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Ecosystem Services, Threat and Dynamics of Phumdis: Comprehensive Study on Loktak Caldera Lake, Manipur through Remote Sensing and Ground Visit

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Abstract

Phumdis, a distinctive geomorphic-hydrologic-pedogenic landform at Loktak Lake, is a vital interface zone between aquatic and terrestrial ecosystems. These spherical landforms, flooded and saturated with water throughout the year Phumdis consist of a body of soil, vegetation, and organic material floating on the surface of a lake. Loktak Lake and Phumdis offer essential ecosystem services for preserving the environment and facilitating human activities. These services include water filtration, ecosystem productivity, flood regulation, and habitats for various species, all of which are crucial for the region's sustainability. The present study is associated with the ecosystem services of Loktak Lake and Phumdis. Its research objectives also include assessing the threat and dynamics of Phumdis. The study has been done through mapping in geospatial techniques, and intensive field study. The Phumdis support the natural ecosystem and are sometimes used for agricultural activities. However, changes in hydrology caused by climate change and intensive human activities are leading to the decline of the Phumdis. This threatens the ecosystem and habitat of the Sangai deer seriously. Human encroachment and development processes, coupled with alterations in the lake area, also endanger the natural habitat and biodiversity of the lake. Loktak Lake is an important ecological resource with distinct floating islands, rich biodiversity, and central significance to livelihood and culture at the local level. However, it faces many environmental issues that require collective conservation efforts to maintain its ecological balance.

Keywords

Lake, Ecosystem, Agriculture, Thereat, Conservation

1. Introduction

Lake ecosystem is a complex community of living organisms, including plants, animals, and microorganisms, that interact with the nonliving physical and chemical elements of their environment. Wetlands are highly productive ecosystems that provide numerous valuable ecosystem services (Devi, 2017; Khwairakpam et al., 2021). Lakes, in particular, are among the most productive and resourceful areas. They supply food and various non-edible aquatic resources, maintaining ecological balance for local populations and entire nations (Laishram, 2021). Wetlands are crucial for transitioning between aquatic and terrestrial ecosystems (Kangabam & Munisamy, 2017). The productivity of wetland ecosystems yields numerous ecosystem services, and their diversity varies significantly based on location, water patterns, soil and sediment characteristics, origin, and key species (Khwairakpam et al., 2021). Sustainable human development in the current Anthropocene age relies heavily on freshwater supplies, and the sustainable growth of a region is intrinsically linked to its wetland resources (Singh & Rai, 2015). Loktak Lake is a crucial water source for the local community's irrigation and domestic needs. It is an essential area for water birds, particularly ducks, during the winter and migration seasons (Devi, 2017). The lake supports local livelihoods through fishing, agriculture, and the collection of vegetables (Laishram & Dey, 2014). Loktak Lake holds a significant socioeconomic and cultural significance for the people of Manipur (Devi, 2017). These wetlands play a critical role in providing ecological and economic security to the region by supporting fisheries, housing rare and endangered biodiversity, and facilitating hydropower generation and irrigation (Sharma & Sharma, 2018; Sharma, 2019). Despite being over 266 sq. km, Loktak Lake exhibits signs of shrinking and reduced wetland coverage (Devi, 2017; Devi & Singh, 2017).

The construction of the controversial Ithai Barrage began in 1971, downstream of the Manipur River (also known as the Imphal River). It was completed in 1983, resulting in the inundation of the surrounding land and leading to significant changes in fish availability, related resources, and fishing methods in Loktak Lake (Laishram, 2022). Loktak Lake faces pollution issues that must be addressed to prevent further degradation, the spread of waterborne diseases, and the use of contaminated water for household purposes (Laishram & Dey, 2014). The lake is home to 116 bird species and 21 migratory waterfowl (Singh, 1991, 2010). Studies have shown that Loktak Lake hosts 86 macrophyte plant species distributed throughout the lake during different seasons of the year (Singh & Rai, 2015). The masses of organic matter called Phumdis consist of decaying waste, plants, and soil. Some of these floating communities are big enough to accommodate stores and homes. Extensive research has been conducted on Loktak Lake, particularly regarding its biodiversity, conservation challenges, and socio-economic significance; however, several research gaps still require attention.

Comprehensive long-term research on the impact of climate change, including altered rainfall patterns, on the lake's hydrology, and how sustainable watershed

management should be implemented upstream. Detailed modeling of future hydrological scenarios resulting from climate change, including temperature fluctuations, water flow, and evaporation rates, should be conducted to predict the long-term impacts of climate change on the lake environment. Detailed and systematic research is required to determine the formation, decay, and threat posed by Phumdis. Investigating sustainable ways to manage Phumdis dynamics, including eco-friendly techniques for restoration and their impact on the lake's overall ecosystem, can be a key focus area. The objective is to assess the ecosystem services of Loktak Lake for the surrounding communities (WISA & LDA, 2004). It also aims to thoroughly examine the importance of Phumdis and the potential threats they face. Another key objective is to identify and address the significant challenges of Loktak Lake and its catchment area. Additionally, the project will propose community-based ecosystem management systems and policies to promote sustainable development and inform long-term policy-making.

2. The Study Area

Loktak Lake, situated in the southern part of the Imphal valley of Manipur, spans between 93˚46' and 93˚55' E and from 24˚25' to 24˚42'N' (**Figure 1**, **Figure 2**). It is shaped like an oval, with a maximum length and width of 26 Km and 13 Km, respectively (Laishram & Dey, 2014; Laishram, 2022). The Loktak Lake wetland is located in the Bishnupur district of Manipur, India, and is the largest freshwater wetland in Northeast India (Devi, 2017). The depth of the lake ranges from 0.5 to 4.58 m, with an average depth of 2.7 m (Laishram, 2022). Covering an area of 246.72 km^2, it is the largest freshwater lake in northeast India and forms a part of the Indo-Burma Biodiversity Hotspot (Kangabam & Minusamy, 2017). The surface area of Loktak Lake is recorded as 286 sq. km. (Singh, 2010).

Loktak Lake is considered a sub-basin of the Manipur River basin (Laishram, 2022) and plays a crucial role in flood control (Devi, 2017). It has a direct catchment area of 980 square kilometers and an indirect catchment area of 7157 square kilometers (Laishram, 2022). Loktak Lake is deemed the lifeline of Manipur and is deeply intertwined with the socioeconomic and cultural life of the people in the state (Devi, 2017). The catchment area of Loktak Lake is recorded as 980 square kilometers (Singh, 2010). The lake is surrounded by 55 rural and urban settlements, with a population of approximately 100,000 (LDA, 1996; 2011; LDA & WISA, 1999; Laishram, 2022; LDA & WI, 2002). Its significance to Manipur's economy makes it an essential resource for the local population's socioeconomic and cultural well-being (Ursa & Arunkumar, 2023). Approximately 12 towns and 52 settlements, housing a population of 220,017 individuals, are situated around the lake, accounting for 9% of Manipur's total population (Office of the Registrar General & Census Commissioner, India, 2011). These populations rely directly or indirectly on the lake's resources for their socioeconomic condition (Kangabam et al., 2015a, 2015b; Kangabam & Munisamy, 2017; Kangabam et al., 2017).

