands accounting for approximately 35% decline (Ramsar Convention, 2018). In the 1980's and early 1990s, the total areal spread of wetlands in India estimates at around 58.3 m ha, of which the paddy fields accounted for nearly 71% share (Woistencroft et al., 1989; WWF & AWB, 1993). The National Wetland Atlas (SAC, 2011), prepared based on the Ramsar Convention, estimated an aerial extent of about 15.26 m ha, covering around 4.63% of the country's geographical area. The inland wetlands contribute 1.05 m ha of land in the Indian subcontinent, of which the state of Maharashtra accounts for 0.036 m ha of artificial wetlands classified as reservoir/barrage (SAC, 2011). The Ujjani wetland is an artificial wetland and a potential Ramsar site in Maharashtra (Islam & Rahmani, 2008; Samant, 2012), which came into existence after the creation of earth-cum-masonry gravity dam on river Bhima, a tributary of river Krishna. It was primarily built for irrigation, fisheries, and hydel power but has also emerged as a necessary feeding and roosting ground for resident and migratory waders (Kumbhar & Mhaske, 2020). Recent studies have highlighted water pollution, rapid population growth, land encroachments, eutrophication, rampant sand mining, excessive fishing, and unplanned tourism as significant factors for wetland degradation and loss (Sangpal et al., 2014; Dede, 2016; Kumbhar & Mhaske, 2017, 2019; Karikar et al., 2019).

Wetlands experience large-scale ecological disturbances from anthropogenic and natural factors (Ramsar Convention, 2018; Han et al., 2017; Xie et al., 2010). However, the impact of human-induced changes are more rapid (Mabwoga & Thukral, 2014), primarily resulting from agriculture (Syphard & Garcia, 2001). With the advent of remote sensing technologies and Geographic Information Systems (GIS), mapping, monitoring, and management of wetland resources has become effortless, meticulous, and expeditious (Lyon et al., 2001; Adam et al., 2010; Lang et al., 2015; LaRocque et al., 2020). The application of satellite data such as LANDSAT (MSS, TM, ETM+, OLI), LISS III, and Sentinel 2 greatly helps in wetland studies to analyse the extent of degradation (Ozesmi & Bauer, 2002; Manju et al., 2005; Garg et al., 1998; Panigrahy, 2017; Slagter et al., 2020; Pena-Regueiro et al., 2020; Elemuwa et al., 2021). Many workers in the past have

