ORIGINAL ARTICLE

Assessment of factors affecting hydrologic variability of Wadhvana wetland, Gujarat (India)

Jatin Soniya[1] · Dhara Kakwani[1] · Neha Singh[1]

Abstract

The Wadhvana wetland, a Ramsar site, is a wintering place for migratory birds, including endangered species. The current study aimed to evaluate the variables influencing the hydrologic variability of the Wadhvana wetland through an analysis of water distribution throughout the pre- and post-monsoon seasons. The Modified Normalised Difference Water Index (MNDWI) was computed using Landsat data to estimate the water spread. The wetland's catchment region was analyzed using SRTM Digital Elevation Model data to examine the drainage pattern and drainage basin. The results of the analysis indicate that the premonsoon water coverage area decreased significantly between 2003 and 2022. However, the postmonsoon water amount is sustained through imports from the Narmada Canal. The drastic change in the water spread may affect the wetland's aquatic flora as in the dry season the wetland would be prone to cattle grazing or agricultural activities by nearby residents. Predominant land use in the drainage basin is the usage of land for agriculture, where water requirement is fulfilled either with groundwater drawn from tubewells or water from the Wadhvana wetland. The random survey conducted in the villages near the wetland indicates that the residents depend on the wetland for irrigation and livestock farming. The wetland and the aquifer in the basin are hydraulically connected, thus for long-term sustenance of the wetland, conservation efforts and measures would be required to improve the irrigation techniques and maximize the rainwater harvesting for groundwater recharge so that the pressure on the wetland can be minimized.

Keywords Wadhvana wetland · Water spread · Land use · Drainage basin · Groundwater

Introduction

According to Mitsch and Gosselink (1993), wetland areas are "lands transitioning between terrestrial and aquatic ecosystems". These areas are either covered by shallow water or have a water table that is normally at or near the surface. These ecosystems are vital for delivering crucial ecosystem services like acting as a natural floodwater storage area, assisting in the recharge of aquifers, treating wastewater and pollutants, enhancing overall water quality, offering a habitat for a variety of plant and animal species, and enhancing biological productivity (Myers 1987; Verhoeven et al. 2006; Webb et al. 2010; Ji et al. 2015; Estrada et al. 2015). The

conversion of wetlands in India for industrial, agricultural, and other development objectives poses a severe threat to the environment. These operations have had several detrimental repercussions, including changing the hydrology and polluting the environment. The extent, distribution, and function of wetlands are all expected to be significantly altered by climate change. Wetland area changes directly as a result of precipitation, and a continual decrease in precipitation may result in a wetland decline. Energy flow, productivity, distribution, and general functionality of the wetland ecosystem can all be significantly impacted by this. In addition, human activities like urbanization, agriculture, and forestry can modify the physical structure of wetlands (Marti-Cardona 2013; Costanza et al. 2014), which directly affect how much water can be stored in them and how it moves through the ecosystem. Lower productivity will result from the changes in rainfall patterns that influence the water content of streams and wetland ecosystems. Less water might also bring poor water quality throughout the summer.

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Understanding the effects of climate change on wetlands and creating practical plans for their protection and management can be accomplished with the help of remote sensing (RS) and geographic information systems (GIS) (Adam et al. 2010; Lang et al. 2015; Mahdavi et al. 2018). Multispectral Remote Sensing are useful to identify the changes in the surface water reservoirs, factors affecting the changes (Ling et al. 2020; Peng et al. 2021; Tariq and Qin 2023). wetland extent, vegetation cover, and water levels are important indicators of the health and function of wetlands, and these changes can be monitored using satellite images (van der Valk 2005; Gallant et al. 2014). Water body extraction from satellite images frequently makes use of spectral indices including the Normalized Difference Water Index (NDWI) (McFEETERS 1996), Modified Normalized Difference Water Index (MNDWI) (Xu 2006), Normalized Difference Vegetation Index (NDVI) (Tucker 1979), Simple Ratio (SR), and Modified Simple Ratio (MSR). Ribeiro et al. (2020) determined the land use in Brazilian continental wetland Ramsar sites and their surrounding area to analyze the main environmental pressures. Dervisoglu (2021) have analyzed the temporal changes of Inland Ramsar sites in Turkey using Google Earth Engine by evaluating the changes in water surface area using Landsat satellite data and NDWI index. Böhme et al. (2016) quantified spatiotemporal dynamics of water availability in the wetland by relating the soil moisture, land use, groundwater levels. Liu et al. (2020) studied the response of wetland vegetation under water level dynamics by using the vegetation based surface energy partitioning algorithm. Wang et al. (2016) have reported the use of MODIS data product for monitoring of fluctuation and variation of water surface area and the variation of wetland in response to change in water level of Poyang Lake. Zhao and Liu (2014) in their study have reported that water level fluctuation in the lake regulates the evapotranspiration rate of the wetland.

