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Tracing the roots of wetland degradation in India: a systematic review of anthropogenic drivers, ecological consequences and conservation strategies

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Abstract India's wetlands, estimated to cover 15.26 million hectares, have experienced significant degradation due to human activities. Urbanization, population growth, land transformation, encroachment, and pollution have all contributed to the shrinking of wetlands, which were earlier estimated to be 58.2 million hectares. This review analyzes the root causes of wetland degradation in India, providing insights from more than 100 studies conducted over the last four decades. It also examines the impacts of population growth, urbanization, land transformation, encroachment, and pollution on wetlands, and their associated ecological consequences. The paper highlights the need for conservation and management efforts to protect these vital ecosystems, which provide numerous benefits to human societies and biodiversity. From the above review, it can be inferred that approximately 64% of wetlands have suffered degradation in terms of wetland coverage as a result of these drivers. Additionally, metropolitan areas are experiencing a continuous reduction in wetland size due to overpopulation and urbanization, which serve as the primary contributing factors. The majority of research conducted on wetlands in India concentrates on the ecological and environmental aspects of the wetland ecosystem. Moreover, the physical factors, such as alterations in land use within the catchment area, and the socio-economic factors, including population growth and changes in economic activities, which lead to modifications in wetland surroundings, have not been extensively investigated. So, there is a necessity for further research to be conducted on the physical, socio-economic, and conservation aspects that influence the state of wetlands and their utilization. Also, this research calls for the development of more effective and comprehensive management strategies in response to escalating stress from various climatic and particularly anthropogenic factors, because the governmental and scholarly attention towards wetland management policies, rules, regulations, and organizations has only recently emerged.

Keywords Wetlands · Land change systems · Anthropogenic drivers · Sustainability · Systematic review

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Introduction

Wetlands have long been important to global ecosystem rejuvenation and cultural landscapes but have remained undervalued by policy makers in national plans. 'Wastelands', a term that was much more associated with the wetlands of the past, and the treatment was done with negligence. Occasionally, these areas were used as mosquito breeding points. However, the Ramsar Convention of 1971 called for attention to the international recognition of wetlands. The Ramsar Convention spotlighted wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporal, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters" (Ramsar Convention, 1971; Finlayson and Valk, 1995). These were regarded as the most important ecosystems on the planet, essential for species diversity protection and conservation by promoting, prospering, and rapid growth of various varieties of native vegetation and acting as a spawning site for fish, migratory birds, and other wildlife habitats (Ramsar Convention Secretariat, 2008).

People in certain places around the world have a direct or indirect relationship with these ecosystems and benefit from them in respect of services they offer, such as fuelwood, building materials, fishing, hunting, and the production of herbs, as well as for agricultural, livestock, and industrial purposes (Kumar & Choudhury, 2021; Boyd & Banzhaf, 2007; Sahana et al., 2020). They also provide society with a means for generating income (Naimul, 2017). The survival and proper operation of the biosphere depend on these terrestrial ecosystems. However, manmade processes like industrialization, population increase, and land use development pose a grave threat to these delicate ecosystems (Atasoy et al., 2006; Fluteau, 2003; Sahana et al., 2020; Tong & Chen, 2002).

Every wetland possesses the capacity to operate as a unique and independent ecosystem. Differences arise in terms of the resident species, geographical location, connection to varied landscapes, prevailing climate, and various other factors. Additionally, factors like their surroundings, water sources, and atmospheric conditions can impact their control, as wetlands are also adept at regulating these elements (Bhowmik, 2022). These ecosystems serve as an important carbon sink and play an essential role in terrestrial carbon sequestration (Ajibola et al., 2016; Callaway et al., 2012; Li et al., 2023). The interactions between traits, structures, and processes lead to ecological functions. These include activities like nutrient removal, toxic retention, nutrient retention, groundwater recharge, floodwater control, and food web support (Maltby et al., 1996; De Groot et al., 2012). Agriculture, fisheries, irrigation, jute-retting, fuelwood, raw materials for home construction, and small-scale businesses like pottery and handicrafts, feed for livestock, and ecotourism are all examples of sustainable practices that wetlands in India provide to sustain local livelihood (Das et al., 2022; Sarkar et al., 2020; Jha et al., 2014).

However, despite the increased attention on the benefits of wetlands in recent times, 50% of the world's wetlands were destroyed throughout the twentieth century as a result of intensive agricultural production, excessive water extraction for domestic and industrial use, urbanization, infrastructural development, pollution, and ultimately costing towns and corporations a lot of money (Ajibola et al., 2016). This has an immediate effect on biotic diversity and contributes, through modifying the ecosystem, to local and regional climate change and soil degradation (Shodimu, 2016; Johnson et al., 2005). Given the importance of wetlands, there is a greater focus on their conservation. While there are several economic and ecological factors responsible for wetland degradation, the main reason for encroachment is purely economic or anthropogenic.

With these aspects in mind, the objective of this paper is to analyze the various anthropogenic drivers responsible for wetland deterioration and shrinkage in India. This paper provides an overview of wetland shrinkage due to anthropogenic reasons mainly in the last four decades. More than 100 papers were reviewed with respect to four categories: population growth, land transformation, urbanization, encroachment, and pollution being the important reasons for its deterioration.

The above map (Fig. 1) shows the state-wise total number of wetlands in India as per 2017–18. Out of these, the most degraded ones are recognized by the Ramsar Wetland Convention to protect them from extinction. The Ramsar Convention is an international treaty for the conservation and sustainable use of wetlands. The basis of selection is that they should be rare, unique, internationally important for the conservation of biodiversity,