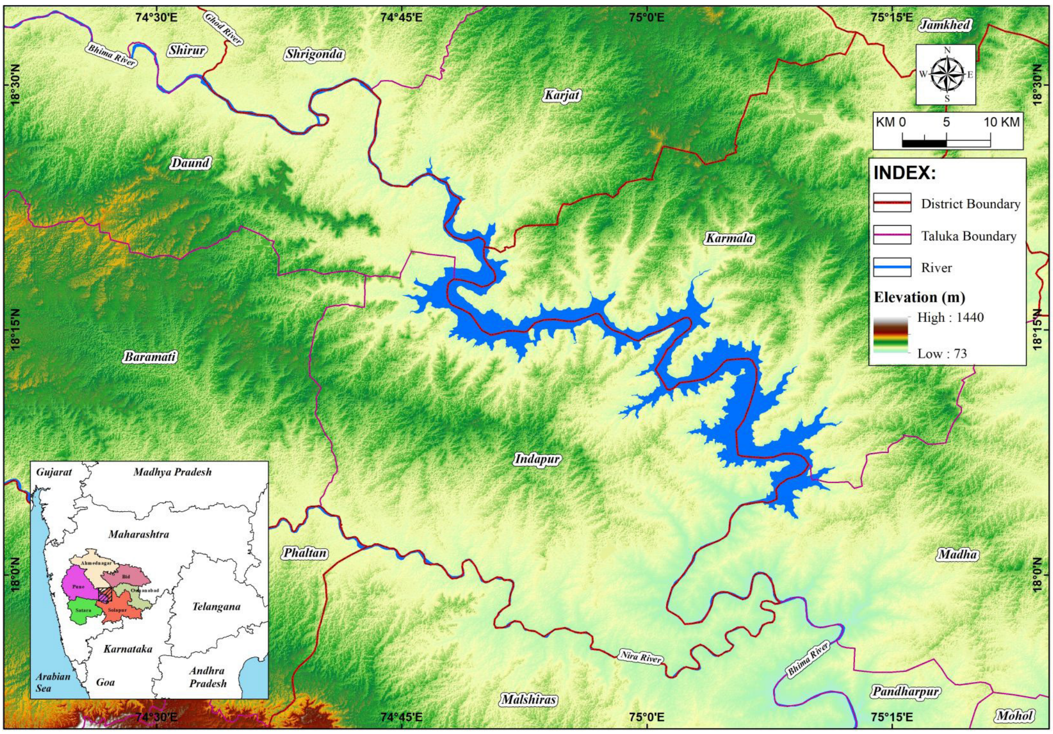


Fig. 1. Location and administrative map of Ujjani wetland overlaid on SRTM DEM

estimated the spectral indexes of water, land, and vegetation using arithmetic operations of two or more bands for delineating change detection (McFeeters, 1996; Guha et al., 2020; Bhattacharjee et al., 2021; Abebe et al., 2022; Yengoh et al., 2015; Islam et al., 2021). For the detection and delineation of water features and high soil moisture areas, the normalized difference water index (NDWI) is commonly used (McFeeters, 1996; 2013). The current research focuses on using the NDWI for change detection of surface water of Ujjani wetland from 1981 to 2021. The study also examines the seasonal relationship between the water surface area and factors such as rainfall, temperature (T_{MAX}), and population. This research will aid the authorities and planners in better wetland ecosystem management and future environmental planning.

2. Study area

The Ujjani wetland in the state of Maharashtra covers parts of Pune and Solapur districts, bounded between latitudes 18°03'N to 18°24'N and longitudes 74°45'E to 75°12'E. Spatially, it spreads along the eastern

Table 1. Details of the datasets considered for the study

Imagery Date	Satellite used	Resolution (m)	Path/ Row	NDWI = (Green-NIR)/ (Green+NIR)
25.05.1981	Landsat 3 (MSS)	60 (Visible, NIR)	157/47	Band 4: Green band Bands 6 & 7: NIR band
17.05.1991 14.05.1996	Landsat 5 (TM)	30 (Visible, NIR) 120 (TIR)	146/47	Band 2: Green band Band 4: NIR band
17.05.2000 04.05.2001 10.05.2003	Landsat 7 (ETM)	30 (Visible, NIR, SWIR) 60 (TIR) 15 (PAN)		
31.05.2008 02.05.2009 05.05.2010 08.05.2011	Landsat 5 (TM)	30 (Visible, NIR) 120 (TIR)		
13.05.2013	Landsat 8 (OLI/TIRS)	30 (Visible, NIR) 100 (TIR) 15 (PAN)		Band 3: Green band Band 5: NIR band
13.05.2014	LISS III (Resourcesat 1 and 2)	24 (Visible, NIR)	96/60	Band 3: Green band Band 4: NIR band
19.05.2015 05.05.2016	Landsat 8 (OLI/TIRS)	30 (Visible, NIR) 100 (TIR) 15 (PAN)	146/47	Band 3: Green band Band 5: NIR band
20.05.2017	Sentinel 2A (MSI)	10 (Visible) 20 (NIR)	105	Band 3: Green band Band 8: NIR band
11.05.2018 14.05.2019	Landsat 8 (OLI/TIRS) Landsat 8 (OLI/TIRS)	30 (Visible, NIR, SWIR) 100 (TIR) 15 (PAN)	146/47	Band 3: Green band Band 5: NIR band
09.05.2020	Sentinel 2A (MSI)	10 (Visible) 20 (NIR)	105	Band 3: Green band Band 8: NIR band
03.05.2021	Landsat 8 (OLI/TIRS)	30 (Visible, NIR) 100 (TIR) 15 (PAN)	146/47	Band 3: Green band Band 5: NIR band