As a wintering habitat for migrating waterbirds, including more than 80 species that migrate along the Central Asian Flyway, the Wadhvana wetland in Gujarat's Vadodara district is a designated Ramsar site and of international significance for its wildlife. Using Google Earth Pro to analyze the general patterns of the Wadhvana wetland, inconsistent water coverage was discovered as shown in Fig. 1. This eventually led to an investigation of the Wadhvana wetland's susceptibility to anthropogenic pressure. Previous researches available for Wadhvana wetland report the suitability of water for irrigation purpose, hydrophytes diversity and associated flora in the nearby region, but no study has been reported yet for the factors affecting the hydrologic variability of the Wadhvana wetland. A changing water regime, a changing climate, and changes in the pattern of land use/land cover (LU/LC) are some of the anthropogenic and environmental elements that determine the degree of vulnerability of wetlands (Pal and Talukdar 2019; Debanshi and Pal 2020a, b; Pal and Paul 2020). In order to manage wetlands, geospatial approaches can also be useful for monitoring structural elements and water balance (Murthy and Panigrahy 2012). To increase the effectiveness of migratory bird conservation efforts, wetland flooding spatiotemporal patterns must be taken into consideration. Though this wetland is managed by importing the water through Narmada canal, the purpose of this study is to determine the pattern of wetland shrinking and the contributing causes. This study focuses on the seasonal fluctuation of the water spread and have used the secondary data for Land use and groundwater level of published reports for better understanding of the variables.
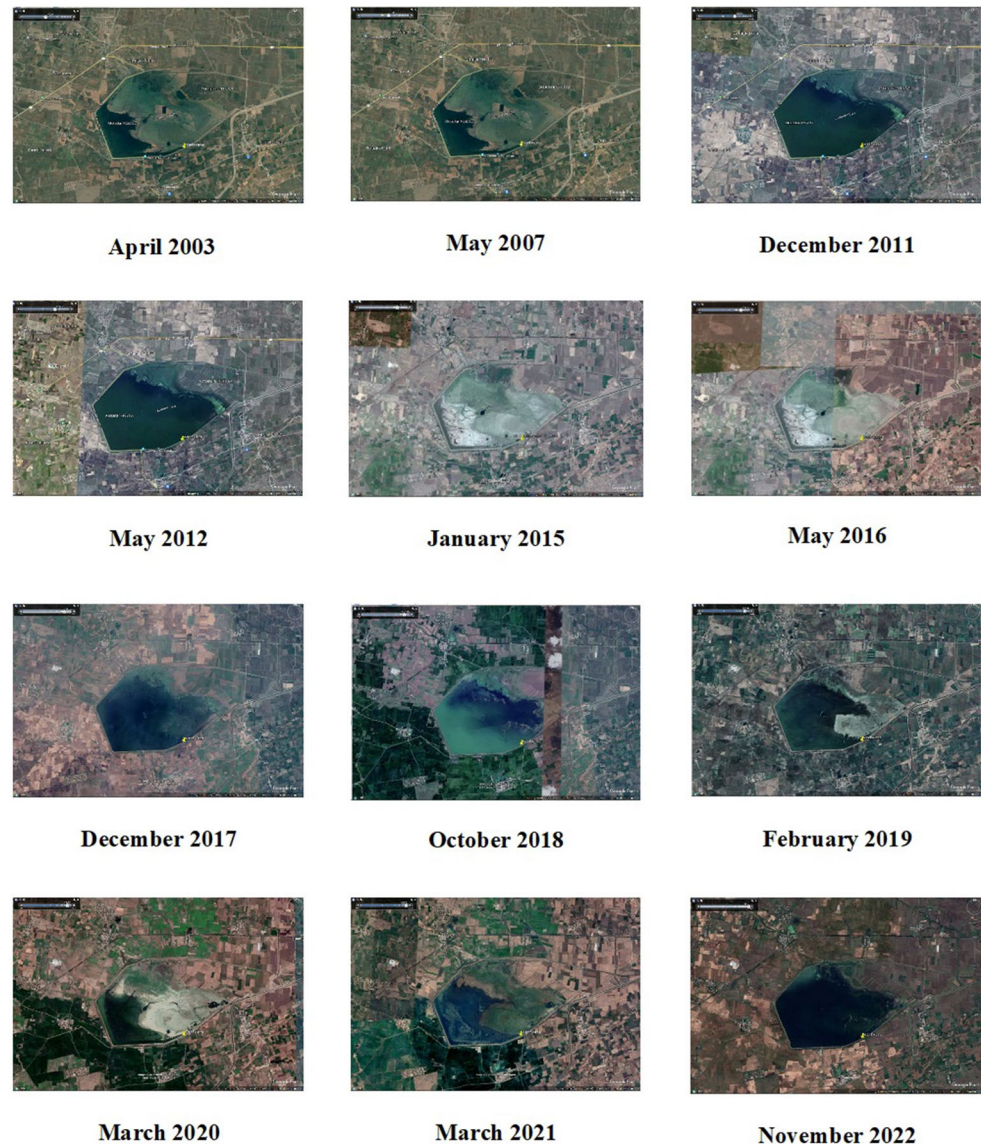
Materials and methods

Study area

The Wadhvana Irrigation Reservoir (WIR) is a significant wetland that was built more than a century ago (https://rsis.ramsar.org/ris/2454), and is situated around 45 km southeast of Vadodara (22°09'42''N and 73°28'32''E) (Suthar et al. 2019). The reservoir, which has a capacity of around 5 billion cubic feet, is surrounded by a dam that is about 8.2 km long and a periphery of almost 11.2 km (Nirjara et al. 2014). Inlet and outlet canals, as well as a number of subcanals, transfer the water to agricultural areas. The dam was constructed to supply water for irrigation to farmers in 25 nearby communities. The reservoir receives water from the Jojwa dam on the Orsang River as well as, more recently, from the Sardar Sarovar on the Narmada River, making it a dependable source of water (Vankar et al. 2019). Owing to avifaunal richness, abode of a number of waterfowl, and Central Asian Flyway for migration, the reservoir is of international significance and the local community established "PRAJIV" (Prakruti Jiv Sansthan Wadhvana) to preserve the region's biodiversity.

The area's climate is characterized by hot summers and general aridity (Management Action Plan For Wadhavana wetland Vadodara District, Gujarat State). Depending on the season, there is a substantial variance in maximum and minimum temperatures. The hottest month of the year is May, with temperatures progressively increasing from March to May. The minimum temperature decreases to 20 °C during this season, and the maximum daily temperature might rise to 44 °C or even 45 °C. The Southwest monsoon, which occurs from June to September, is responsible for the majority of the yearly precipitation. Winter (November to February) and occasionally summer (April to May) also see

Fig. 1 Water coverage observed in google earth pro

April 2003

May 2007

December 2011

May 2012

January 2015

May 2016

December 2017

October 2018

February 2019

March 2020

March 2021

November 2022

isolated rains. The precipitation patterns are variable and irregular, with intermittent strong downpours followed by protracted dry spells.

Methodology

Dataset

In the present study, Landsat satellite data, SRTM Digital Elevation Model were downloaded from the Earth Explorer (https://earthexplorer.usgs.gov/). SRTM DEM was processed to calculate the drainage network and drainage basin of the Wadhvana wetland. Drainage basin gives the information about the land area contributing to the surface runoff. ESRI platform was used to download the Global Land Use Land Cover with spatial resolution of 10 m. The Land Use Land Cover map was clipped for the drainage basin to

see the land use in the basin containing Wadhvana wetland. Considering the fluctuations observed in Google earth from 2003 to present scenario, water spread was calculated for two season's i.e. premonsoon and postmonsoon taking the regular interval of five years to see the overall trend in the pattern of Wadhvana wetland. The Table 1 lists the specific days during which cloud-free Landsat imagery was obtained for analysis in each year. Methodology adopted in the study is briefed in Fig. 2.

Water spread estimation

Modified Normalised Difference Water Body is a better approach than Normalised Difference Water Index for improving the precision of water extraction and efficiently reducing and removing built-up land noise (Xu 2006). The MNDWI is advantageous for automation since it can

Table 1 Cloud-free Landsat imageries were used in this study

Satellite	Year	Pre-monsoon (March to May)	Post-monsoon (November to December)
Landsat – 7 ETM+	2003	03/05/2003	02/12/2003
	2007	03/05/2007	13/12/2007
	2012	30/04/2012	10/12/2012
Landsat – 8 OLI & TIRS	2017	22/05/2017	30/11/2017
	2022	25/05/2022	06/12/2022