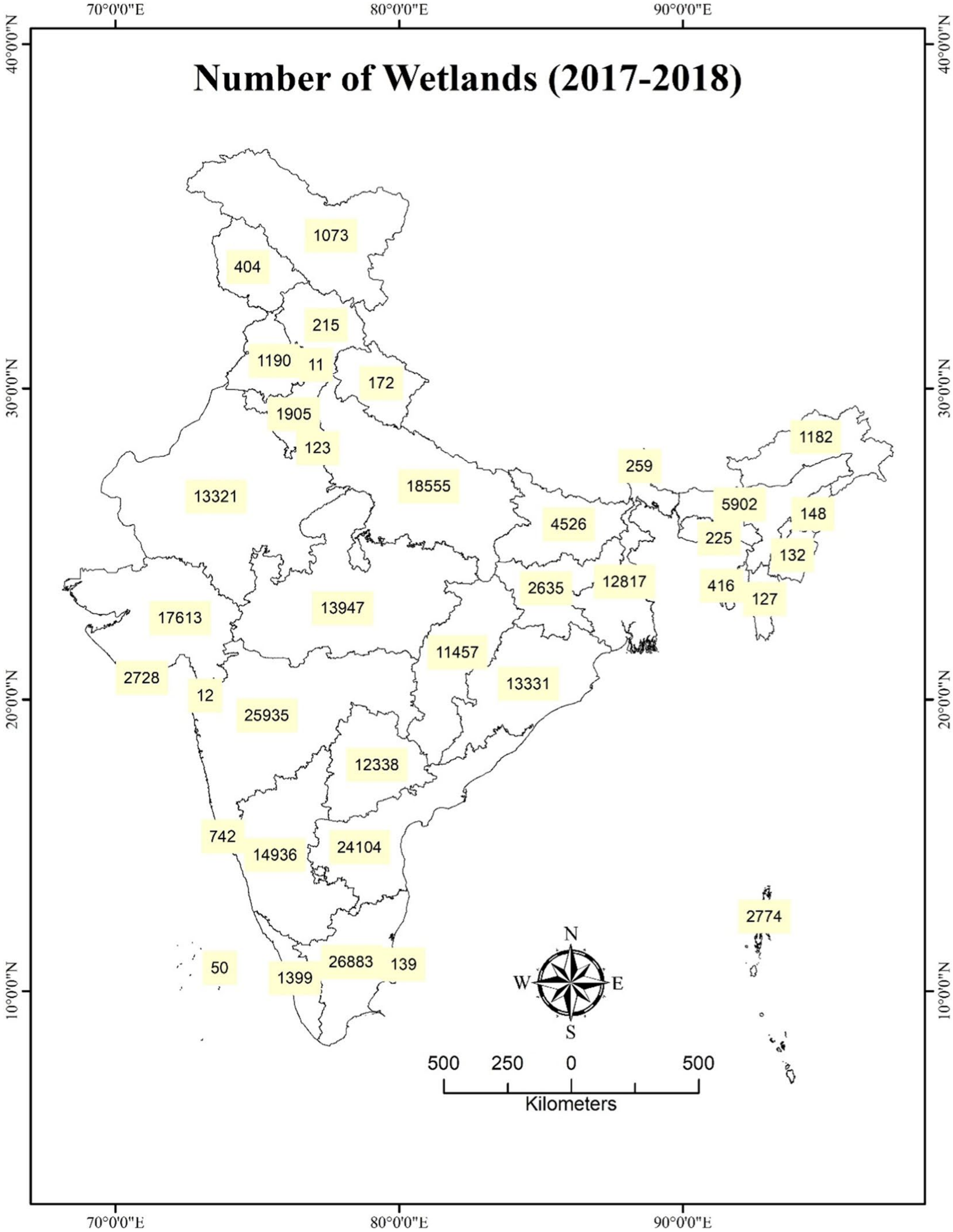

Fig. 1 Number of wetlands in India (2017–2018). Source: Adopted and modified by Researchers from Space Application centre ISRO, 2021

and supporting vulnerable, endangered ecological communities. As of September 2021, there are 2418 Ramsar sites designated in 171 countries, covering a total area of 252.5 million hectares. In India, there are currently 75 Ramsar sites, as shown in Fig. 2. However, there are still a number

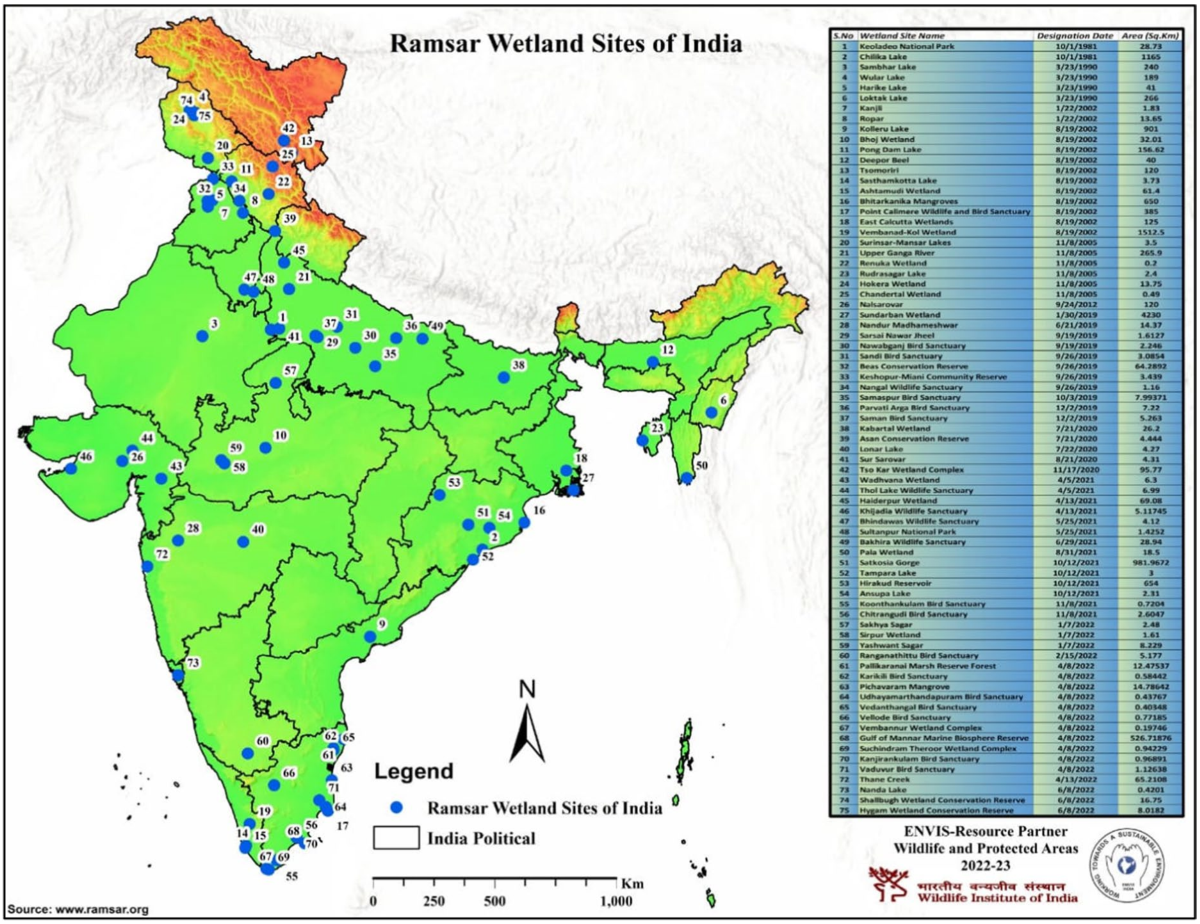

Fig. 2 Ramsar wetland sites of India. Source: Ministry of Environment and Forest, GOI (2022–23)

of wetlands that need to be recognized so that they can be spared from getting deteriorated.

Methodology

The methodology adopted for critically reviewing the anthropogenic drivers is as follows:

The major causes of significant wetland degradation in India were identified based on a literature survey, and the challenges and gaps in investigating anthropogenic drivers responsible for the degradation of major wetlands across India were analyzed. The study examined the impact of anthropogenic drivers on wetlands in both urban and rural areas, as well as drawing on experience from similar causes identified in different countries.

To understand the extent of anthropogenic stress, a review of peer-reviewed publications published between 1990 and 2020 was conducted using databases such as ISI, Web of Science, Google Scholar, Elsevier, Springer, and Scopus, etc. The most pertinent papers were chosen in line with the study's objective, and grey literature sources such as Times of India, Political Weekly, and Down to Earth were also reviewed.

In addition, VOS-viewer software was used to conduct a bibliometric study to determine the primary focus of improved publications. Using this software, we were able to identify the pattern of the study on anthropogenic as well as ecological stress on wetlands over the selected time period. The main conclusions drawn from the use of this programme is that it produced connections between every facet of data analysis and offered strong visual analysis capabilities. The keyword analysis done by this software helped in revealing the content of different papers compactly and contributed to a better understanding of the relationships and patterns among India's wetlands. Further it also gave insights into how wetland vulnerability research has developed over time and also provide information about current research trends and the main causes of repetition-induced degradation.

The visualisation of the top referenced journals is carried out by network analytics. This provided crucial information regarding the connections inside the nation between the main threats and the drivers responsible for the depletion of wetlands**.** The bibliometric map created on the basis of co-authors provided insights, how and which works and studies relevant to wetland degradation in India are connected directly or indirectly via different measures, parameters, and threat variables etc. It also gave us a foundation for literature and enabled us to connect many factors so that we could summarise the research in a glance.