fringe of Daund, Baramati, and Indapur talukas and to the western fringe of Karmala and Madha talukas (Figure 1): It stretches for around 670 km along the rim periphery. It came into existence after constructing an earth fill cum masonry gravity dam in June 1980 on the Bhima River (NRLD, 2019), one of the main tributaries of River Krishna. Since then, it has become a lifeline of water supply, major agricultural activities, and home to many migratory birds. The area experiences broadly tropical monsoon to semi-arid climate (Koppen classification system), with mean daily temperatures ranging around 31°C to 33°C in summer and 18°C to 20°C in winter. The soils are typically fine clayey, deep to moderately well-drained, calcareous inceptisols and vertisols (Challa et al., 1999).

3. Materials and methods

The study aims to assess the changes in the water surface area of the Ujjani wetland using remote sensing imageries and its relationship with indicators like rainfall, mean annual temperature (T_{MAX}), and population. Available cloud-free LANDSAT and Sentinel 2 imageries of Ujjani wetland for the period between 1981 and 2021 were acquired from the United States Geological Survey (USGS) database (http://earthexplorer.usgs.gov.in), while LISS-III data for the year 2014 from the National Remote Sensing Centre portal (http://bhuvan.nrsc.gov.in/) in GeoTIFF format.

As the study area is rain-dependent and experiences large scale climatic fluctuations during post- and pre-monsoon phases, the imagery data of the dry period, especially May month, were targeted for the estimation of maximum change in the waterline boundary. The study uses nineteen (19) imageries from the LANDSAT, Sentinel 2, and LISS III databases (Table 1) for the preparation of image composites in the GIS environment (ArcGIS 10.4). Firstly, the Normalized Difference Water Index (NDWI) was determined using the green and near-infrared (NIR) bands (McFeeters, 1996; 2013), ranging between -1 and +1. The negative NDWI values indicate built-up areas and bare land lacking water surfaces, while the positive NDWI values suggest water and vegetation surfaces. Later, with the help of the normalized difference vegetation index (NDVI), vegetation and water surface features were masked.

Validation of the extracted multi-temporal water surface areas were also carried out using the maximum likelihood classification algorithm in the GIS environment. Four major LULC classes like vegetation, built-up area/bare land, agricultural land, and waterbody were identified, which were later categorized into waterbody and other lands. This method is simple, yet effective in categorization of classes based on mean and covariance algorithm, centred on the foundation of visual estimation of cell values by the user. The categorized data was compared with the NDWI and NDVI outputs to generate the precise water surface area of Ujjani wetland. Second-level of rudimentary validation involved visual examination of surface water area boundaries using Google Earth historical imageries, topographical maps (Source: Survey of India), and LULC maps (Source: BHUVAN).

Three different natural as well as anthropogenic factors were tested and compared with the estimated water surface area of wetland for different years. The natural factors comprised the annual rainfall and annual mean temperature (max), while the anthropogenic involved the population. The available monthly rainfall data for Pune and Solapur districts were downloaded from 1999 to 2020 from the Maharashtra government website (https://maharain.maharashtra.gov.in). The downloaded data corresponds to the average annual rainfall recorded at Baramati, Indapur, Daund, Madha, Karmala, Pandharpur, and Sangola stations (clustered close to the Ujjani wetland) during pre-monsoon, monsoon, and post-monsoon periods. For the mean annual temperature, the high-resolution data for the period from 1981 to 2020 were downloaded