Fig. 2 Methodology flow chart
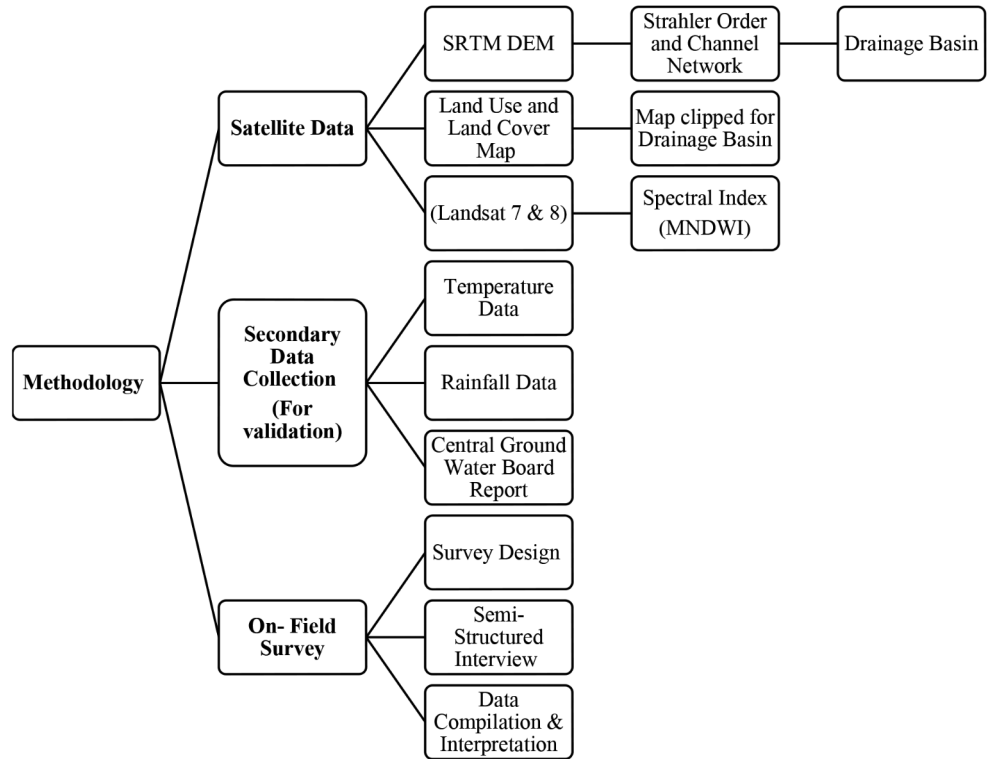
achieve better water extraction accuracy than the NDWI with a default threshold value of zero, according to Xu (2006). Additionally, the MNDWI can show additional information about open water, assisting in the detection of minute variations in water quality. The mid-infrared (MIR) and green or blue spectral differences are used instead of the near-infrared (NIR) difference in the modified normalised difference water index (MNDWI). Using Landsat data for the seasons of premonsoon and postmonsoon with a 5-year interval for the years 2003, 2007, 2012, 2017, and 2022, MNDWI was used to determine the water spread of Wadhvana Lake.

$$MNDWI = \frac{Green - MIR}{Green + MIR}$$

Because water absorbs more MIR light than NIR light, MNDWI offers more advantages than NDWI in terms of positive values. Both soil and plants will still have negative values since soil reflects MIR light more than NIR light and vegetation reflects MIR light more than green light.

Secondary data collection

Temperature Data from 2002 to 2021 was collected from NASA website. Rainfall data of Vadodara district was collected from India Water Resources Information System for the year 2002 to 2022. The on-the-ground survey was conducted in the vicinity of Wadhvana wetlands. The questionnaire was administered in four villages, namely Vadhvana (22°8'59.82"N, 73°29'49.79"E), Akotadar (22°10'10.48"N, 73°28'10.32"E), Gopalpura (22°10'45.69"N, 73°30'5.70"E), and Simaliya (22°11'7.66"N, 73°28'48.60"E), which are among the principal villages Hansapura, Kajapur, Morpura, Pansoli, Samsherpura, and Kukad. These villages were selected since people living there depend on the Wadhvana wetlands in one way or another. The survey employed a Likert scale-based approach with various questions to gauge respondents' attitudes and perceptions regarding their

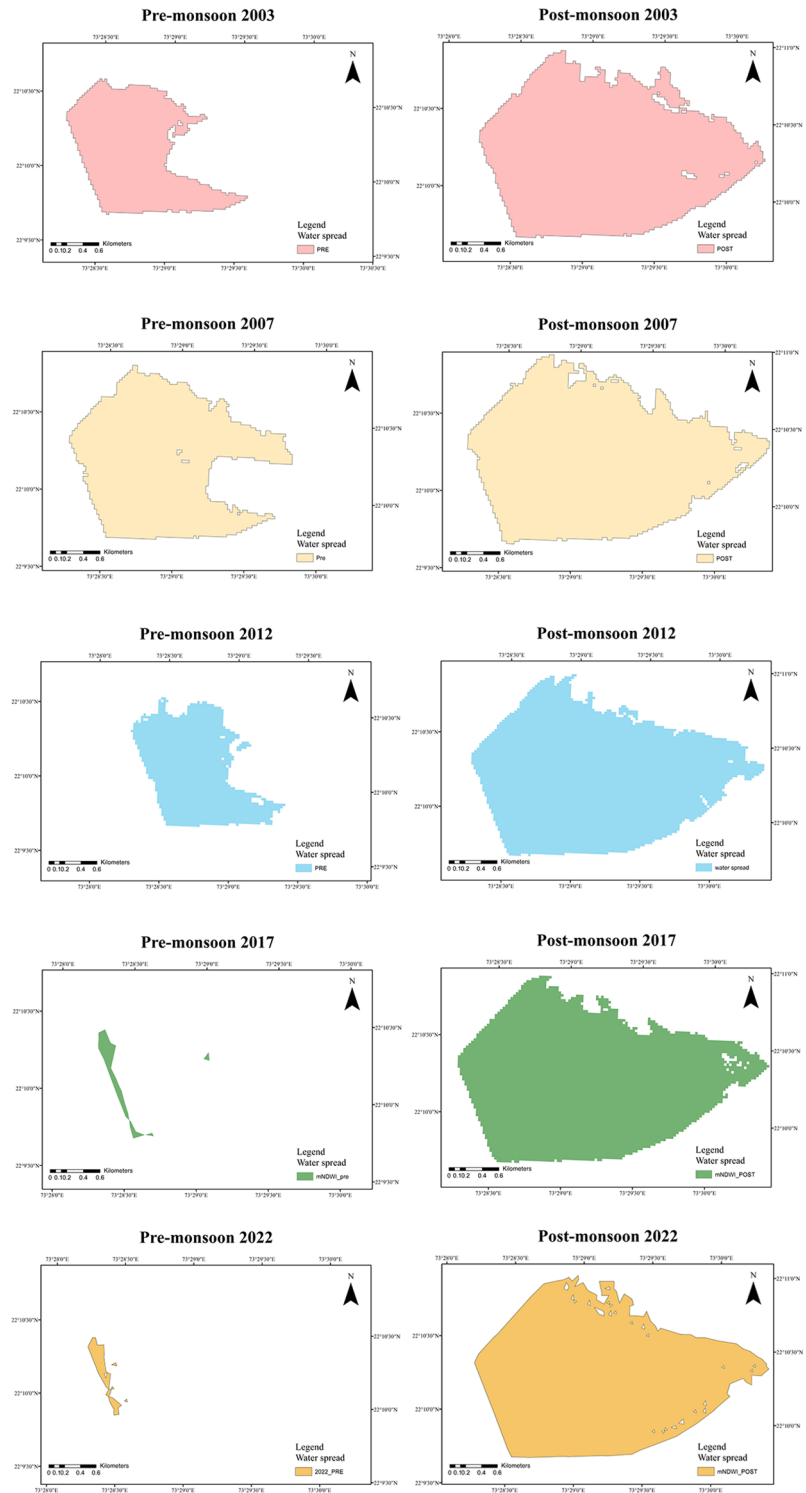**Fig. 3** Water Spread of Wadhvana lake in premonsoon and postmonsoon seasons