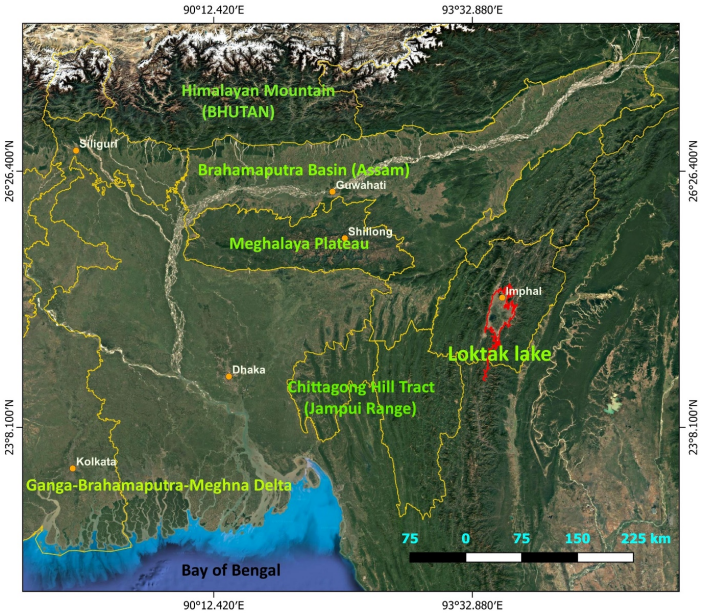

Figure 1. Location of Loktak Lake catchment area according to surrounding landscape. Loktak is the face of an extinct super volcanic caldera in Northeastern India, surrounded by significant landscapes. Loktak Lake, situated on the Chittagong Hill Tract, was formed due to the subduction of the Indian plate into the Burma plate. Shillong Plateau and Brahmaputra Valley are located in the northwestern part of Loktak Lake.

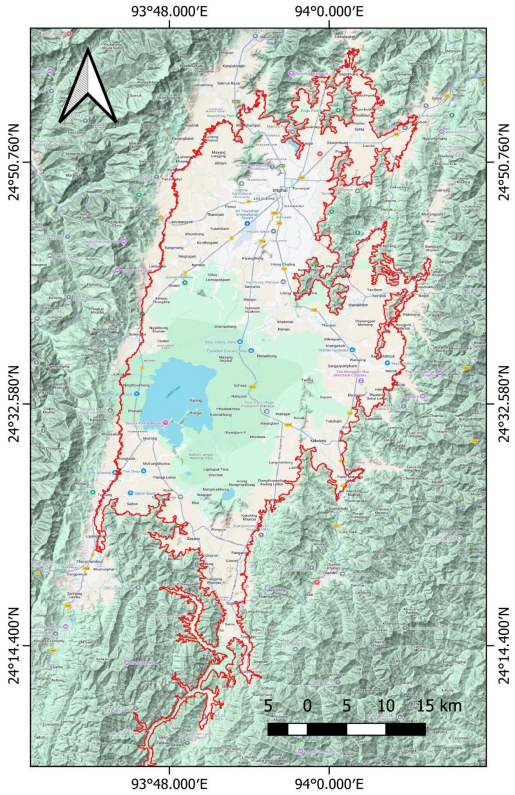

Figure 2. Location of Loktak Lake catchment area. A 1000 m contour demarcates the red colour catchment boundary. Couture has been generated by SRTM DEM (30 m) in open-source geoinformatics software.

Loktak Lake is vital to the economy of the state (Singh, 2010). The ancient Loktak Lake is a water source for hydropower generation, drinking water supply, and irrigation (Ursa & Arunkumar, 2023). Loktak Lake, the largest freshwater wetland in Northeast (NE) India, was designated as a wetland of international importance by the Ramsar Convention in 1990 (Devi, 2017). It was designated as a Ramsar site (Site No. 463), thereby being recognized as a Wetland of International Importance, on March 23, 1990 (Ramsar Convention Secretariat, 2012). Loktak Lake, located in Manipur's Bishnupur district, is a unique natural ecosystem with significant national and international importance under the Ramsar Convention (Kangabam & Munisamy, 2017). The Keibul Lamjao National Park, situated on Loktak Lake, is the world's only floating national park and serves as the last natural habitat of the Sangai, the dancing deer of Manipur. The park is the last refuge of the endangered Sangai, Manipur's state animal, also known as the brow-antlered deer (Ursa & Arunkumar, 2023). Loktak Lake is renowned for its floating island, locally known as Phumdis (Kangabam & Munisamy, 2017). It is also referred to as the only Floating Lake globally due to the floating Phumdis, a heterogeneous mass of soil, vegetation, and organic matter at various stages of decomposition (Ursa & Arunkumar, 2023). The lake is home to about 230 species of aquatic plants, 100 types of birds, and 400 species of fauna, including barking deer, sambar, and Indian python (Ursa & Arunkumar, 2023). Rich in biodiversity, Loktak Lake is considered the lifeline of Manipur Valley. It was recognized as a Wetland of International Importance (Ramsar site no. 463, declared on 23 March 1990) and added to the Montreux Record on 16 June 1993 (Singh & Rai, 2015).

3. Data and Methodology

The methodology for the study on Loktak Lake has been structured around the specific objectives outlined. The ecosystem services of Loktak Lake have been assessed by reviewing existing studies and reports. An intensive literature survey was conducted using published books, unpublished theses, published maps, data sets, policy papers, and previous photographs. A field survey has been conducted. The field survey details interviews with ground officials of the national park, locals, expert historians, and lake stakeholders. Mapping has been conducted using remote sensing data (SRTM, Landsat 5 & 8) in open-source geoinformatics software (**Figure 3**, **Figure 4**). The German eTrex 10 GPS handset was used to locate the desired position. High-end DSLR cameras and the Google Pixel 7 have been used to take photographs during the field survey. The importance and Threat of Phumdis are examined through mapping and evaluation. Threats to Phumdis have been identified and categorized through stakeholder consultations and environmental assessments. Band rationing and pixel classification techniques (NDVI, NDWI, LULC) have been used to create a map of various aspects of the lake ecosystem services.