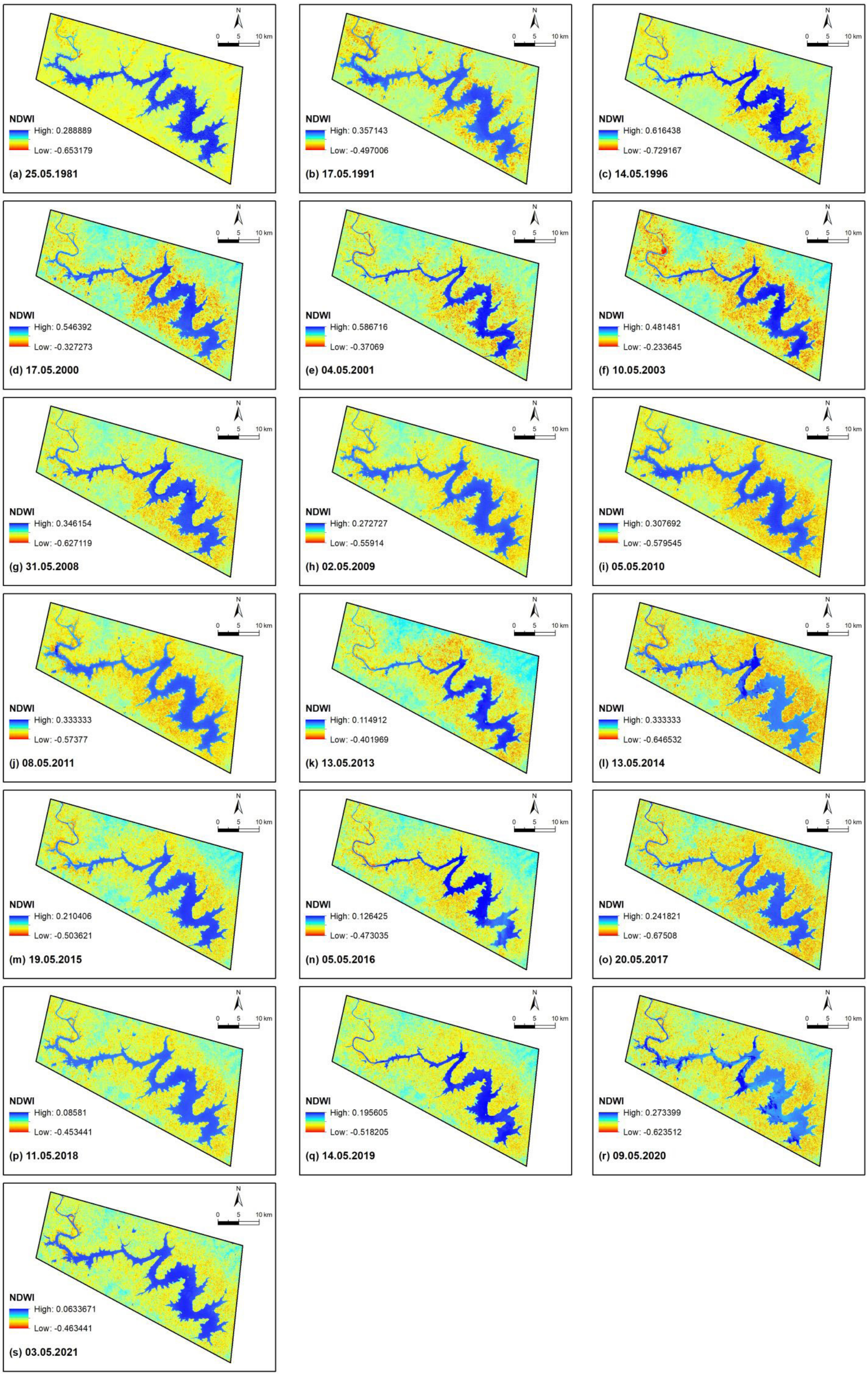


Fig. 2. Spatio-temporal distribution of NDWI for Ujjani wetland from 1981-2021 (LANDSAT 5, 7, 8, Sentinel 2B and LISS-III satellite imageries, USGS and BHUVAN portal)

from the Indian Meteorological Department (IMD) portal (https://www.imdpune.gov.in) (Srivastava et al., 2017). The downloaded T_{MAX} grid database for the study area was extracted in the QGIS platform (v. 3.22) using the python console. The mean annual T_{MAX} database is categorized to pre-monsoon, monsoon, and post-monsoon seasons. The study area cover parts of Karmala, Madha, and Indapur talukas of the Solapur and Pune districts, hence the population data of these districts were targeted for comparison with the wetland waterline changes. The population database of these talukas was downloaded from the Census portal (https://censusindia.gov.in) for the years 1991, 2001, and 2011 respectively.