Table 2 Water spread area of Wadhvana wetland

Year	Pre-monsoon water spread (m²)	Post-monsoon water spread (m²)
2003	2,038,500	4,903,200
2007	3,261,600	4,957,200
2012	1,687,500	4,941,900
2017	110,526	5,056,200
2022	98,689	5,205,332

dependence on wetland water and its impacts on their occupations. The Likert scale questions provide nuanced insights into respondents' experiences with wetland water dynamics and its influence on their livelihoods.

Results and discussion

Seasonal fluctuation in water spread area

Figure 3 shows the seasonal fluctuation in the water-filled area of the Wadhvana wetland from the year 2003 to 2022. The analysis shows a gradual decline in water spread from 3,261,600 m^2 in 2007 in the premonsoon season to 98,689 m^2 in 2022 (Table 2). While in post-monsoon analysis significant increase was observed from 4,903,200 m^2 in 2003 to 5,206,332 m^2 in 2022. The statistics show that the wetland's water-spread regions exhibit significant temporal fluctuation. Post-monsoon water spread area is nearly consistent as the water level is regulated by the Forest Officials to maintain minimum water level in the wetland as the habitat for migratory birds. The decrease in water spread area in premonsoon season may be a major concern for the wetland management because the lesser the water availability in the wetland more the requirement of water import through the Narmada canal.

Hydrological characteristics of Wadhvana wetland

Several rivers that flow through the center region of the Vadodara district constitute the Dhadhar river basin, which includes the Wadhvana wetland. Three river basins—the Narmada, Mahi, and Dhadhar—are depicted in the Vadodara district's previously released CGWB report (Fig. 4).

Based on the catchment area contributing to certain tributaries, the drainage basin constructed using SRTM DEM using the channel network and drainage basin tool in GIS demonstrates that the Dhadhar river basin is a separate small river system with numerous drainage basins within it. Figure 5 depicts one of the drainage basins in the Dhadhar River Basin along with the location of the Wadhvana wetland. The drainage pattern in the area can be seen within basin, with Strahler order 1 indicating the starting position of the runoff and Strahler order 7 representing the tributaries that result from the convergence of numerous streams. It is noticeable that the Wadhvana wetland is located at the drainage basin's origin, where the Strahler order varies from 1 to 3. It indicates that the wetland gets minimal surface drainage from the surrounding area.

As per the CGWB report of the Vadodara and Chota Udaipur districts, the groundwater flow is towards the sea (Fig. 6) and the Wadhvana wetland plays a significant role in Groundwater recharge. A hydrograph prepared from continuous monitoring of water level data (available at CGWB portal) of two locations near the wetland shows a similar trend in water level rise during the winter season. It can be seen from the hydrographs (Fig. 7) that the water level increases in the winter season especially from October to February each year when the water level is maintained in the wetland for migratory birds, which indicates that the wetland is hydraulically connected to the aquifer of the drainage basin.