4. Results and Discussion

4.1. Evolution of the Landscape and General Geology

Loktak Lake is located in the northeastern Indian state of Manipur. It is the largest

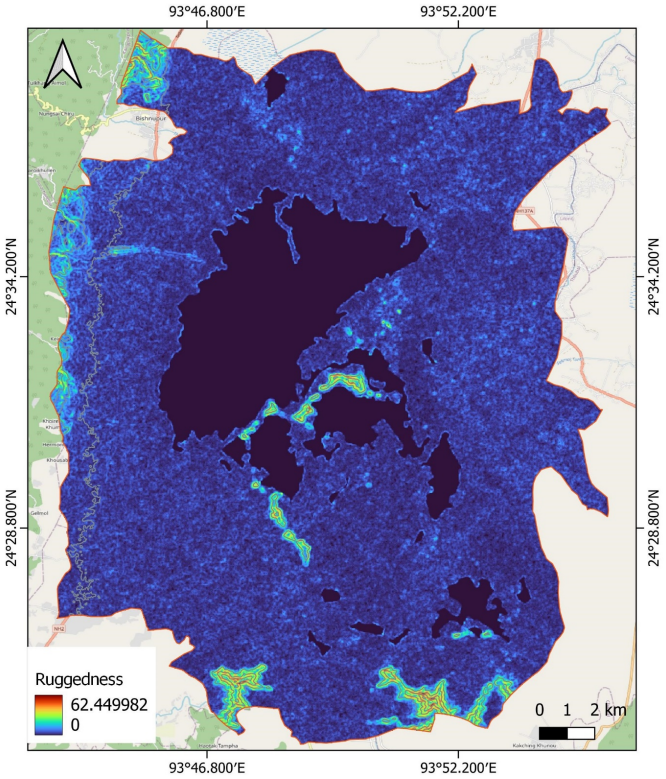

Figure 3. The Ruggedness map of Loktak Lake and its surrounding area (Map has been prepared from SRTM DEM 30M).

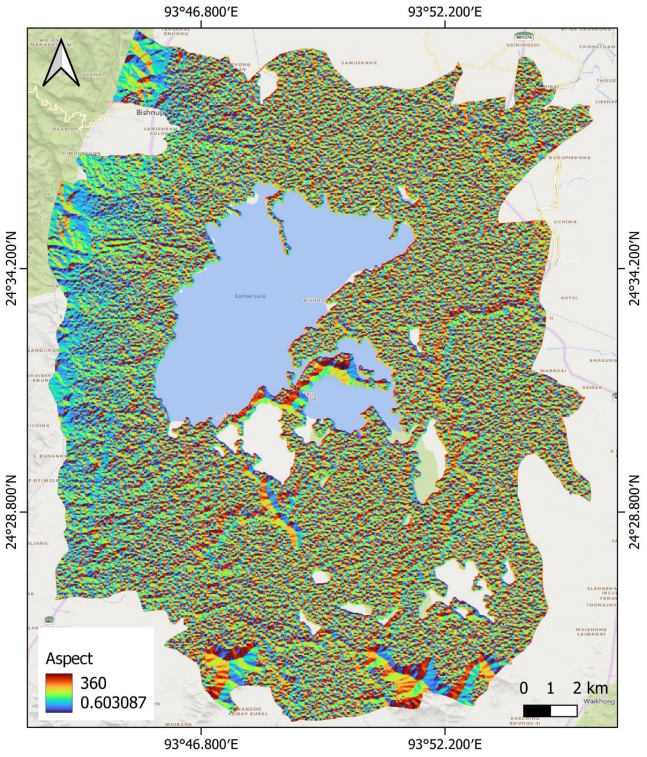

Figure 4. The Aspect map of Loktak Lake and its surrounding area (Map has been prepared from SRTM DEM 30M).

freshwater lake in Manipur and northeastern India and is associated with significant ecological, cultural, and geological importance. Loktak is part of the Burmese tectonic arc and is situated in a valley surrounded by hills in the state of Manipur. The geological formation of Loktak Lake is closely tied to the uplift of the Himalayan region and the tectonic movements that have shaped the landscape of Northeastern India. The lake is in an endorheic basin, meaning it does not drain into the sea but collects water from its surrounding hills (Tripathi et al., 2017). Loktak Lake is situated in the ancient super-volcanic caldera. Powerful and catastrophic volcanic events formed Loktak Lake during the subduction of the Indian Plate under the Burma Plate (Tripathi et al., 2017; Sharma & Singh, 2018).

4.2. Geomorphology of the Landscape

The geomorphology (elevation, slope, and hydrology) of Loktak Lake is unique and vibrant because the landscape combines features of lacustrine, fluvial, and wetland environments (**Figure 5** and **Figure 6**). A floating, thick composition of organic matter, called Phumdis, added adherent uniqueness to the landscape (**Figure 7**, **Figure 8**). Water accumulated in the depression of the foothill area of the Loktak basin, which was surrounded by hills and formed Loktak Lake. Loktak Lake is formed in the basement of the Loktak basin (**Figure 6**). Loktak Lake is an irregular basin formed due to the movement of the Indo-Burmese Plate. Loktak Lake is well connected to the Manipur River. The Manipur River is also considered the central outflow of the lake's hydrology (**Figure 6**). The sediment composition

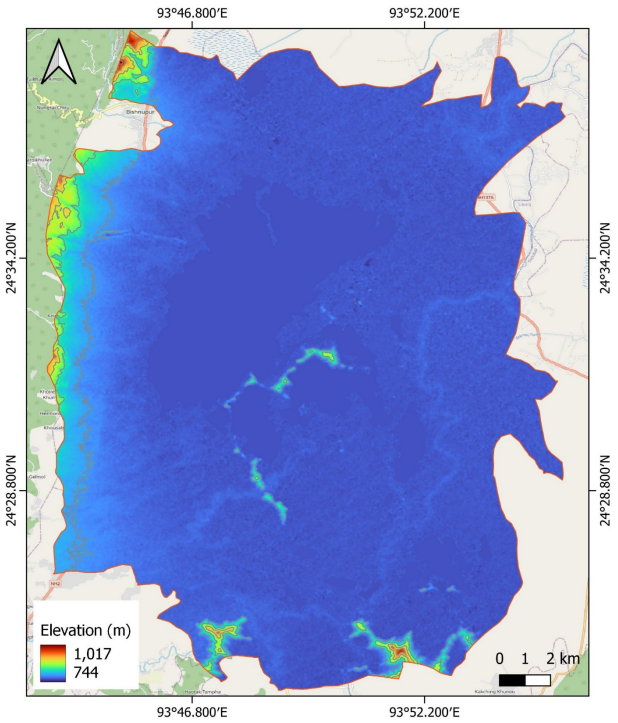

Figure 5. The elevation map of Loktak Lake and its surrounding area (Map has been prepared from SRTM DEM 30M).