Lastly, the statistical analysis involving correlation analysis and linear regression model was performed on the surface water area of the wetland and influential factors and at the significance level of 0.01 using Microsoft Excel. The Pearson's correlation coefficients were also applied to detect the direction and strength of significant linear relationships.

4. Results

The spatio-temporal changes in water surface area are vital in monitoring and evaluating the impact on the wetland ecosystem from environmental and anthropogenic factors. Water surface area

Table 2. Long-term spatio-temporal changes of surface water line in Ujjani wetland

Sr. No.	Imagery Type	Date	Area (km^2)	Amount of change		Rate of change	
				(km^2)	(%)	(km^2/yr)	(%/yr)
1	LANDSAT-3	25.05.1981	216.106	--	--	--	--
2	LANDSAT-5	17.05.1991	222.876	6.77	3.13	0.68	0.31
3	LANDSAT-5	14.05.1996	151.873	-64.23	-29.72	-4.28	-1.98
4	LANDSAT-7	17.05.2000	167.273	-48.83	-22.60	-2.57	-1.19
5	LANDSAT-7	04.05.2001	140.055	-76.05	-35.19	-3.80	-1.76
6	LANDSAT-7	10.05.2003	141.448	-74.66	-34.55	-3.39	-1.57
7	LANDSAT-5	31.05.2008	168.106	-48.00	-22.21	-1.78	-0.82
8	LANDSAT-5	02.05.2009	200.853	-15.25	-7.06	-0.54	-0.25
9	LANDSAT-5	05.05.2010	219.575	3.47	1.61	0.12	0.06
10	LANDSAT-5	08.05.2011	209.298	-6.81	-3.15	-0.23	-0.11
11	LANDSAT-8	13.05.2013	134.013	-82.09	-37.99	-2.57	-1.19
12	LISS-III	13.05.2014	183.999	-32.11	-14.86	-0.97	-0.45
13	LANDSAT-8	19.05.2015	167.530	-48.58	-22.48	-1.43	-0.66
14	LANDSAT-8	05.05.2016	127.080	-89.03	-41.20	-2.54	-1.18
15	Sentinel-2A	20.05.2017	151.125	-64.98	-30.07	-1.81	-0.84
16	LANDSAT-8	11.05.2018	194.878	-21.23	-9.82	-0.57	-0.27
17	LANDSAT-8	14.05.2019	130.035	-86.07	-39.83	-2.27	-1.05
18	Sentinel-2A	09.05.2020	185.825	-30.28	-14.01	-0.78	-0.36
19	LANDSAT-8	03.05.2021	196.505	-19.60	-9.07	-0.49	-0.23
Grand mean in 2021				-44.31	-20.50	-1.62	-0.75
Standard Deviation				30.38	14.06	1.36	0.63
Median value in 2021				-48.29	-22.34	-1.60	-0.74