Fig. 4 Drainage & basin map of Vadodara and Chhota Udaipur District. (source: central groundwater board report of Vadodara District)
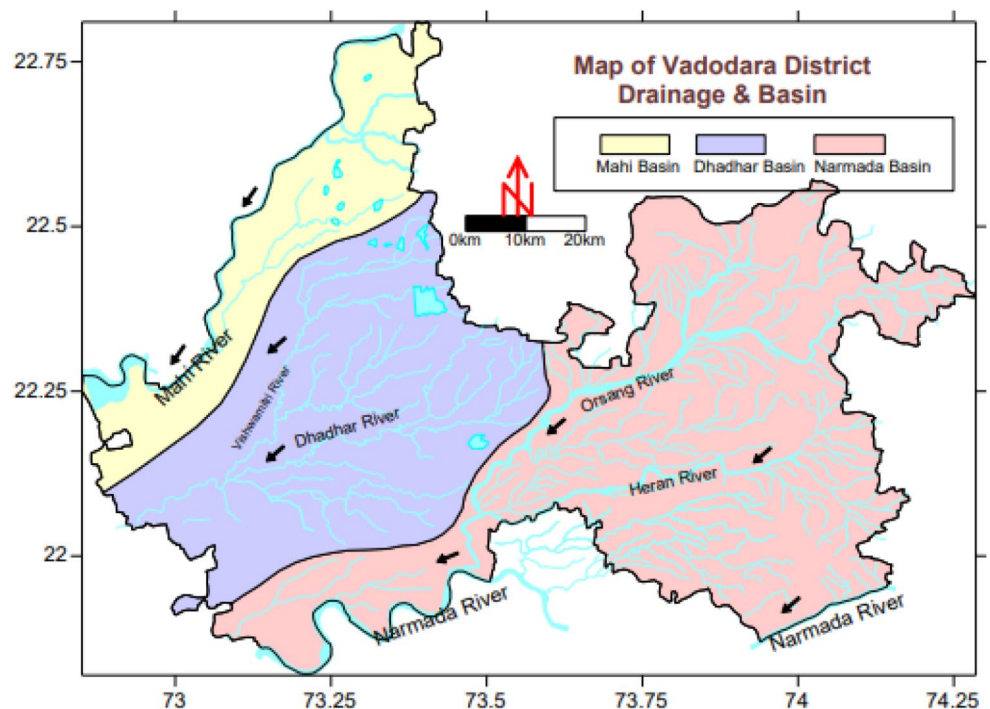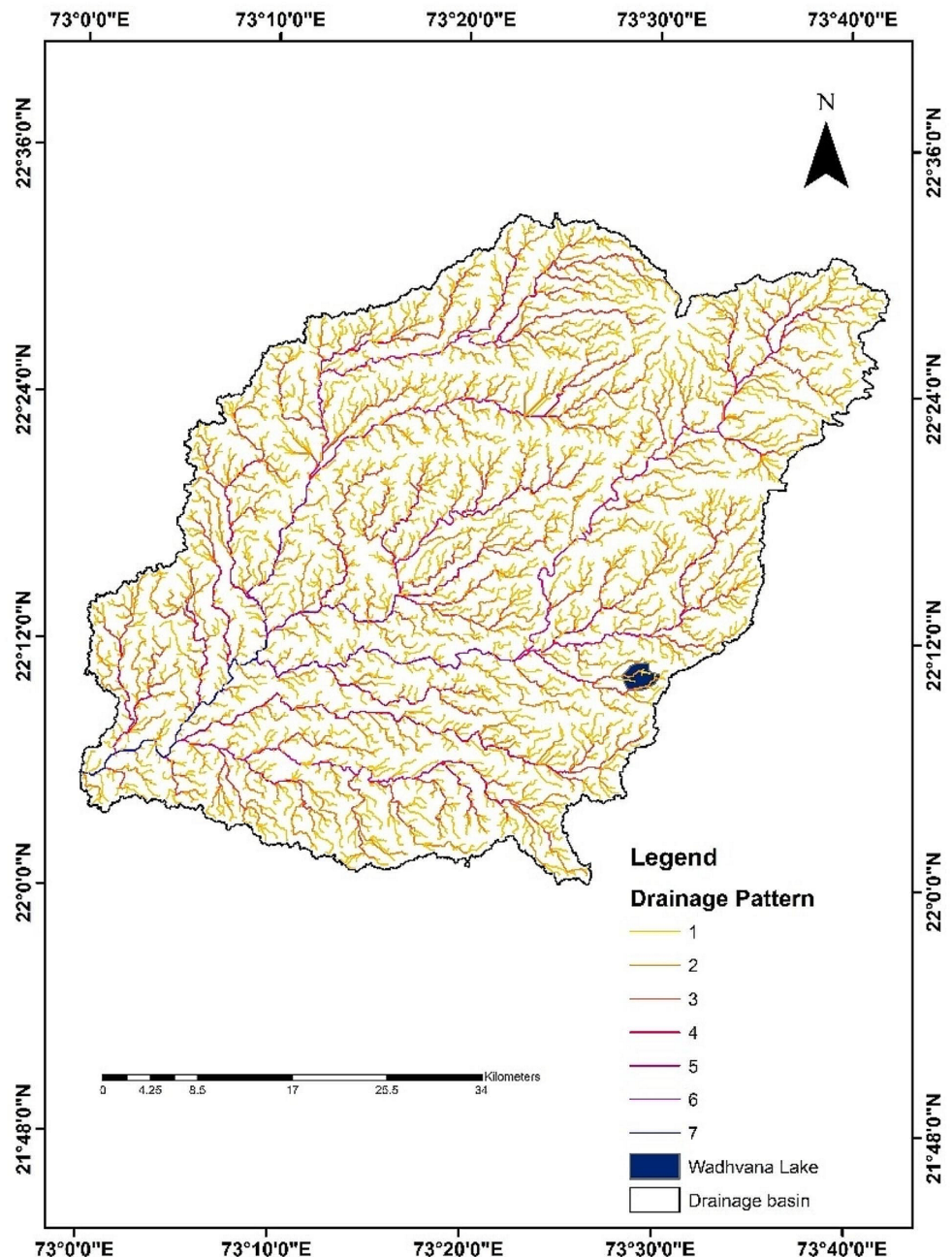
Fig. 5 Drainage basin within Dhadhar river basin showing drainage pattern and Wadhvana wetland


Temperature and rainfall profile of the area

The temperature profile of the place shows minimal fluctuation in the maximum and minimum temperature from 2002 to 2021 (Fig. 8). The wetland's water balance may be affected by the temperature increase in the summer season as higher temperatures will cause greater evaporation rates, eventually resulting in less water being available in the wetland.

The Wadhvana wetland's yearly rainfall data from 2002 to 2022 exhibits a changing trend (Fig. 9). The rainfall has been above average in certain years and below average in others. The year with the most rainfall, 1625.27 mm, was recorded in 2006, while the year with the least, 528.97 mm, was recorded in 2015. According to the statistics, the wetland experienced a sharp reduction in rainfall from 2006 to 2009, with 2009 seeing the lowest amounts. However, successive years saw a rise in rainfall, with 2013 being the most. In 2015, rainfall in the wetland again decreased significantly, although it steadily improved in the years that followed.

Fig. 6 Groundwater flow and level data. (source: central groundwater board report of Vadodara District)
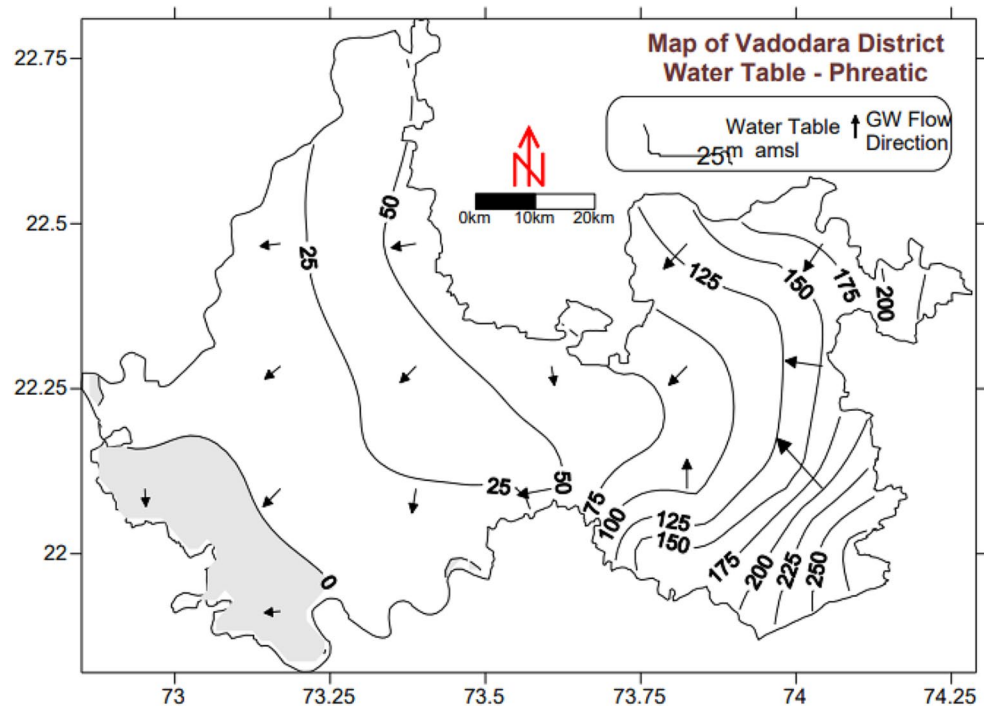
Land use in the drainage basin

The global land use/ land cover map available at https://livingatlas.arcgis.com/landcoverexplorer was used as secondary data to derive information about the land use in the drainage basin (Fig. 10). This Land use map is generated with Impact Observatory's deep learning AI land classification model using Sentinel-2 Level 2 A image and has a spatial resolution of 10 m. Water class is used for the areas where water is predominantly present throughout the year, Trees refer to the areas having dense vegetation with clustering of tall trees, Flooded vegetation refers to areas having intermixing of water with vegetation, Crops refer to human-planted/fallow plots of structured land, rangeland refers to open areas having grasses but no structured plotting. The Land use map shows that a major portion of the drainage basin is agricultural land having crop cultivation.