The network-assisted bibliometric map of keywords enabled to become familiar with the variables or activities that are either directly or indirectly associated to wetland degradation from one location to another (based on the size of the circle). It enables us to connect the problems that are more prevalent in wetland degradation locally or worldwide and to show the main threats.

Bibliometric analysis using Scopus database

The current research utilized the Scopus database to conduct a bibliometric analysis and generate a map using the VOS viewer software. On November 18, 2022, papers were searched and selected. Scopus was selected for its global use in the research field. The study focused on the primary theme of 'Anthropogenic Stress on Wetlands,' and research articles were the primary material searched for. Based on these papers, two network visualizations were prepared, namely, author keyword co-occurrence and co-authorship.

Result and discussion

In Fig. 3, it is demonstrated that the frequency of keywords used in publications was determined using co-occurrence analysis. However, to narrow down the search, the title, abstract, and keywords were used. Out of a total of 187 keywords in 60 papers, the top 33 keywords with a minimum occurrence of three were examined and mapped. The co-occurrence network map generated allowed us to study the most significant issues relating to anthropogenic drivers on wetlands and include them in our review paper. The keyword 'Environmental monitoring' was found to occur most frequently, followed by article, ecosystem, controlled study, Wetland, human, vegetation, India, river, lake, remote sensing, agriculture, climate change, urbanization, land-use land-cover, natural wetland, eutrophication, sediment, vegetation, India, land-use change, remote sensing, ecology, wetland management, and others. Different clusters with similar areas of study were indicated by different colors. Less researched keywords such as soil conservation, risk assessment, unclassified drug, environmental impact assessment, pollutant, forest, conservation, flooding, factor analysis, Landsat, climate, toxicity, extraction, sea-shore, hydrology, and others were identified. The largest circle on the graph represents the keyword that occurs most frequently, whereas the smaller circles highlight areas that have not been extensively studied and hold promise for future research.

The bibliometric map shown in Fig. 4 was generated using the document "Availability" as the basis. It analyzes co-authorship in relation to the theme of "Anthropogenic drivers of Wetlands." The co-authorship network diagram (Fig. 4) displays a total of 44 co-authors, meeting the threshold criteria of a minimum of two documents and citations. The final selection of authors was determined by software-generated criteria. Sarkar, Chatterjee K., Das Ghosh, Begam M., published the most documents, and other prominent authors include Mukherjee K., Chandra P., Singh J., Das P., Mishra PK, Basak SK, Sarkar S., Borah BC., Ali S., Gogoi P., Meena DK., Chakraborty S., and others. The map employs various techniques, such as color variations, thickness of lines, and proximity, to show groups of writers who share common interests in specific subjects.

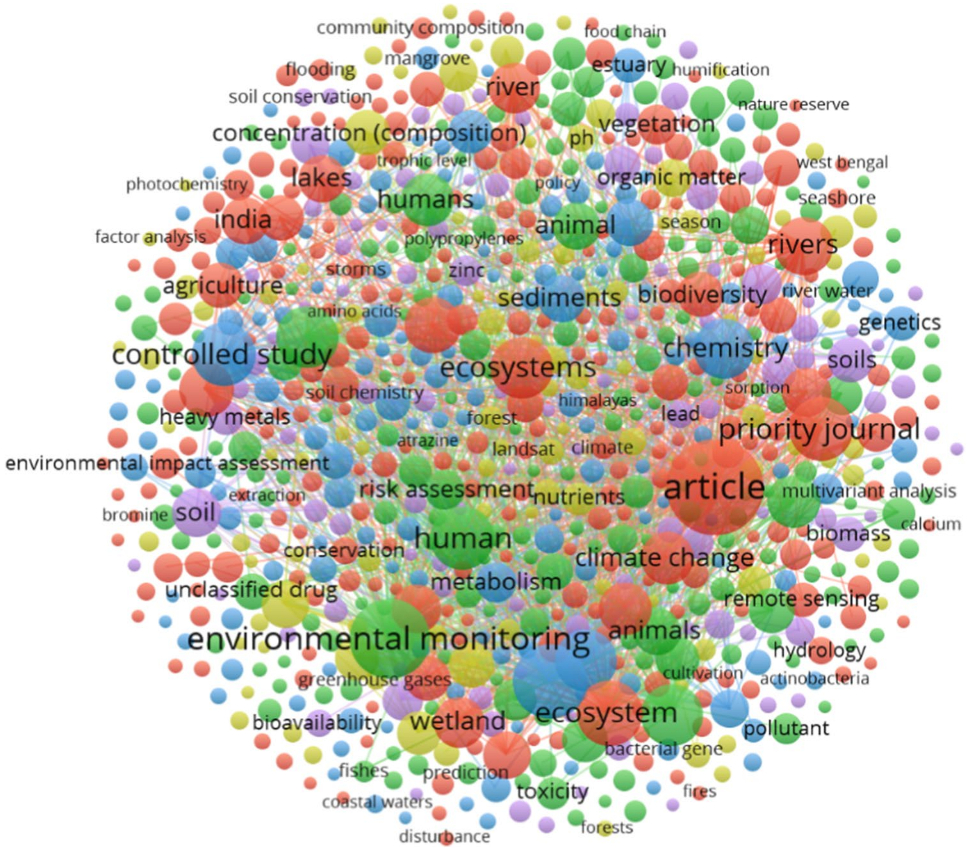

Fig. 3 Bibliometric map based on author keywords co-occurrence with network visualization

Population boom: a ticking time bomb for the future of wetlands

Wetlands are considered to be one of the most delicate ecosystems on earth, yet they are also the most overlooked and poorly managed resource on the planet's surface. The majority of the issues faced by these fragile ecosystems are due to anthropogenic activities occurring in the surrounding wetland environs. As a result, wetlands are under threat from various negative changes, primarily caused by anthropogenic stress (Jamal et al., 2022a, b).

Overpopulation, which occurs when a population exceeds the optimal number of individuals, is a significant environmental issue in the modern world. It can covertly trigger the agents responsible for causing environmental contamination, the disappearance of wetlands and habitats, the destruction of coral reefs and forests, the deterioration of ecosystems, and other related issues (Huu Nguyen et al., 2016). The human population's disproportionately high growth rate has led to the expansion of settlements and croplands at the expense of natural land cover, particularly water bodies such as wetlands and lakes. These changes have a significant impact on the physical environment of a location and also affect the social and economic conditions of the individuals living there. As the population expands rapidly, people tend to migrate towards delicate ecosystems such as mountains, wetlands, and forests, in order to meet their growing land resource requirements. This action directly interferes with and alters the natural land cover of an area, leading to severe environmental problems. The unbalanced increase in the human population has resulted in an expansion of farmland and settlements, which has been detrimental to natural land cover, particularly water bodies such as wetlands and lakes. These changes have a significant impact on the physical environment of a location and also affect the social and economic conditions of the individuals living there (Zubair, 2006).