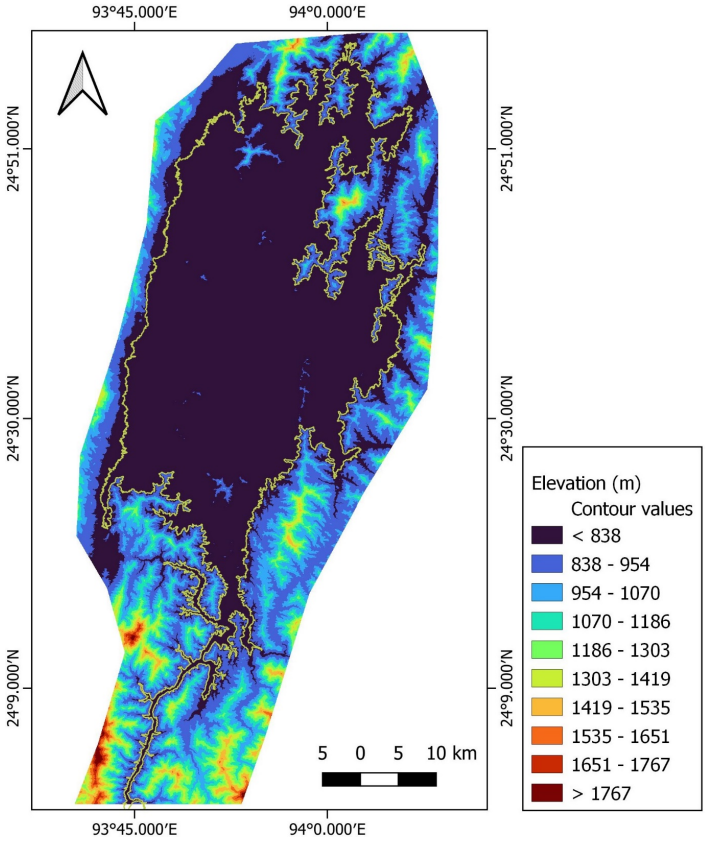

Figure 6. The elevation map of Loktak Lake Catchment area (Map has been prepared from SRTM DEM 30M).

Figure 7. Loktak lake. The photograph was taken from the southeast side of the lake (on the balcony of a restaurant associated with Sendra resort). In this photograph, a floating Phumdis is spotted. Those Phumdis are disturbed by different anthropogenic activities. A local fisherman uses this Phumdis to demark their fishing boundary. In Loktak Lake, encircled patches are not Phumdis, but the floating mat demarks the fishing areas. (*Camera model*: *Canon EOS* 550*D*, *F-stop*: *f*/10, *Exposure time*: 1/320 *sec*., *ISO Speed*:*ISO*-160, *Focal length*: 250. *Geographical Coordinates*: *Latitude*: 24 °30'45.06"N, *Longitude*: 93 °47'38.59"E, *DoP*: 20/09/2024).

Figure 8. Encircled artificial areas (a) are used for fishing, demarcated by local fishermen. One or two encircled areas are associated with one hut (b). The fisherman has used this temporary hut. (a) is prepared from Google Earth using open-source GIS software. (b) is a photograph taken from Thanga Island, northeast of Loktak Lake. (*Camera model*: *Canon EOS* 550*D*, *F-stop*: *f*/5.6, *Exposure time*: 1/400 *sec*., *ISO Speed*: *ISO*-100, *Focal length*: 250. *Geographical Coordinates*: *Latitude*: 24˚31'24.47"N, *Longitude*: 93˚49'53.12"E, *DoP*: 20/09/2024).

of the Manipur River is responsible for shallowing the lake due to excessive sedimentation and a decline in the lake's hydrological cycle. It also produces several wetlands associated with the principal wetland. Significant seasonal fluctuations in the water level of Loktak Lake have been observed. Loktak wetland is subjected to floods during monsoon and dries out during summer.

The Manipur River flows from the northern portion of Loktak Lake, almost through the lake, and towards the south of the lake (**Figure 6**). The left-bank tributaries of the Manipur River are *Iril* and *Thoubal*, and the right-bank tributaries are *Khuga*. Many tributaries originated from the Manipur Western Hill Range and flowed along the regional landscapes with Loktak Lake. Water withdrawal from the lake is a prime example of anthropogenic intervention in the lake ecosystem. That is subject to the metaphase in a state of dynamic equilibrium. The lake landscape comprises several geological faults formed by large-scale tectonic activity in the area's geological history.

4.3. Form and Occurrence of Water

Loktak Lake is associated with a subtropical monsoon climate, characterized by hot and wet summers and cold and dry winters (Singh, 2010). The form and occurrence of water in Loktak Lake are unique and significant due to its complete geological basement, geomorphological variation, dynamic hydro-ecological configuration, and seasonal and annual rainfall fluctuations (**Figure 9**). Seasonal groundwater level fluctuations are also a common phenomenon in this lake ecosystem. The primary water source in the Loktak freshwater ecosystem is rainfall, primarily due to the monsoon current (Devi et al., 2015). The main body of Loktak Lake consists of surface water flowing from the Manipur River. The lake water covers the central open area, including the unique floating Phumdis, and serves as a habitat for fish and aquatic life, which is essential to local fisheries. Phumdis absorb and store water in

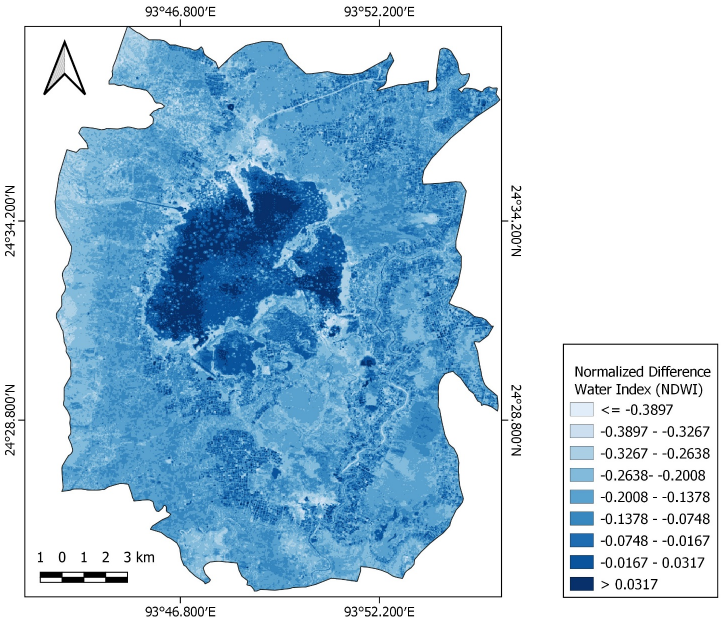

Figure 9. Normalize Difference Waer Index map of Loktak Lake and its surrounding area. Deep blue indicates the maximum water depth; lighter blue is the signature of rugged topography.