The villages that are close to the Wadhvana wetland like Vadhvana, Simaliya, Akotadar, and Gopalpura were randomly surveyed. The wetland is a vital resource for the community's survival, either directly or indirectly. A total of 130 people were surveyed regarding their main occupation, the crops they cultivated (if they worked in the agricultural field), and whether or not they kept livestock.

Figure 11 highlights the strong connection of the local population to agriculture, with a significant portion of people either owners of or working on farms. It also shows that vegetable vending and livestock farming are common occupations. The relatively small number of people engaged in

retail or ration shop operations suggests that these may not be the primary sources of income for the local population.

The majority of the people engaged in farming; 74 out of the total are engaged in paddy cultivation (Fig. 12). The remaining farmers cultivate different crops such as sorghum, toor dal, cotton, and wheat.

It can be interpreted that buffalo and cow are the most commonly kept livestock among the villagers, with buffalo being slightly more popular than cow (Fig. 13). The relatively low number of goats may suggest that they are not as well-suited in the community. Local people informed cattle go to the wetland on regular basis for grazing and bathing in the summer. This suggests that the wetland plays an important role in supporting the livestock. Cattle dung is also a valuable source of key macronutrients including nitrogen, phosphorus, potassium, sulfur, magnesium and calcium in the wetland.

Discussion

Wadhvana wetland has international importance as it provides a wintering ground to many migratory birds including over 80 species that migrate on the Central Asian Flyway (https://rsis.ramsar.org/ris/24540). In the 2020 mid-winter waterbird census, about 46,000 individual birds were counted. The site offers a worldwide illustration of how a wetland that was first developed for irrigation has transformed into a crucial habitat for waterbirds, a focal point for tourists, and a source of environmental education. Regulating the appearance

Fig. 7 Hydrograph of two locations near to Wadhvana wetland. (source: central groundwater board report of Vadodara District)
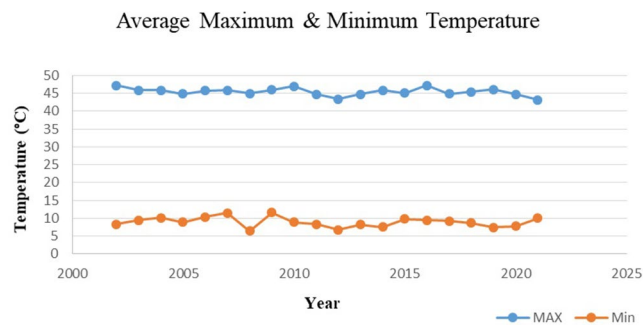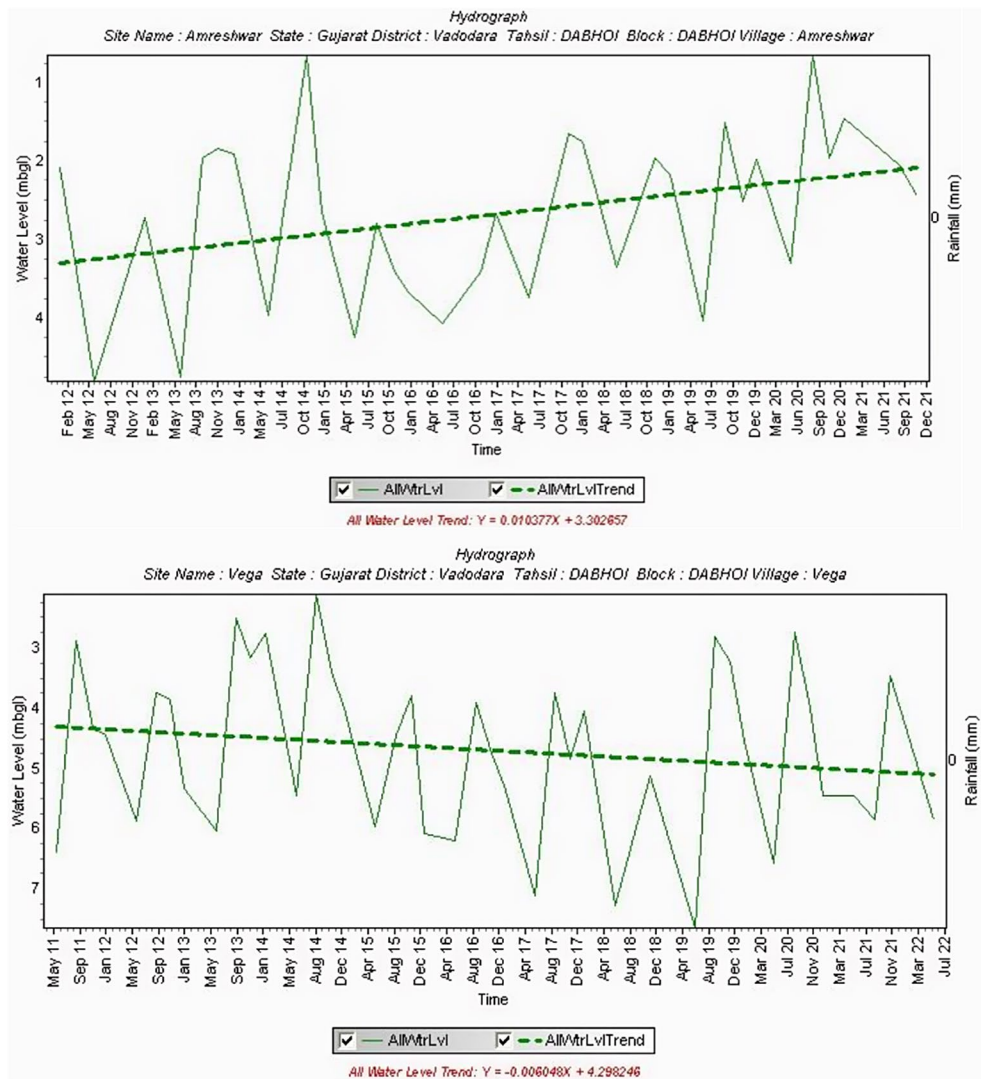

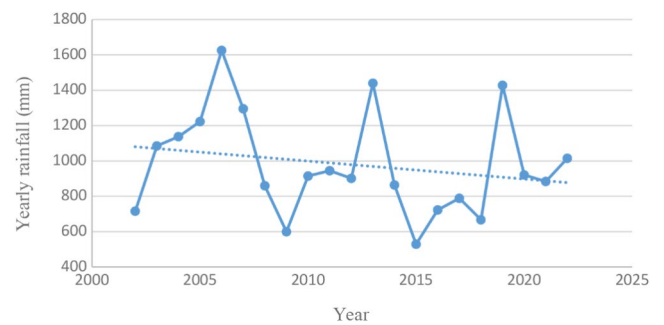**Fig. 8** Average maximum and minimum temperature (Year 2002–2021)