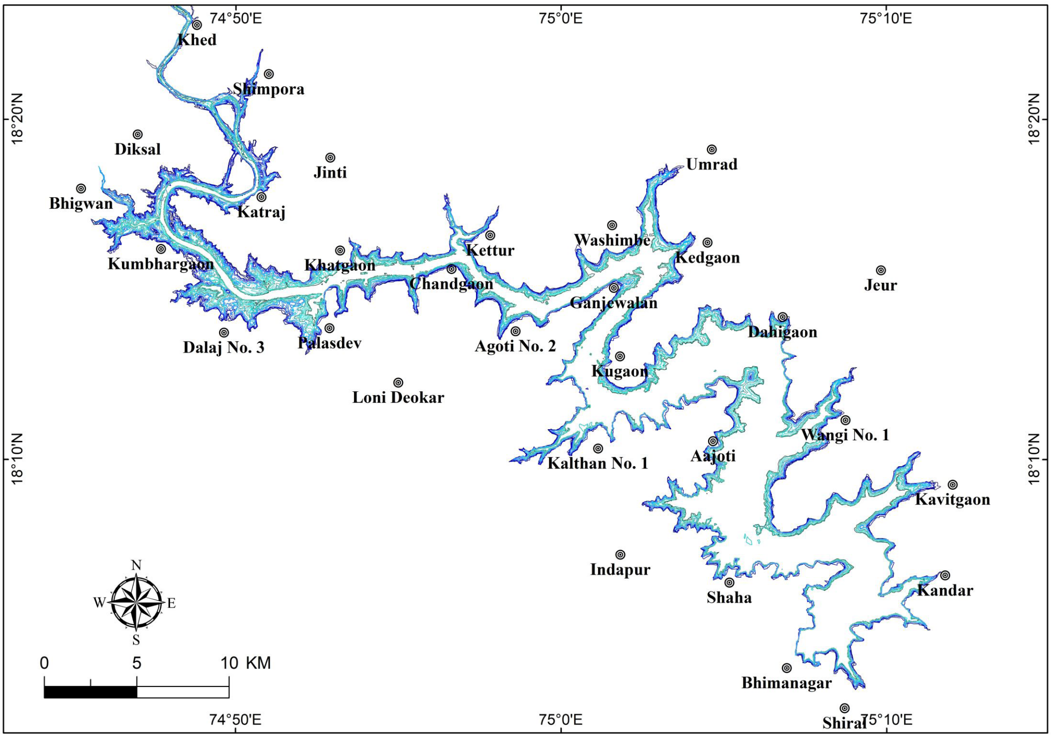


Fig. 3. Water surface areas changes of Ujjani wetland for the period from 1981 to 2021

estimated on yoy-1 basis is presented in Table 2, which displays the long-term waterline changes in Ujjani wetland spanning over four decades. The wetland came to existence post-construction of Ujjani dam at Shiral Tembhurni in the year 1981. Hence, 1981 was considered as the base year for assessment of changes in the wetland water surface area. Water surface area in 1981 is calculated to be 216.11 km^2. The maximum and minimum water surface areas were reported from 1991 at 222.88 km^2 and from 2016 at 127.08 km^2, respectively. Comparison of yearly data over four decades, indicate an average decrease of 20.50% (44.31 + 30.38 km^2) and 0.75%y-1 (1.62 + 1.36 km^{2}y^{-1}) in transformation amount and rate of change, respectively.

Median-based change detection was also followed in order to minimize the skewness of the data. But it appears to be congruous with the mean-based analysis, and displays similar decrease in transformation amount (22.34%; 48.29 km^2) and rate of change (0.74%y-1; 1.60 km^{2}y^{-1}), respectively. Significant decrease (>80 km^2) in the total water surface area since 1981 is reported during the years 2016 (89.03 km^2; 41.20%), 2019 (86.07 km^2; 39.83%), and 2013 (82.09 km^2; 37.99%) (Fig. 3.4A). Marginal increase in the total water surface area is estimated only during two instances throughout the period of four decades, one in 1991 (6.77 km^2; 3.13%), and in 2010 (3.47 km^2; 1.61%). Mostly, the rate of change in the water surface area of Ujjani wetland yoy-1 is estimated to be more than 1%. Significant waning of water surface area in terms of the rate of change yoy-1, is marked in the years 1996, 2001, and 2003, respectively. Two rhythmic patterns of fluctuations from decreasing to being constant are also observed, viz. from 1996 to 2009 and 2011 to 2021, respectively. Fig. 3 shows the gradual decrease in water line for Ujjani. Among the villages located at a close proximity to the Ujjani wetland, Shimpora, Katraj, Diksal, Bhigwan, Khumbhargaon, Dalaj No. 3, Palasdev, and Khatgaon displayed a sizeable drop in the water surface area (Fig.

3). Besides, the rate of decrease in the central sector (near Kettur, Chandgaon, Agoti No. 2, Washimbe, Umrad, Kedgaon, Kugaon, Kalthan No.1), even though small in comparison to the western sector, exhibits slow but amplified decline in the water surface area. (Fig. 3).

5. Discussions

As briefed earlier, the role of influencers in shaping of the wetland water surface area were explored by comparison of rainfall, MAT_{MAX}, and population over the period of four decades.