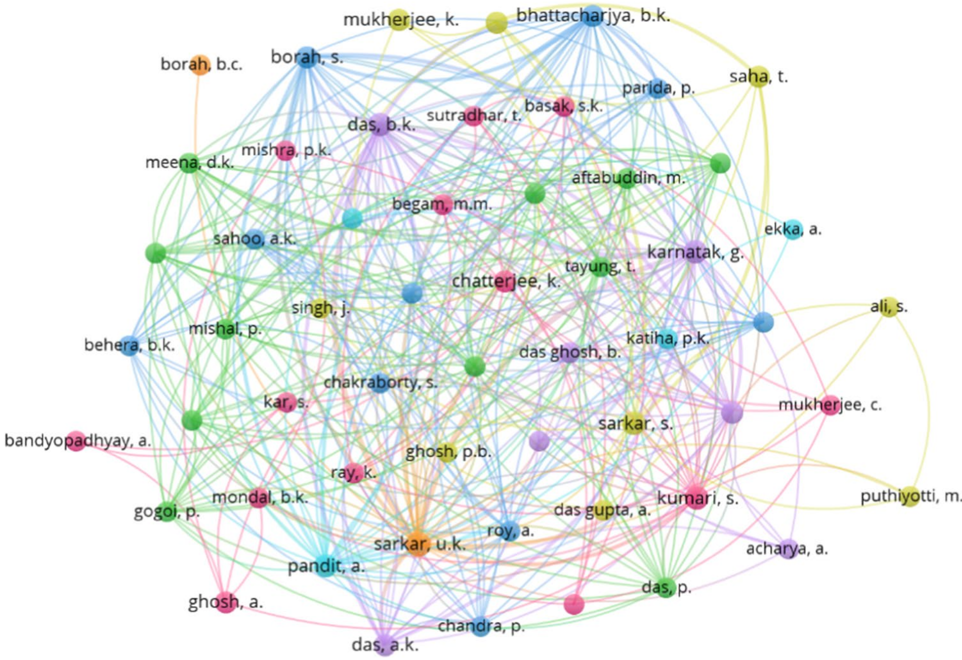

Fig. 4 Bibliometric map of Co-authorship with network visualisation

India's wetlands are experiencing a stark rise in human activity, and the degradation of delicate ecosystems such as Wular Lake in the western Himalayas has made it essential to consider the impact of an expanding human population on these areas. Wular Lake, the largest freshwater lake, has undergone or witnessed degradation due to the dramatic rise in human population in its catchment over the past few decades. This magnitude of high population growth has also resulted in environmental degradation, heavily impacting the wetlands of the Srinagar city, resulting in the loss of 9119 ha of wetland area between 1901 and 2004 (Rashid & Naseem, 2008).

India's population experienced significant growth, increasing from 0.4 billion to 1.2 billion between 1951 and 2011, with an average decadal growth rate of approximately 22%. This rapid explosion of population resulted in a situation where, over a 90-year span from 1901 to 1991, there were twice as many urban centers as there were urban dwellers (Bassi & Kumar, 2012). Consequently, wetlands in India faced immense pressure and became ecologically vulnerable. The deterioration of wetlands can be attributed to two primary factors. Firstly, there has been a widespread loss and fragmentation of freshwater habitats, as documented by (Kumar et al., 2008) This loss and fragmentation occur due to various human activities such as urban expansion, agriculture, and infrastructure development, which encroach upon and disrupt the natural wetland ecosystems. Secondly, there has been a reduction in environmental flows, primarily caused by excessive water allocation for agricultural and industrial purposes. The growing demand for water in these sectors has led to overuse and withdrawal of water from rivers, streams, and other freshwater sources. This overallocation further exacerbates the problem by limiting the amount of water available for maintaining the ecological balance of wetlands (Zhao et al., 2006).

As a consequence of these destructive forces, the river basins in southern and western India are already facing environmental water scarcity. The water withdrawals have reached such high levels that the remaining amount of water in these basins is insufficient to sustain the freshwater-dependent ecosystems. This situation poses a significant threat to the biodiversity and overall health of these ecosystems (Smakhtin et al., 2004) (Fig. 5).

In this regard, the Driver-Pressure-State-Impact-Response (DPSIR) approach of the European

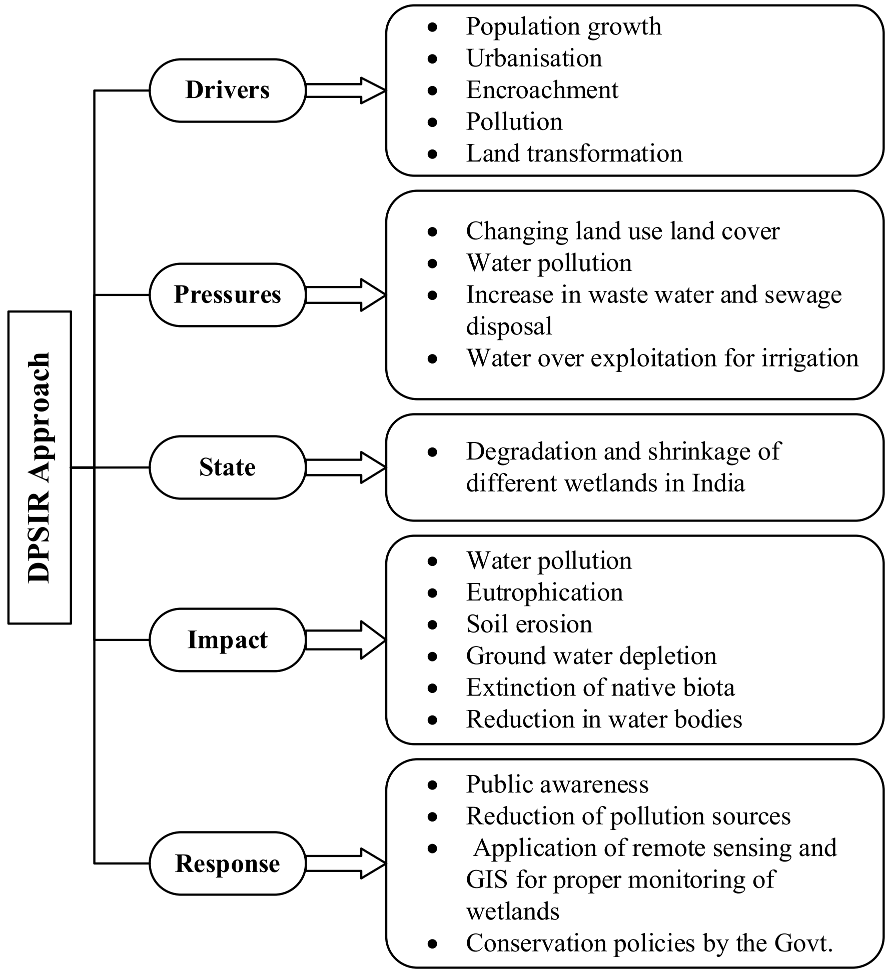

Fig. 5 Flowchart of DPSIR approach. Source: Abridged and transformed from the Zacharias et al. (2008) and Appiah and Yankson (2012)

Environment Agency is frequently employed. The DPSIR method is a variant of the Pressure-State-Response (PSR) framework, as reported by Zacharias et al. (2008), Smeets & Weterings (1999) and Malekmohammadi & Jahanishakib (2017).

Overall, 35 percent of the world's wetlands have disappeared between 1970 and 2015, and this trend has been accelerating annually since 2000. The driving factors behind these losses include climate change, population growth, land transformation, urbanization (particularly in coastal and river deltas), and changes to land and water use and agriculture. Table 1 and Fig. 6 indicate a negative change in wetland area with the burgeoning population, whether it is coastal or inland wetlands. In 2001, the population was 1028.7 million, and it increased to 1210.2 million in 2011. Accordingly, inland wetlands decreased from 45.1% in 2007 to 43.9% and coastal wetlands decreased from 24.1% in 2007–08 to 22.67% in 2017–18.