Fig. 9 Annual rainfall (Year 2002–2022)

of water in wetlands also heavily depends on subsurface connectivity and river water spilling. According to a study on the Nalsarovar Lake in Gujarat, the water distribution in Nalsarovar has varied between 2002, 2009, and 2018 based on the monsoon pattern in these years (Chauhan et al. 2021). In 2002, a dry year, there was relatively little overall precipitation, which significantly decreased the amount of water disseminated in Nalsarovar. According to the land use shift, there is a decrease in salt-affected area and a rise in built-up, agricultural, wetland, and water body land. Irrigated crops currently depend significantly more on groundwater withdrawal due to the consequent spread of irrigated agriculture into semi-arid regions with

**Fig. 10** Land use in the drainage basin
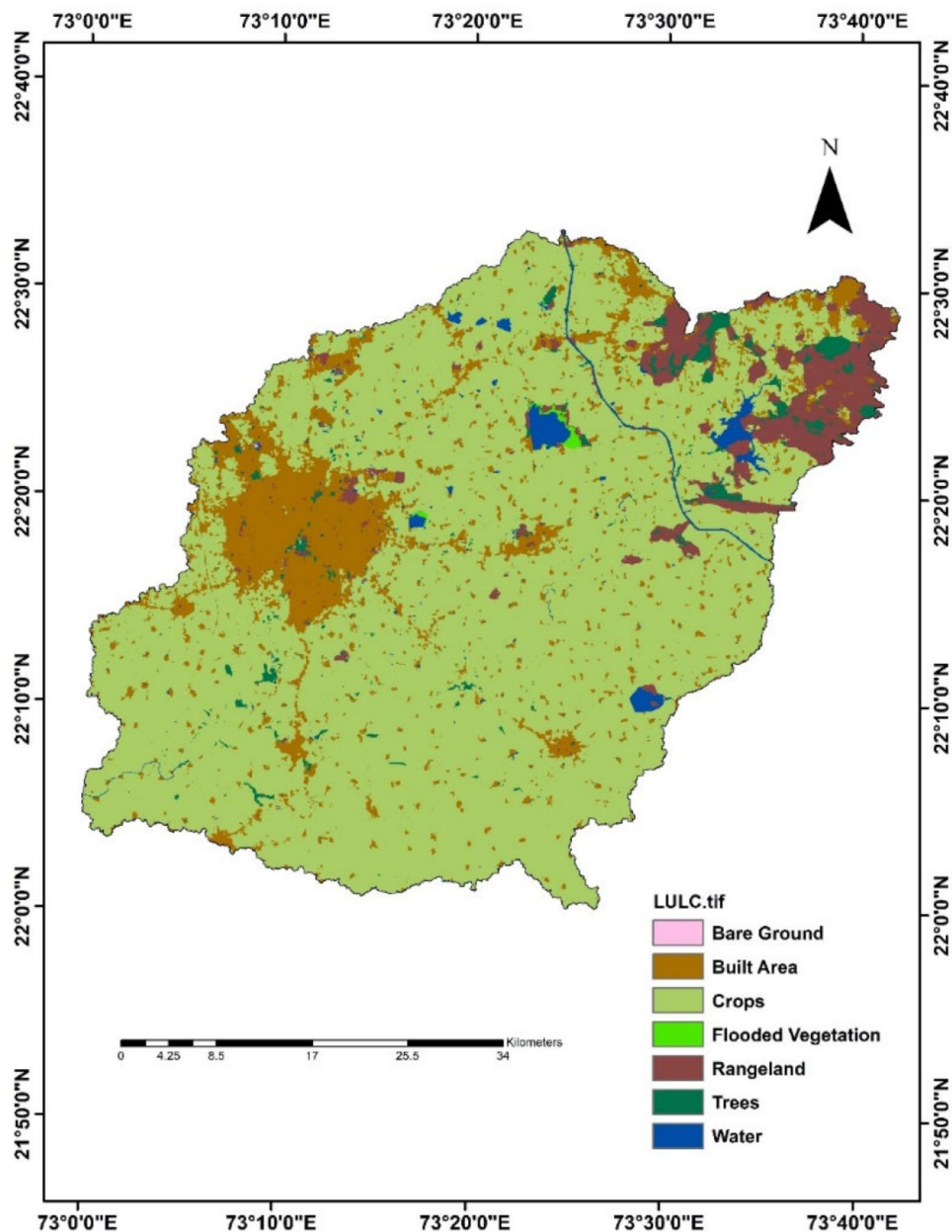
little surface water and precipitation (Bierkens and Wada 2019). The Wadhvana wetland is presently managed by the Forest Officials and proper precautions are taken to maintain the minimum water level in the wetland. The change in water spread in pre-monsoon and post-monsoon season maybe a major concern and it requires management at a larger scale. The drastic change in water area may lead to the drying of a larger patch of land which will be vulnerable to cattle grazing, and may affect the aquatic flora of the wetland.

Suthar et al. (2019) did a comparative study of hydrophytes in three wetlands of Central Gujarat and accounted for very

little presence of rooted submerged species in the Wadhvana wetland. Seventeen hydrophyte species were reported in Pariej, 13 in Kanewal wetland, and nine in Wadhvana wetland where emergent hydrophytes were mostly dominant on the western shore of the wetland. Though the wetland receives very little surface runoff from the catchment, apart from its direct use in irrigation, it also recharges the groundwater of the area. When it comes to determining how human disturbances and fluctuation in precipitation affect urban landscapes together, wetland dynamics can be a dependable and sensitive indicator (Ji et al. 2015). This indicator's assessments at different scales in relation to these driving forces offer an alternative viewpoint on how urban land