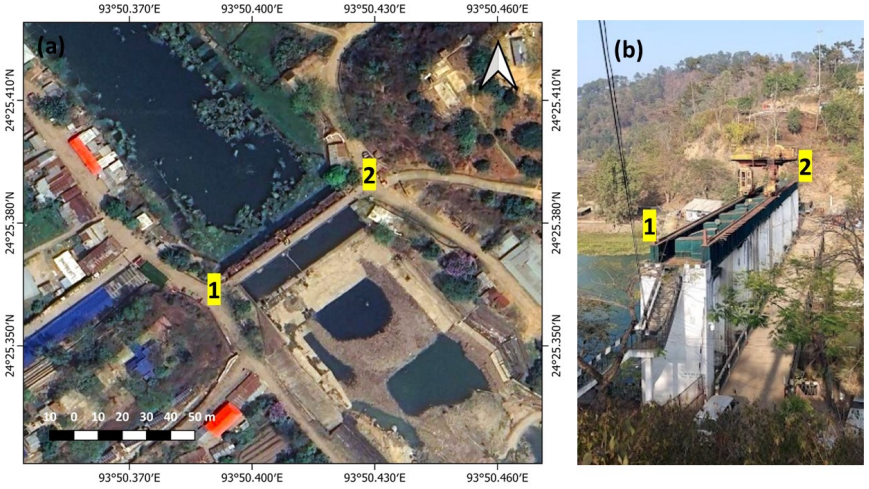

Figure 10. Ithai Barrage is located on the Manipur River (a), and photographs (b) were taken from the river's right bank of Manipur River. The Ithai Barrage is a critical infrastructure project for irrigation and power generation in Manipur. Although it is essential for agriculture and energy, it also challenges environmental sustainability and local livelihoods. Balancing development objectives with ecological preservation is crucial for the region's long-term viability.

their cells to promote the nutrient cycle, establishing a life support system for diverse vegetation, organisms, and fauna. The absorption of lake water by the root zone of the flora of Phumdis maintains and enhances their floating capacity (Devi, 1993; Devi et al., 2012). The regional groundwater level is closely linked to the surface water of Loktak Lake. Torrential rainfall during July, due to the current monsoon and its seasonal variation, is related to lake ecology, Phumdis move-

ment, and water availability for agriculture, fishing, and local communities. The annual rainfall at Loktak Lake is 138 cm (Singh, 2010). The Ithai barrage regulates the outflow of lake water to a great extent. This barrage was constructed on the Manipur River, just below the confluence of the Imphal and Kunga Rivers (**Figure 10**). During the monsoon season, the Manipur River Lake experiences successive amounts of sediment in the lake ecosystem due to the inflow of tributaries and the slope of the river. This leads to turbid water conditions, which in turn enhance sedimentation in the lake and riverbed. There are 34 streams from the western hill that feed Loktak Lake directly as well as indirectly (Singh, 2010).

4.4. Population and Society

The population and society surrounding Loktak Lake are deeply intertwined with the lake's rich biodiversity and the vast lake ecosystem. Floating Phumdis and large volumes of freshwater create conditions that support life in human society. The Meitei, a dominant ethnic group in Manipur, reside here with the support of the lake ecosystem (**Figure 11**, **Figure 12**). Another population inhabiting the surrounding lake belongs to Lois, Marams, etc. Some Indigenous Naga communities are also located in the Loktak Lake area ecosystem service zone. People depend on the Loktak Lake ecosystem to sustain their livelihoods through traditional fishing, harvesting, and the culture of native fish species (**Figure 13**). The Loktak Lake ecosystem contributes to food security and the local economy. People use Phumdis to delineate their fishing areas (**Figure 8**). Some stable Phumdis are occasionally used to grow vegetables and crops, such as chestnuts. Nowadays, ecotourism has become a vital source of income for economic development in this lake area. Some ecotourism huts have been constructed on the Phumdis for ecotourism purposes. Literate people reside in Mayang Imphal village (**Figure 14**).

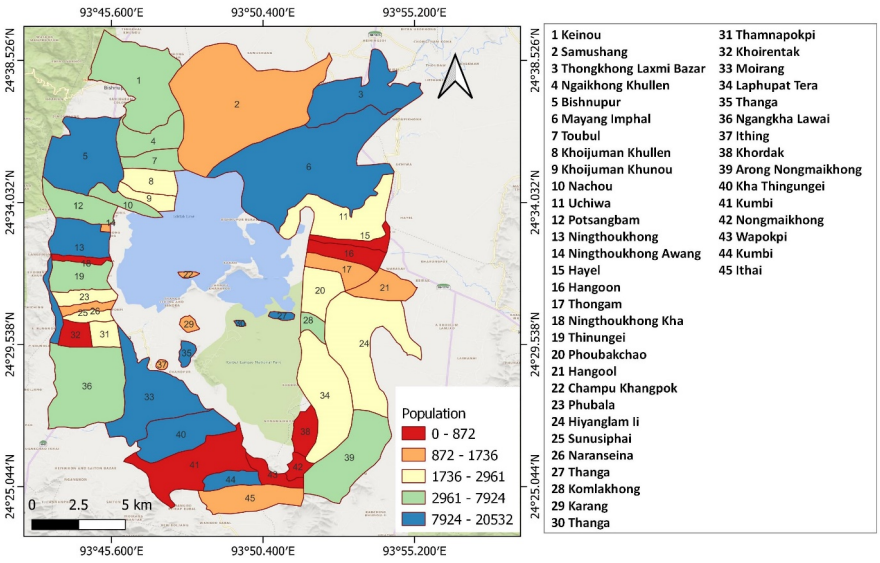

Figure 11. The Population map of Loktak Lake and its surrounding area (Map has been prepared from SRTM DEM 30M).