Urbanization dilemma: the price of development

Urbanization was once not considered a threat, but unplanned urban sprawl is now affecting land use in many regions, including wetlands (Jamal et al., 2019). It significantly impacts the structure and function of wetland ecosystems. Approximately 80% of the world's wetlands are either degrading or vanishing, and the growth of urban areas is a major contributor to this loss (Shodimu, 2016). Wetlands in India are under tremendous pressure due to reckless urbanization, causing nutrient enrichment and a massive loss of wetland area over the past few decades

Table 1 Coastal and inland wetlands

	2006–07	20017–18
Natural Coastal Wetlands		
Lagoon	1.4	1.35
Creek	1.5	1.60
Sand/Beach	0.3	0.28
Intertidal Mud Flat	15.8	14.41
Salt Marsh	1.0	0.93
Mangrove	3.2	3.17
Coral Reef	0.9	0.93
Total shrinkage	24.1	22.67
Natural Inland Wetlands		
Lake/pond	4.5	4.33
Oxbow lake/Cut-off Meander	0.7	0.71
High Altitude Lake	0.8	0.82
Riverine wetlands	0.6	0.62
Waterlogged	1.8	1.7
River/stream	36.7	35.72
Total shrinkage	45.1	43.9

Source: Space Application centre ISRO, 2021

in Kashmir (Prasad et al., 2002; Anand & Oinam, 2020; Roy-Basu et al., 2020). Unplanned and haphazard urbanization has destroyed numerous streams and channels that connect ecologically vulnerable wetlands, making them biologically unstable (Dar et al., 2021). Wetlands, especially those near urban areas, are under increasing development pressure for various man-made activities (Roy et al., 2022). Urban wetlands are the primary source of freshwater for the general population (Aslam et al., 2021). Open land/wetland in urban or suburban areas is considered as wasteland and repurposed into different developmental activities, including light industry or residential housing, designated by local governments. Due to multiple ongoing development activities in adjoining uplands, urban wetlands have become inefficient in maintaining water quality and flood control (Shan et al., 2021; Mondal et al., 2017). The ability of the wetland to perform vital ecosystem services, particularly water filtering, may be impacted by the change in hydrological regimes brought about by urbanisation, which may impair their water quality and quantity (Paul and Meyer (2001). A wide variety of species call wetlands home, and the loss of these ecosystems due to expansion of cities, Changes in temperature and precipitation patterns can affect the species composition and functioning of these ecosystems Erwin (2009) and Jamal et al. (2023), ultimately resulting in habitat loss and fragmentation Marzluff and Ewing (2001).

Table 2 and Fig. 7 indicate a continuous increase in urban population since 1981, resulting in unplanned urbanization and an increase in the number of metropolitan cities. As a consequence, important metropolitan cities are grappling with water security issues and a degraded environment. Inefficient waste management, increasing pollution, and unchecked urban growth have proved to be the main reasons for the shrinkage of wetlands in these cities. Since 1971, Chennai has lost 90 percent, Vadodara 30.5 percent, and Hyderabad 55 percent of wetlands due to these reasons. Mumbai has lost 71 percent, Ahmedabad 57 percent, Bengaluru 56 percent, Pune 37 percent, and Delhi-National Capital Region has lost 38 percent of wetlands, mainly due to construction and eutrophication from pollution (WISA, 2014).

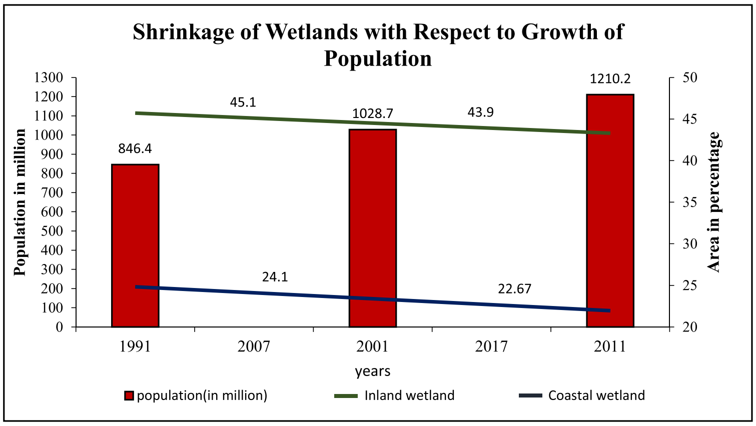

Fig. 6 Shrinkage of wetlands with respect to growth of population

Table 2 Level of urbanization

Increasing concentration of urban population in larger cities	Year			
	1981	1991	2001	2011
Number of metropolitan cities (population-million)	12	23	35	53
Population (million)	42	70	108	161
Percentage of total urban population	26	32	37	42

Source: Census of India, 2011

The menace of encroachment

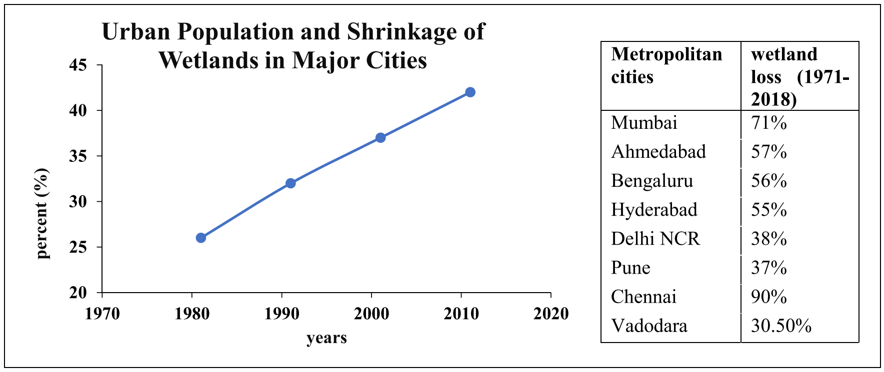

Fig. 7 Urban population and shrinkage of wetlands in major cities. Source: WISA 2014, Down to Earth, 2014

The level of encroachment, particularly in urban areas, has increased due to intense competition for land, real estate development, industrial operations, and agriculture, significantly affecting the health of wetlands. The wetlands are constantly impacted by urban residential encroachment, as the majority of inhabitants dispose of their domestic waste into nearby bushes and wetland borders, according to Agyapong et al. (2018). Additionally, most of the town's drains release water contaminated with silt into the feeder streams, which eventually reach the wetland. The most frequently noted wastes were plastic and metal containers. While some of the trash is swept downstream and gets entangled in aquatic vegetation, other fragments float on the water and block the free flow of the stream, reducing the current. The stream bed gradually becomes silted, causing a shrinkage. For instance, urban wetlands, primarily in Kashmir, have become hypereutrophic due to unauthorized encroachments near the wetland, according to Dar et al. (2020). Even most of the Indian lakes are presently being deteriorated due to siltation and encroachment. Wular lake in Kashmir, Chilka lake in Orissa, Kolleru lake in Andhra Pradesh, and the man-made Sukhna lake in Chandigarh are among the lakes that have experienced a decrease in water holding capacity over the past two decades (Behera et al., 2023). The unsustainable use of natural resources, such as overfishing in wetland catchment areas, has created a clear threat to aquatic wildlife, particularly waterfowl, in these lakes. The largest natural lake in eastern India, Loktak Lake, located in the southern part of the Manipur Valley, has been severely impacted due to inadequate resource use in its watershed area and unplanned land use. The Kaliveli lake in Tamil Nadu has experienced a reduction in its water-spread area and the number of water bird species, such as pelicans, storks, and flamingos, potentially due to encroachment by paddy fields and poaching for meat, respectively, leading to their migration. Several lakes, such as Kolleru lake in Andhra Pradesh, Deepar beel in Assam, Pyagpur and Sitadwar Jheels in Uttar Pradesh, and Hokersar lake in Kashmir, have shrunk due to repossession for agriculture. These pristine ecosystems are under severe threat from human interference and the transformation of natural processes, including climate regulation. The degradation of water quality in many of the country's lakes is primarily due to eutrophication and weed infestation, which have impacted the ecological health and biodiversity of Dal Lake in Srinagar and Loktak Lake in Manipur (Rashid & Aneaus, 2020). Water pollution is rapidly spreading in Harike Lake in Punjab, contaminating about 75% of the wetland area. Anthropogenic activities are mainly responsible for the increased pollution, loss of biological diversity and natural resources, and a sharp decline in water-spread areas. Rural areas, despite the obvious presence of natural vegetation in the catchment area, face a different level of stress due to soil erosion compounded in catchment areas devoid of vegetation due to overgrazing and cultivation (Ahmad et al., 2022). Soil erosion and degradation in agricultural catchments are caused by the overuse of fertilizers and non-biodegradable pesticides, as well as silts from surface and subsurface runoff, according to Chopra et al. (2001), Jayanthi et al. (2006), Sengupta and Deb (2022), and Silambarasan and Sundaramanickam (2017).