Fig. 11 Type of occupation

Fig. 12 Crop cultivation

Fig. 13 Livestock farming
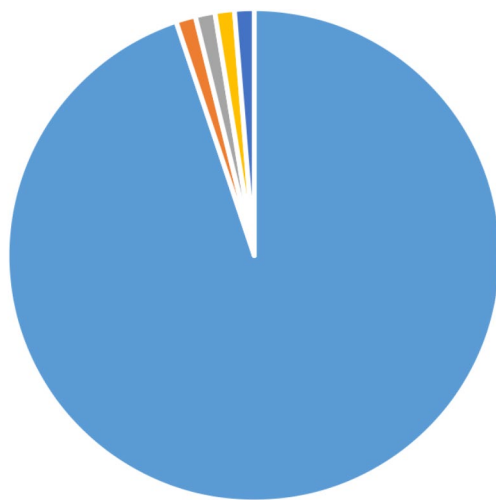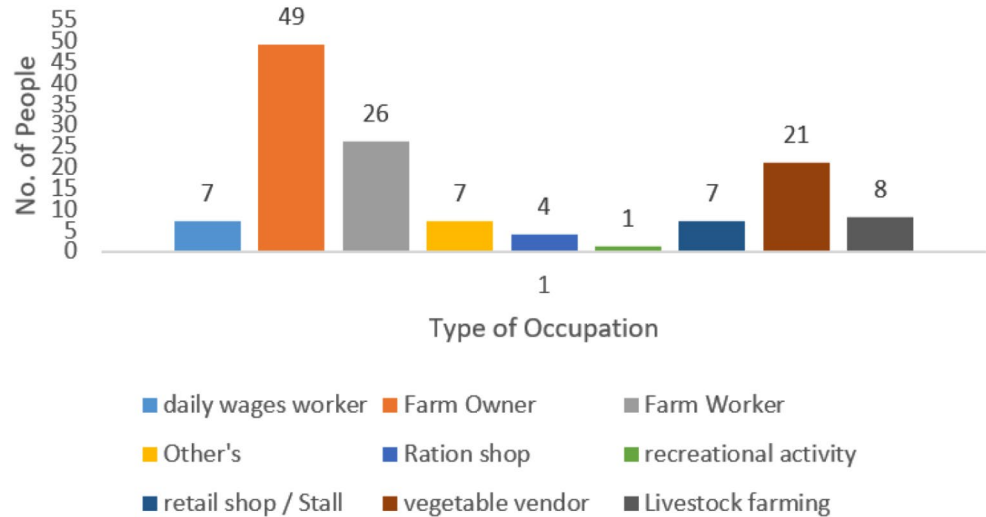
transformation occurs throughout global development. A crucial component of ecosystem function is wetland hydrology; yet, few longitudinal studies have been conducted to record how wetland hydrology has changed in response to alterations in socioeconomic and environmental factors such as land development, precipitation patterns, and groundwater extraction. Groundwater extraction may lengthen the duration that wetlands are replenishing the aquifer because upland-embedded wetlands get water from precipitation, groundwater discharge, and surface runoff (Mushet et al. 2015). Using time series remote sensing imagery, Chen et al. (2014) were able to monitor wetland change dynamically and discovered that the water area had a non-significant dropping trend with an average yearly change rate of 33.25 km², suggesting that Poyang Lake was becoming drier. As can be seen from the Land Use map, the entire catchment
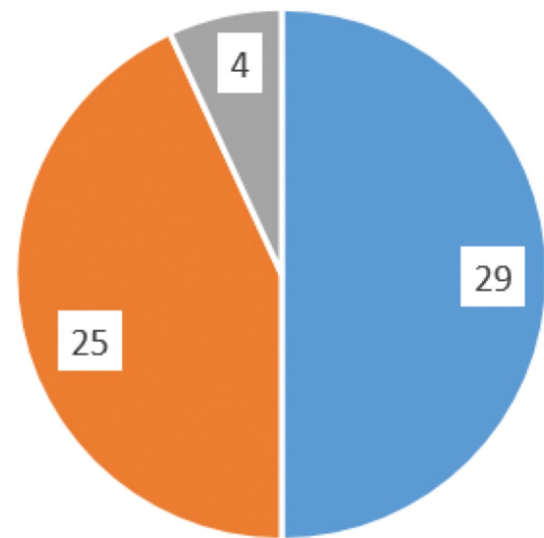
is mostly agricultural fields. A large percentage of farmers use tubewells for irrigation on their fields. The area's water table could decline as a result of ongoing water extraction for high demand, which might allow water to seep into the unconfined aquifer.

Biswas and Pandey (2019) used the qualitative approach in a case study to evaluate the climate change variability of Gujarat's Nalsarovar Lake. The article addresses the long-term repercussions of climate variability by using the example of wetland disasters including droughts and intense rains that have occurred since 1984. It also examines how these events have affected the livelihood of locals who are either directly or indirectly dependent on the wetland. According to a study by Kumar et al. (2007), the main human risks to the Nal Sarovar Bird Sanctuary include the gathering of fuelwood, locals' means of subsistence from fishing, boating,

horseback riding, and waterfowl hunting. In their review of how climate change is affecting ecosystems, Salimi et al. (2021) noted that increased rainfall and temperature sustain wetlands' functions and that a crucial water level is necessary for the ecosystem's ecological services. According to the survey carried out in the villages, paddy cultivation is the main livelihood and the local people depends on the wetland for irrigation and animal farming. About twenty-five villages are irrigated by it, and the Narmada Canal's inflow mostly controls the water level (Vankar et al. 2019). The effects of precipitation and temperature change would be much less in the Wadhvana wetland than they would be in the natural wetland, which mostly depends on rainfall for replenishment. There would be a significant seasonal variation in water levels due to increased recharge from the wetland caused by groundwater extraction downstream or in adjacent areas. However, long-term management should take into account the water harvesting structures downstream of the drainage basin due to its ecological significance and connectivity with the aquifer.

Conclusion

The ecological significance of Wadhvana wetland led to its recent designation as a Ramsar site. The governing Forest Officials' efforts have resulted in an annual increase in the number of bird counts. The current study was carried out to investigate the factors that may have an impact on the wetland's management over an extended period, as previous research has documented on the flora associated with wetland areas and the water quality. The decrease in the wetland's pre-monsoon water spread area between 2007 and 2022 is concerning because it may result in less water being available during the summer, expose the land to agricultural practices and cattle grazing, and may have an impact on the existence and development of aquatic species. The lesser the water availability in the wetland in the summer season, the more will be the amount of water to be imported from the Narmada River. This would have an indirect negative effect on the ecological status at the downstream of Sardar Sarovar Dam. The water spread in wetlands is influenced by changes in climate variables such as rainfall and evaporation and extraction of water in nearby agricultural fields. In the present study, it was found that the area has nearly consistent maximum and minimum temperatures and it receives fluctuating precipitation. But as this wetland lies in the starting point of the drainage basin, the probability of collecting surface runoff decreases. As Wadhvana wetland is a human-regulated wetland, lesser precipitation can be compensated by more import of water through the Narmada canal but to have a stable ecosystem it is essential to develop sustainable practices to protect and conserve the wetland, considering the interconnected relationship between the wetland, aquifer and the local communities. Education and awareness programs can be initiated to promote sustainable practices such as rainwater harvesting, efficient irrigation techniques, and judicious use of water resources.

Author contributions Mr. Jatin Soniya conceptualised the study, collected and analysed the data, conducted the field survey, and wrote the initial draft. Dhara Kakwani provided assistance in writing the manuscript and creating the map. Dr. Neha Singh supervised the study and prepared the final manuscript.

Data availability Not applicable.

Declarations

Ethical approval The work done is original and has not been submitted to any other journal.

Consent to participate Yes.

Consent to publish Yes.

Conflicts of interest None.

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