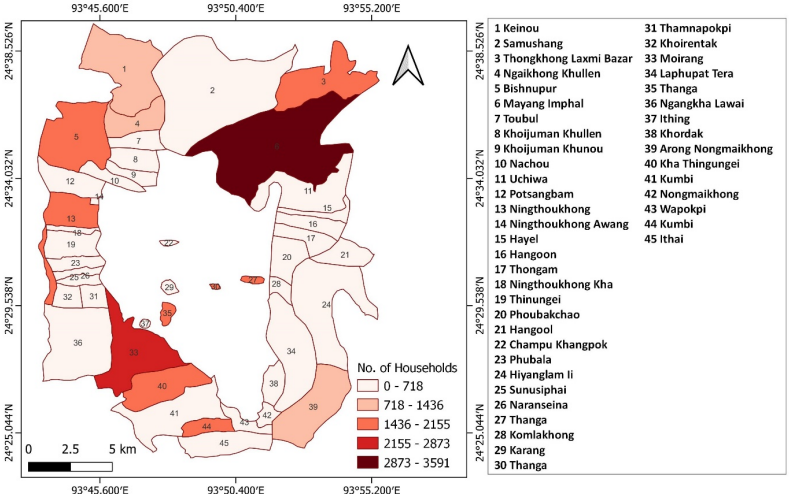

Figure 12. The Household map of Loktak Lake and its surrounding area (Map has been prepared from SRTM DEM 30M).

Figure 13. A countryman is catching fish from Loktak Lake for his livelihood. (*Camera model*: *Canon EOS* 550*D*, *F-stop*: *f*/4.5, *Exposure time*: 1/400 *sec*., *ISO Speed*: *ISO*-100, *Focal length*: 74. *Geographical Coordinates*: *Latitude*: 24˚31'11.05"N, *Longitude*: 93˚47'59.99"E, *DoP*: 20/09/2024).

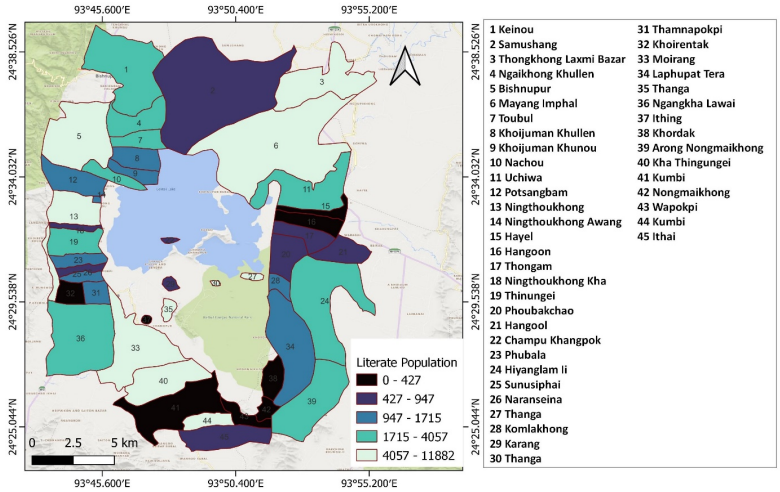

Figure 14. The Literate Population map of Loktak Lake and its surrounding area (Map has been prepared from SRTM DEM 30M).

4.5. Ecosystem and Its Services

4.5.1. Provisioning Services

Loktak is a significant freshwater body located in the northeastern part of India. The lake is a significant source of fresh water for human consumption, domestic use, agricultural irrigation, and hydroelectric power generation. The Loktak Lake water system supports a rich biodiversity, providing various resources to the people who depend on its ecosystem. Residents of Loktak engage in household and livestock farming within the lake's catchment area. The lake plays a vital role in recycling nutrients, purifying water, recharging groundwater, and supplying drinking water, as well as fish, fodder, and fuel. It also serves as a wildlife habitat, regulates urban runoff, and acts as a recreation center in the state (Rai & Singh, 2014). The lake is home to a diverse range of aquatic flora and fauna, including several species of fish and birds. Loktak Lake is a crucial habitat for the endangered Sangai deer. Keibul Lamjao National Park, located within Loktak Lake, is the world's only floating national park (**Figure 15**), spanning approximately 40 square kilometers. Fishing is an essential livelihood for many in the surrounding communities, with many rural fishermen relying on Loktak Lake (**Figures 16-18**). It is documented that 90 percent of fish production in Manipur originates from this lake. Additionally, the lake ecosystem is a primary source of medicinal plants for the local population.

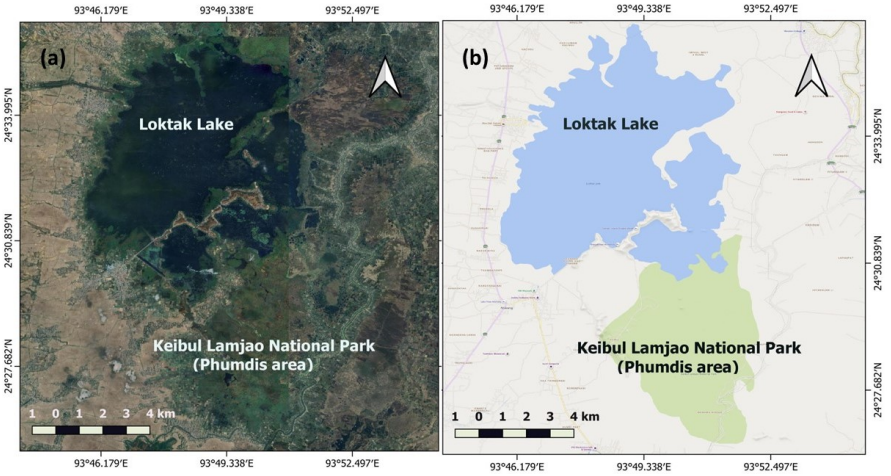

Figure 15. Loktak Lake landscape, the water area, wetted perimeter (a), and Location of Loktak Lake and Keibul Lamjao National Park. Phumdis covers a significant part of the national park.

4.5.2. Supporting services

Taking care of ecosystems is really important for a healthy environment. This includes supporting vital ecosystem services and protecting riparian areas and wetlands, which help manage water flow and recharge underground water sources. Restoring damaged ecosystems, like through reforestation or wetland repair, boosts their ability to function and provide benefits. Using methods like agroforestry and permaculture can improve soil health, prevent erosion, and promote

nutrient cycling. It is also essential to preserve natural habitats and reduce fragmentation to maintain the rich diversity of life and ecosystem integrity. The essential services that supply food, water, regulate climate and water quality, and offer recreational and spiritual benefits rely on these supporting services. When these foundational services are strong, ecosystems become more resilient, better able to handle shocks and adapt to changes, ensuring a healthy planet for everyone.

Figure 16. Fishing spot made of bamboo at Loktak Lake. (*Camera model*: *Canon EOS* 550*D*, *F-stop*: *f*/4.5, *Exposure time*: 1/2000 *sec*., *ISO Speed*: *ISO*-100, *Focal length*: 55. *Geographical Coordinates*: *Latitude*: 24˚31'15.05"N, *Longitude*: 93˚47'58.99"E, *DoP*: 20/09/2024).