Every year, agribusiness, dam construction, and other activities encroach on wetland areas (McAllister et al., 2001) which made it ecologically vulnerable. Wetlands often serve as critical stopover points for migratory birds, providing essential resting and feeding grounds during their long journeys. When wetlands are encroached upon or destroyed, it disrupts the migration patterns of migratory birds, negatively impacting bird populations. The destruction of these habitats disrupts their migration routes, affecting their ability to find suitable resting and feeding sites (Zockler et al., 2010). It also has far-reaching ecological consequences, including the loss of biodiversity, altered hydrological balance, and decline in water quality (Mitsch et al., 2012), (Tiner, 2003). So, it is essential to recognize the value of wetlands and implement effective conservation measures to protect these vital ecosystems.

Land transformation and its effect

Anthropogenic-driven land transformation has been blamed for the recent rapid changes in the dynamics of the global environment (Ahmad et al., 2024; Singh et al., 2020; Ma et al., 2019). Land use change, which refers to the alteration of the natural landscape caused by human actions, is one of the key components of environmental dynamics. The desire to maximize human economic gains primarily drives land alterations. The growth in human population, the spread of settlements, the production and consumption of food, the need for energy, deforestation, the intensification of agriculture, the alteration of natural landscapes, and the excessive use of natural resources are the main drivers of land use change (Kobayashi et al., 2020; Jamal & Ahmad, 2020; Lambin et al., 2001).

At different scales, these transformations alter the relationship between the land and the air, the hydrological cycle, and ecosystem functioning. Anthropogenic land-use and land-cover change have significantly impacted natural processes, including climate, ecosystem functions, and even the extinction of some species (Goldewijk & Ramankutty, 2009). The exponential increase in human population and related activities is changing land resources and altering housing, industrial, and agricultural infrastructure (Wilson & Weng, 2010; Ganaie et al., 2018).

Land use and land cover changes have substantial impacts on ecosystem services and operation. Changes in land use and land cover are among the most significant variables influencing the world's ecological systems (Vitousek, 1994; Ganaie et al., 2021). Anthropogenic land-use changes contribute to a range of environmental problems, including climate change, the greenhouse effect, eutrophication, desertification, flooding, acidification, and the loss of biodiversity. Careless urban development has caused numerous wetlands to disappear over the past 50 years, and those that remain are facing the same fate (Liu et al., 2010; Bassi et al., 2014;). These changes have an immediate effect on biotic diversity and contribute, through modifying the ecosystem, to local and regional climate change and soil degradation (Shodimu, 2016). Long-term consequences include the depletion of dissolved oxygen, which is required for the lagoon's aquatic life to remain healthy. Henceforth, farming activities, population growth, and modern civilization have converted large expanses of wetlands, lakes, and river floodplains into paddy fields with significantly increased spatial extent in India (Mozumder & Tripathi, 2014; Singh et al., 2020). However, changes in land-use can have significant ecological consequences. Wetlands, for instance, plays a critical role in maintaining water cycles so, when the land is transformed, it disrupts these cycles, which can lead to detrimental effects such as water shortages or flooding (Barbier et al., 1997) Moreover, it possesses valuable organic soils that are essential for carbon storage but unfortunately, due to the transformation activities taking place, there is a significant increase in soil erosion and

Table 3 Urban population and shrinkage of wetlands in major cities

Metropolitan cities	Wetland loss (1971–2018)
Mumbai	71%
Ahmedabad	57%
Bengaluru	56%
Hyderabad	55%
Delhi NCR	38%
Pune	37%
Chennai	90%
Vadodara	30.50%

Source: WISA 2014, Down to Earth, 2014

Table 4 Land use land cover change (2005–2016)

Class Name	2005–2006	2015–16
Built Up	0.56%	2.98%
Agriculture	41.95%	42.22%
Current fallow	11.76%	9.66%
Waterbodies	2.95%	0.72%

Source: Adopted and modified from (Mohan Rajan et al., 2020) and (Pathan et al., 2008)

degradation. (Brinson & Malvárez, 2002; Mao et al., 2018). This process releases stored carbon into the atmosphere, making a substantial contribution to climate change (Mitsch et al., 2007, 2013). Furthermore, the alteration in land utilization results in agricultural runoff, which often contains pesticides and fertilizers. When this runoff contaminates wetlands, it causes eutrophication and declines the water quality. As a consequence, aquatic life is negatively impacted, posing a threat to human safety (Carpenter et al., 1998; Roy-Basu et al., 2020). The disruption in water cycles caused by land transformation also leads to nutrient pollution, specifically nitrogen and phosphorus, in water bodies (Reddy & DeLaune, 2008). Overall, Land transformation has multiple ecological repercussions. These consequences have far-reaching effects on the environment, affecting both the quality of water resources and the well-being of various aquatic organisms, including humans (Table 3).

On the basis of the land use/land cover data obtained, it is clear that the built-up area in India has significantly increased from 0.56% to 2.98% (as shown in Table 4 and Fig. 8). Furthermore, both agriculture and current fallow lands are continuously expanding, leading to a consecutive decrease in the number of water bodies. Changing land use categories is only possible by transforming the existing class into other classes. Unfortunately, the positive change in built-up and agriculture classes comes at the cost of a negative change in water bodies and fallow land.