Rainfall

The average annual rainfall of Karmala, Madha, and Indapur talukas of the Solapur and Pune districts was calculated for a total of 15 years and trends in rainfall fluctuations were assessed. Table 3 provides the details of average annual rainfall in the study area. The average annual rainfall from 1999 to 2020 varies from 208.63 mm in 2018 to 923.75 mm in 2020, with a standard deviation of 183.36 mm (Table 3). The change in the annual average rainfall with the mean annual average rainfall indicate sharpest decrease in the years 2018, 2015, and 2014, registering ≥25% decline, while an increase of >25% is reported during the years 2020, 2010, 2009, and 1999, respectively (Table 3). Comparison of average annual rainfall with surface water area suggests a strong influence, with rain-deficient years displaying lower water surface areas. The lower recorded rainfall in the years 2002, 2014, 2015, 2016, 2018 show significantly less water surface area spread in comparison to other years (Table 3).

Temperature

The mean annual temperature (T_{MAX}) defines the warming of the region, and an exponential increase in temperature results in higher evaporation of water from the surface water bodies. It serves as a vital indicator in estimation of variations due to worldwide climate change, that can cause disbalance in the water budget of any wetland over a larger period of time. The mean annual T_{MAX}

Table 3. Comparison of average annual rainfall (mm), change (%) and estimated area (km^2)

Sr. No.	Year	Avg. Annual Rainfall (mm)	Change (%)	Est. Area (km^2)
1	1999	710.30	28.96	167.27
2	2000	521.93	-5.24	140.06
3	2002	356.04	-35.36	141.45
4	2007	576.88	4.74	168.11
5	2008	506.03	-8.12	200.85
6	2009	724.83	31.60	219.58
7	2010	836.14	51.81	209.30
8	2013	541.91	-1.61	184.00
9	2014	415.61	-24.54	167.53
10	2015	350.05	-36.45	127.03
11	2016	450.93	-18.13	151.13
12	2017	580.22	5.34	194.88
13	2018	208.63	-62.12	130.04
14	2019	558.51	1.40	185.83
15	2020	923.75	67.72	196.51

Table 4. Changes in the temperature (TMAX) during pre-monsoon, monsoon and post-monsoon seasons from 1981-2020

Period	Mean Annual T_{MAX} (MAT) (°C)					
	Pre-Monsoon	Change (%)	Monsoon	Change (%)	Post-Monsoon	Change (%)
1981-1990	36.884	--	30.023	--	30.657	--
1991-2000	37.292	1.11	30.211	0.62	30.553	-0.34
2001-2010	37.563	1.84	30.217	0.64	31.503	2.76
2011-2020	37.645	2.06	30.355	1.11	31.294	2.08

of the area shows a significant increase on a decadal scale, with 2.06% and 1.11% during the pre-monsoon and monsoon seasons of the 2011 to 2020 periods, respectively (Table 4). Besides, a drastic increase in temperature in the post-monsoon seasons is also reported (Table 4).

Population

Rapid population surges and urbanization have caused significant disruption of the wetland ecosystem worldwide. Maharashtra state has witnessed an exponential increase in the population density from 3.96 crores in 1961 to 11.24 crores in 2011 (Directorate of Economics and Statistics, Govt. of Maharashtra). The decennial population growth rate from 2001 to 2011 for Pune and Solapur districts recorded more than 30% and 12%, respectively (Economic Survey of Maharashtra 2021-22). The Ujjani wetland covers parts of the Karmala, Madha, and Indapur talukas of the Solapur and Pune districts which directly exploit influence and meddle with the water resources of the wetland. Large-scale anthropogenic interference in the form of unsystematic withdrawal of water using high-capacity submersible pumps all along the rim periphery of the wetland is common. Hence, assessment of clustered population growth of these areas to validate the anthropogenic influence was attempted. From 1991 to 2011, a substantial population increase is reported in Indapur taluka, with an increase of more than 79%, while Karmala and Madha talukas show more than 40%, respectively (Table 5).