Figure 17. Fishing village located on the eastern side of the Loktak Lake. (*Camera model*: *Canon EOS* 550*D*, *F-stop*: *f*/9, *Exposure time*: 1/200 *sec*., *ISO Speed*: *ISO*-100, *Focal length*: 123 mm. *Geographical Coordinates*: *Latitude*: 24˚31'4.47"N, *Longitude*: 93˚47'48.56"E, *DoP*: 20/09/2024).

Figure 18. A Fishing hut located at Loktak Lake. It was built to monitor fishing activity in the lake area. (*Camera model*: *Canon EOS* 550*D*, *F-stop*: *f*/9, *Exposure time*: 1/110 *sec*., *ISO Speed*: *ISO*-150, *Focal length*: 123 mm. *Geographical Coordinates*: *Latitude*: 24˚324.47"N, *Longitude*: 93˚48'48.56"E, *DoP*: 20/09/2024).

4.5.3. Regulating Services

The primary regulating functions of Loktak lake include water quality regulation, nitrogen cycle functioning, pollutant filtration, and maintaining water quality. By absorbing surplus nutrients from the lake, the aquatic vegetation of Phumdis has naturally purified the water and trapped sediment. Loktak Lake acts as a natural barrier, helping to manage and control floods during the rainy season by absorbing surplus rainfall. The aquatic vegetation in Loktak Lake facilitates carbon sequestration, which helps combat climate change by absorbing carbon dioxide from the atmosphere. The lake also affects local climate patterns, helping to regulate temperatures and contributing to the regional water cycle. Vigorous ecosystems help regulate various animal populations, preventing overpopulation and maintaining ecological balance.

4.5.4. Cultural Services

The cultural services provided by Loktak Lake are closely tied to the benefits derived from its ecosystem, including recreation, cognitive development, relaxation, and spiritual reflection, for the local communities. The scenic beauty of the Loktak Lake landscape attracts tourists at both the national and international levels. The unique floating islands, Phumdis, are a significant draw for visitors. Tourists enjoy boating trips on these Phumdis and participate in birdwatching from designated watchtowers. Visitors can also learn about the biodiversity richness of the region and cultural customs through guided tours of the distinctive floating islands. Several homestays have emerged on the Phumdis to promote tourism in the area. The lake presents significant opportunities for scientific research related to this unique wetland and serves as a vital source of educational information for society. The traditional livelihoods and vibrant cultural activities of the people associated with

Loktak Lake contribute to its status as a cultural heritage site. Various festivals, such as *Lai Haraoba*, celebrate the significance of the lake and the cultural identity of the local communities.

4.6. Phumdis: Scientific Reviews

Phumdis are unique and vibrant floating islands (**Figure 8**) in the serene waters of Loktak Lake in Manipur. These fascinating structures are formed from a rich blend of decaying organic material, including a diverse mix of vegetation and soil, allowing them to float gracefully atop the surface of the lake. Ecologically, Phumdis is recognized as a vital biodiversity hotspot. They host an astonishing variety of flora and fauna, ranging from delicate aquatic plants to a rich array of bird species and fish. The organic matter within these islands is crucial for carbon storage, thereby bolstering efforts to combat climate change. In addition to their role in carbon sequestration. Phumdis act as natural filtration systems, adept at purifying the waters of Loktak Lake. They can absorb excess nutrients, significantly reducing the risk of eutrophication, which can harm aquatic ecosystems. By capturing rainwater, Phumdis helps maintain the water levels of the lake and provides a protective buffer against flooding events, thereby ensuring the stability of this delicate environment.

Moreover, Phumdis are essential for ongoing research into groundwater systems, offering valuable insights into water management practices. These floating islands are not only ecological treasures but also support the traditional livelihoods of the Indigenous communities that dwell around Loktak Lake. The Phumdis are deeply intertwined with these traditions and beliefs of the local peoples, forming a vital component of their heritage. However, the existence of Phumdis is threatened by encroachment and deforestation. Scientific assessments underscore the urgent need for integrated conservation strategies that recognize the ecological significance of Phumdis, support the livelihoods of surrounding communities, and address the environmental challenges they face. The Phumdis of Loktak Lake are well observed from the watchtower and the small resthouse of the National Park (**Figure 19**).

4.7. Dynamics of Phumdis

4.7.1. Origin and Development

Phumdis is accumulated from biomass. The accumulation of biomass in the Loktak aquatic ecosystem is the principal factor resulting in Phumdis. The production of biomass is influenced by the degree of photosynthesis and the intensity of sunlight throughout the day. Biomass refers to the total weight and quantity of living organisms of all species in a particular area. Biomass accumulation is the net change in standing biomass from one time to another. The accumulation of biomass in the lake ecosystem is influenced by the structure, growth, and development of the roots of various hydrophyte communities that have developed within the lake ecosystem. Factors influencing the accumulation of biomass in Loktak Lake include the temperature of the hydrosphere (lake water) and the atmosphere

(surface air), insolation (duration and intensity), precipitation (intensity and duration), genotype, photoperiod, and nutrient availability in both floating soil and water. Accumulation, as well as the increase in biomass, enhances the capacity of the ecosystem to capture and store carbon. Ninety percent of plant biomass consists of carbon, hydrogen, and oxygen (Figure 8, Figure 20).

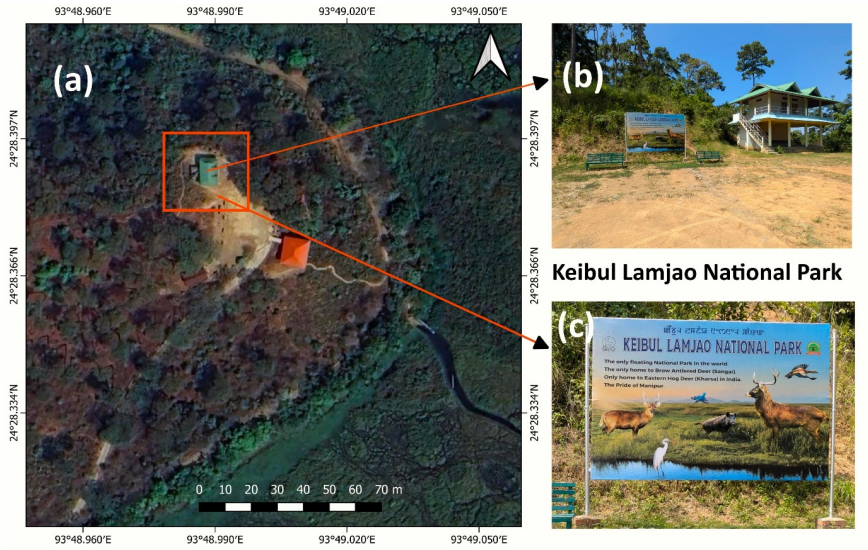

Figure 19. Map(a) shows the location of a small rest house of the forest department. The rest of the house is associated with a watch tower, from where actual Phumdis can be displayed.