Pollution's threat: a risk to ecosystems and biodiversity

In many agricultural and urban landscapes, wetland areas serve as a sink for contaminants. Wetlands have also been recommended as a cost-effective means of reducing point and non-point pollution (Byström et al., 2000). The number of individuals and their various activities directly correlate with water quality, thus having a direct impact on it. Over 50,000 lakes,

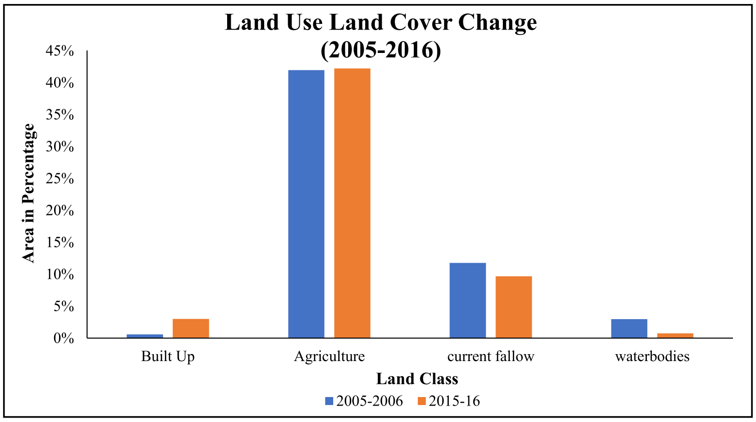

Fig. 8 Land use land cover of India. Source: Adopted and modified from (Mohan Rajan et al., 2020) and (Pathan et al., 2008)

both large and small, are so heavily contaminated that they are deemed "dead" (Chopra, 1985; Prasad et al., 2002). In India, urban areas discharge untreated sewage and waste into wetlands, causing pollution. Wetlands typically filter out pollutants from runoff, but due to urbanization and changes in land use, their capacity to remove nutrients through processes such as nitrification, sedimentation, adsorption, and plant uptake is overwhelmed. As a result, wetlands suffer from negative impacts on their water quality and biodiversity (Verhoeven et al., 2006). Human activities are responsible for the degradation of water quality in lakes and catchments. The discharge of untreated sewage waste and solid waste is a major contributor to water pollution in wetlands. The immersion of idols in water and the disposal of non-biodegradable and biodegradable garbage also negatively impact the physical, chemical, and biological qualities of water in wetlands. Activities such as bathing, washing clothes, recreational activities, and motor-driven boat navigation also affect the biodiversity of wetlands. Drilling, cultivation, and fishing in lakes and wetlands lead to ecological and economic losses. Unmanaged urban, agricultural, and industrial activities have depleted and altered wetlands, causing their complete loss. Human settlements located in catchment areas of wetlands and lakes are sources of liquid and solid waste that contribute to pollution. Soil erosion in catchment areas due to overgrazing, vegetation cultivation, and overuse of fertilizers and pesticides also degrade water quality. Urban wetlands are inefficient in maintaining water quality and flood decrement due to multiple development activities in adjoining uplands. The reduced water holding capacity of concrete and increased flow rate of rivers after heavy rainfall have led to enhanced flooding and pollution. Eutrophication and weed infestation are primary contributors to water quality degradation in popular lakes such as Srinagar's Dal Lake and Manipur's Loktak Lake. Water pollution has contaminated approximately 75% of the wetland area in Harike Lake (Punjab). Anthropogenic activities have led to increased pollution, loss of biological diversity and natural resources, and a sharp decline in water-spread areas (Mozumder & Tripathi, 2014; Singh et al., 2020). Pollution in wetlands can have serious ecological repercussions as well. According to the Environmental Protection Agency, Excess nutrients and other pollutants, "may induce toxic algal blooms, fish mortality, and loss of aquatic vegetation" (EPA, 2021). Additionally, as poisons may be taken by plants and animals and build up along the food chain, pollution can have an effect on the food chain. Similarly, animals that depend on wetlands for survival may experience health issues or perhaps pass away as a result of this (National Wildlife Federation, 2021). Water in most Asian rivers, lakes, streams and wetlands have been heavily degraded, mainly due to agricultural runoff of pesticides and fertilizers, and industrial and municipal wastewater discharges, all of which cause widespread eutrophication (Liu & Diamond, 2005; Prasad et al., 2002; Das & Pal, 2018). About 78% of the total pollution load flows in to the river every day resulting in the deterioration in water quality and hydrological character in the river stretches in terms dissolved oxygen (DO) and biological oxygen demand (BOD).

Management strategies with reference to policy support

Until the early 2000s, there was minimal governmental backing for wetland conservation in India. The approach to wetland management primarily relied on international commitments like the Ramsar Convention, as well as indirect influences from policies such as the National Conservation Strategy and Policy Statement on Environment and Development (1992), Coastal Zone Regulation Notification (1991), National Policy and Macro-level Action Strategy on Biodiversity (1999), and National Water Policy (2002), (Prasad et al., 2002). In 1985–1986, the National Wetland Conservation Programme (NWCP) was initiated in collaboration with State Governments, initially focusing on designated Ramsar Sites (MoEF, 2007). Measures were implemented to prevent degradation of identified water bodies caused by issues like encroachment, siltation, weed infestation, catchment erosion, agricultural runoff carrying pesticides and fertilizers, and wastewater discharge. In 1993, the National Lake Conservation Plan (NLCP) was integrated into NWCP, concentrating on urban and peri-urban lakes facing human-induced pressures (MoEF, 2007; Ragavan etal., 2021).

The National River Conservation Plan (NRCP), operating since 1995, aimed to enhance the water quality of major rivers. The draft National Water Policy (2012) acknowledges the need for scientific conservation of river corridors, water bodies, and wetlands. It underscores recognizing environmental needs in water resources conservation planning (Ministry of Water Resources, 2012). In 2010, the Wetlands (Conservation and Management) Rules were proclaimed, establishing the Central Wetlands Regulatory Authority (CWRA) and the Expert Group on Wetlands (EGOW) to assess action plans for effective management (MoEF, 2012).To counter natural ecosystem depletion, the government promotes afforestation through the Compensatory Afforestation Fund Management and Planning Authority (CAMPA). Despite these policies, many wetlands are still overlooked, with disagreements among national agencies on water body classification (National Wetland Atlas, 2011).

Legal framework

Legal frameworks governing wetlands are often initially designed for specific aspects like forests, the environment, water, land, or marine fisheries. Consequently, there is a lack of a dedicated legislative framework exclusively for wetlands. To address this gap, the Government of India introduced the Wetlands (Conservation and Management) Rules in 2010. These rules were established following the directives of the National Environment Policy of 2006 and the recommendations of the National Forest Commission. These include acts such as the Indian Fisheries Act of 1857, Indian Forest Act of 1927, Wildlife (Protection) Act of 1972, Water (Prevention and Control of Pollution) Act of 1974, Territorial Water, Continental Shelf, Exclusive Economic Zone, and other Marine Zones Act of 1976, Water Cess Act of 1977, Maritime Zone of India Act of 1980, Forest (Conservation) Act of 1980, Environmental (Protection) Act of 1986, Wildlife (Protection) Amendment Act of 1991, Biodiversity Act of 2002, and Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act of 2006 (Wetlands Conservation and Management Rules, 2010; Wetlands Conservation and Management Rules., 2017) (Shan et al., 2021).

These regulations impose limitations on various activities within wetlands, such as reclaiming land, establishing industries in surrounding areas, disposing of solid waste, manufacturing or storing hazardous substances, releasing untreated wastewater, and constructing permanent structures. It also stipulate that certain activities, such as hydraulic alterations, unsustainable grazing, resource harvesting, treated effluent release, aquaculture, agriculture, and dredging, cannot proceed without the consent of the State government. However, these rules apply only to "selected wetlands" deemed significant for the overall well-being of the population. These "selected wetlands" include those designated under the Ramsar Convention, wetlands in ecologically sensitive areas, UNESCO World Heritage sites, wetlands at high altitudes, wetland complexes, and any other wetlands identified by the Authority (Wetlands Rules, 2010). Unfortunately, the absence of regulations, especially for wetlands below 2500 m, results in neglecting management and conservation efforts for crucial smaller wetlands in both urban and rural areas. These wetlands play vital socio-ecological roles and face significant threats from land-filling and reclamation. Additionally, river channels (considered wetlands under the Ramsar Convention) and irrigation tanks do not receive protection under the Wetland Rules (Dandekar et al., 2011). Numerous endeavours to safeguard wetlands in India are based on the establishment of protected areas (PAs). However, certain PAs have demonstrated to be ineffectual in preventing the deterioration and depletion of these areas within their confines, as illuminated by Lavieren et al. (2012), Bassi et al. (2014), and Almeida et al. (2016). Creating protected areas is deemed as the most efficacious approach to ensure the preservation of wetlands, particularly in regions where natural wetlands are abundant and rare or endangered species are concentrated (Mitsch et al., 1998).