Multiple correlation matrix analysis

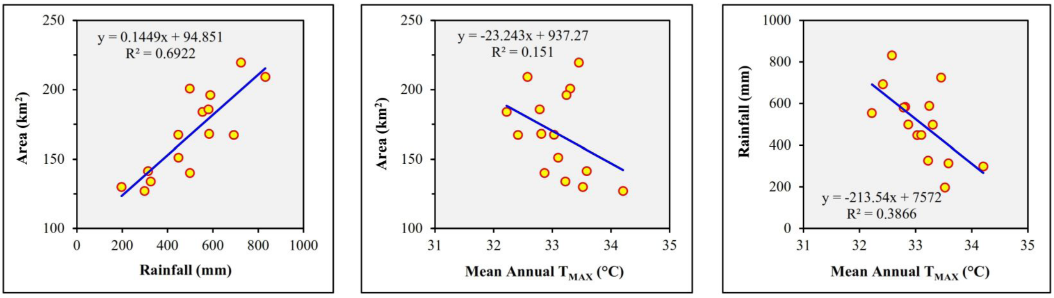
A correlation matrix and regression analysis between water surface area, rainfall, and temperature are carried out to detect the primary influencers. A strong positive correlation (0.831) between surface area and rainfall and a weak negative correlation (-0.388) between surface area and MAT indicates that rainfall is a top influencer in causing changes in the water surface area (Table 6). On the other hand, the relation between rainfall and MAT shows a moderate

Table 5. Growth of population in talukas of Solapur and Pune districts from 1991 to 2011

District	Taluka	1991	2001	2011	Change (%) from 1991 to 2001	Change (%) from 1991 to 2011
Solapur	Karmala	45192	57928	64678	28.18	43.12
	Madha	6656	9137	9367	37.27	40.73
Pune	Indapur	37745	58892	67678	56.03	79.30

Table 6. Pearson's correlation and descriptive statistics

Variable	Area	Rainfall	**MAT**	**Mean**	**SD**
Area	1			168.16	29.27
Rainfall	0.831	1		505.90	168.07
MAT	-0.388	-0.621	1	33.09	0.49
N=15					



Fig, 4. Multiple correlation analysis of Area, Rainfall, MAT (N=15; correlation at 0.01 level) for Ujjani wetland

negative correlation (-0.621), indicating no role of influence between either two. A significant linear relationship appears between the surface water area and the rainfall (r = 0.69; p = 0.0001) and between rainfall and MAT (r = 0.38; p = 0.013) (Fig. 4).

6. Conclusions

The decadal climate changes and the local environmental degradation caused by anthropogenic intervention have significantly impacted the wetland ecosystem worldwide. Wetlands are considered the prime epitomes of the impact from climate change, but are largely not included in global models (Patel et al., 2009). Remote sensing and GIS technology provide a simple yet effective tool for monitoring the spatiotemporal changes of wetlands. Using the NDWI index, fluctuations in the water surface area of Ujjani wetland from 1981 to 2021 show a gradual and significant decrease. More importantly, the upstream section of the wetland near Shimpora, Katraj, Bhigwan, Kumbhargaon, Dalaj No. 3, Palasdev, and Khatgaon localities has experienced more loss, which may cause a substantial decline in the water surface area of the Ujjani reservoir. Average decrease in the waterline of 44.31 km2 and 0.75%y-1 signifies the stress on the Ujjani wetland. Multi-variate statistical analysis concludes primary role of rainfall, however the role of population and also MAT_{MAX} cannot be completely discarded. The cause of reduction is primarily due to the disparate rainfall affected by global climatic variations. However, the exponential increase in population mainly clustered around the urban and rural villages across the rim periphery of the wetland exploit the surface water of the wetland by pumping out through high-capacity submersible pumps. The extracted water is mostly used for irrigation, aquaculture ponds, fisheries, and transported to small-scale sugar mills. Ample availability of water is gradually causing substantial land incursions, crop specialization, and over irrigation. Thus, population increase and surge in the demand for water resources also acts as a slow, but vital threat in shrinkage of Ujjani wetland.

The marginal increase in the surface water area in 2010 attests to heavy precipitation. The rate of decrease of the surface water area in the Ujjani wetland is a severe threat to the biodiversity and wetland ecosystem. Thus, this study strongly recommends periodic monitoring, conservation, and development of a comprehensive management plan and stringent policy for the Ujjani wetland from climatic and socio-economic factors.

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