Recent measures

The Ministry of Environment, Forest, and Climate Change (MOEF&CC) recently replaced the Wetlands (Conservation and Management) Rules, 2010 with the new Wetlands (Conservation and Management) Rules, 2017. This alteration has decentralized wetlands management, granting states the authority to not only identify and notify wetlands within their jurisdiction, but also to monitor prohibited activities. The Central Wetlands Regulatory Authority (CWRA), which was proposed in the Wetlands Rules (2010) has been substituted by a national committee in the Wetlands Rules (2017). This national committee solely serves in an advisory capacity. Some conservationists contend that this modification has undermined existing regulations (MOEF, 2022). Coastal wetlands are also safeguarded by the Coastal Regulation Zone (CRZ) notification (2018), which designates them as ecologically sensitive areas under CRZ Category I. Nevertheless, despite these measures, progress in the conservation and sustainable use of coastal wetlands is limited. Only a few wetlands have received attention and have management action plans in place, supported by financial and technical assistance from government initiatives (Bassi et al., 2014), (Ragavan etal., 2021).In India, there are currently 75 wetlands under the list of wetlands of international importance, out of which 33 wetlands have been designated under Ramsar Sites of country during 2021 and 2022 (MOEF, 2022). These wetlands possess rare or unique biodiversity and play a significant role in safeguarding the ecological biodiversity of a particular area. Moreover, a special scheme called "Amrit Dharohar" was introduced to protect crucial wetlands that support aquatic biodiversity. The primary objective of this scheme is to achieve sustainable ecosystem development in collaboration with local communities. This initiative falls under the 'Green Growth' category, which is one of the seven priorities outlined in the budget. Through "Amrit Dharohar", the government will promote the distinctive conservation values of these wetlands. Over the next three years, this scheme will be implemented to encourage the optimal utilization of wetlands, as well as to enhance biodiversity, carbon storage, eco-tourism opportunities, and income generation for local communities (Down to Earth, 2023). The current regulations encompass comprehensive regulatory provisions aimed at mitigating anthropogenic activities in the proximity of rivers and wetlands. Nonetheless, the absence of stringent enforcement and systematic monitoring promotes unregulated anthropogenic activities that perpetuate the deterioration of water quality in India's wetlands (Seenivasan, 2013).

Conclusion

The wetlands of India are facing a dire situation due to anthropogenic as well as ecological factors that are causing them to shrink. Therefore, it is imperative to protect them through careful planning and management involving all stakeholders, including government agencies, academic institutions, non-governmental organizations, and civil society. Geospatial technology has been a significant boon for the analysis of wetlands, and this review has identified the five primary factors responsible for the anthropogenic stress on wetlands. The paper is organized into six parts, each addressing a specific aspect of wetland degradation. In the first part, an introduction to wetlands is provided. The second part examines the role of population growth as a major driver of wetland degradation. The third part focuses on urbanization as a significant contributor to the shrinkage of wetlands. The fourth part delves into encroachment and land transformation as leading causes of wetland degradation. The fifth part explores pollution as a critical driver responsible for the degradation and loss of wetlands. The sixth part deals with the existing measures for the conservation of Wetlands. Finally, the last part presents the conclusion and suggests further research in this field. This review will serve as a valuable reference for future wetland research in developing countries like India. It sheds light on the progress made in wetland ecosystem services (WES) evaluation, analysis of driving forces, wetland management, and policy design. However, current studies lack unified WES indicators and comprehensive WES studies, leading to uncertainty in research themes, driving forces, and WES types. The study also suggests creating a long-term monitoring programme, designing payment for ES programmes, and generalizing WES evaluation indicators to address these limitations.

Suggestions and recommendations for the conservation and development of wetlands

- **Adopting a Hydrogeomorphic Classification Approach:** Utilize a comprehensive approach that considers the diverse climatic, geomorphic, and hydrological conditions under which wetlands exist. This approach will facilitate the assessment and understanding of wetlands more effectively.
- **Incorporate Landscape-level Planning and Advanced Identification Programs**: Implement landscape-level planning strategies and utilize advanced identification programs (ADID) and Special Area Management Plans (SAMPs) to ensure the protection and sustainable management of wetlands.

- **Utilize Remote Sensing and GIS with a Multidisciplinary Approach:** Harness the power of remote sensing and Geographic Information Systems (GIS) in combination with a multidisciplinary approach to effectively prevent the degradation of wetlands.
- **Develop Standardized Methods for Valuation of Wetland Ecosystem Services:** Establish standardized methods for assessing and valuing the ecosystem services provided by wetlands. This will enhance the comparability of results across different studies and regions, improving the reliability and credibility of valuation outcomes.
- **Enhance Stakeholder Engagement**: Promote active stakeholder engagement as a key strategy for wetland conservation. Encourage the participation and collaboration of local communities, organizations, businesses, and relevant authorities in decisionmaking processes and conservation efforts.
- **Promote Reduce, Reuse, and Recycle Practices:** Encourage the adoption of waste management practices such as reducing, reusing, and recycling to minimize anthropogenic stress on wetlands and mitigate their degradation.
- **Foster Healthy Plant Life and Natural Therapies:** Encourage the growth of healthy aquatic and upland vegetation in wetlands. Promote the use of natural therapies and alternatives to chemical interventions in plantations and gardens to improve wetland health and ecosystem functioning.
- **Conduct Public Awareness Campaigns and Educational Initiatives:** Launch campaigns and educational programs to raise public awareness about wetland habitats, their ecological importance, and the challenges they face. Foster a sense of responsibility and stewardship among the general public.
- **Support Monitoring Programs and Scientific Research:** Provide support for monitoring programs and scientific research initiatives focused on gathering information about wetland biodiversity, hydrology, and ecological health. This knowledge will inform evidence-based conservation and management practices.
- **Facilitate Collaboration and Cooperation:** Foster collaboration among researchers, local communities, and government agencies to ensure effective management and conservation of wetlands. Encourage knowledge-sharing, capacity-building, and coordinated action.
- **Initiate Restoration and Rehabilitation Projects:** Collaborate with local groups and organizations to initiate projects for the restoration and rehabilitation of degraded wetlands. Engage children in activities such as reforestation, removal of invasive species, and the establishment of native plant nurseries to restore damaged ecosystems.
- **Promote Sustainable Livelihood Options:** Create viable livelihood options for communities dependent on wetlands by promoting eco-tourism, environmentally responsible fishing practices, organic farming, and other nature-based businesses that do not harm wetland habitats.

By implementing these suggestions and recommendations, we can work towards the conservation and sustainable development of wetlands, ensuring their long-term ecological integrity and the well-being of communities reliant on these invaluable ecosystems in India and beyond.

Declarations

Conflict of interest All the authors declare that the Authors have no conflict of interest for their entitled research paper "Tracing the Roots of Wetland Degradation in India: A Systematic Review of Anthropogenic Drivers, Ecological Consequences and Conservation Strategies".

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