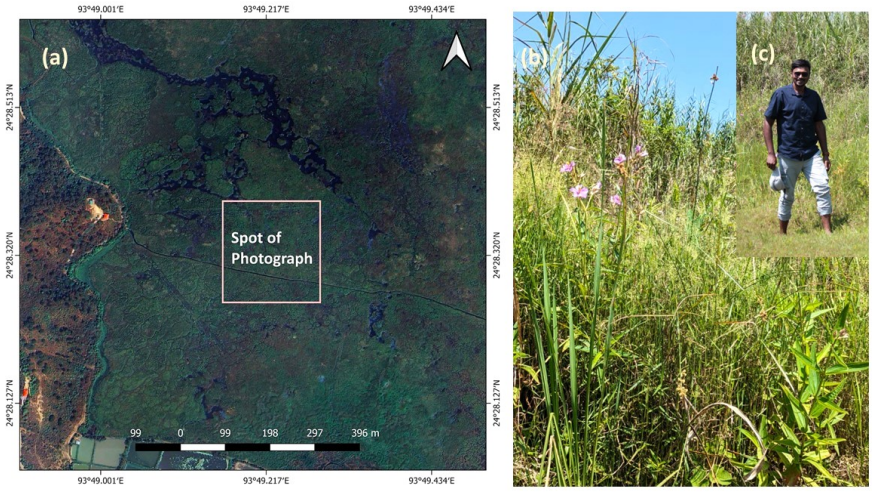

Figure 20. Photographs are taken during a field survey on a floating mat composed of biomass (Phumdis). It is 90 cm thick, floating on water. One of our survey team members is standing on Phumdis. This floating mass can carry almost 100 kg weight. The carrying capacity depends on the thickness and composition of the Phumdis. Vegetation succeeds in sustaining nearly 7 feet in height.

4.7.2. Unique Character of Float

The accumulation of lake vegetation, such as reeds and grasses, along with organic matter from the debris of dead flora and fauna species, forms Phumdis. In the

stages of succession, all organisms bind themselves together with the help of the roots of living plants into the lake ecosystem. These together form a floating mat called Phumdis. Phumdis are floating on 150-175 centimeters of water in the Loktak lake. Phumdis in the Loktak lake generally require a minimum water depth of around 1.5 meters (150 centimeters) to float and sustain. The IIT Roorkee study (2008) and reports by WISA (Wetlands International South Asia) confirm that Phumdis require approximately 1.5 meters of water depth to maintain buoyancy and proper functionality. When water levels decline to approximately 70 - 75 centimeters, there is a detrimental impact on the buoyancy and ecological equilibrium of Phumdis. During dry seasons or periods of inadequate water management, if water levels fall below 1 meter, the Phumdis commence settling at the lakebed, resulting in their decomposition and subsequent destruction (WISA, 2009). The floating ability of Phumdis depends on their size, form, and vegetation composition (**Figure 20**, **Figure 21**). The floating ability of Phumdis is influenced by its composition and density, as well as the density of the lake water beneath it. Phumdis are not anchored to the lake bed. The floatability of Phumdis allows them to migrate within the lake area, driven by wind-air-water interactions, microwaves generated by the prevailing wind in the lake water, and the laminar flow of water currents.

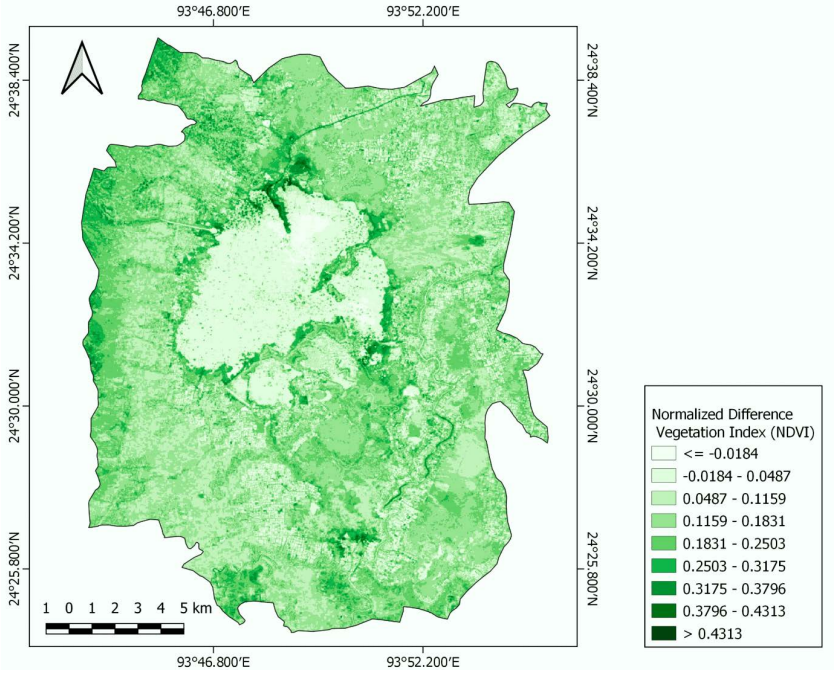

Figure 21. Normalize Difference Vegetation Index map of Loktak Lake and its surrounding area. Deep green indicates the maximum chlorophyll concentration; lighter green is the signature of water.

4.7.3. Expansion, Development, and Fragmentation

Phumdis, the floating islands in lake ecosystems, undergo a natural expansion process as new plant materials accumulate along their edges. This gradual growth

occurs as these larger Phumdis merge with smaller, neighboring ones, creating a more extensive network of vegetation. However, the integrity of these Phumdis can be compromised during periods of heavy rainfall, particularly during the monsoon season or due to western disturbances and local atmospheric depressions. The influx of excess water into the lake can generate strong currents, leading to the fragmentation of these islands (**Figure 7**). Over time, larger Phumdis can also break apart into smaller pieces, driven by strong winds that sweep across the surface of the lake, causing further disruption to this delicate ecosystem.

4.7.4. Natural Decomposition

Phumdis, floating wetland ecosystems, undergo decomposition primarily due to microbial activity, particularly from fungi and bacteria. These microorganisms play a crucial role in breaking down complex organic molecules into simpler forms. This decomposition process is vital for the nutrient cycling of the ecosystem, releasing essential nutrients such as phosphorus and nitrogen into the water. These nutrients are fundamental for the growth of various aquatic plants and organisms. The breakdown of organic matter in Phumdis fosters biodiversity and enhances nutrient cycling, both of which are critical for maintaining the health of wetland ecosystems. In well-aerated environments, microorganisms utilize oxygen to decompose organic matter, producing carbon dioxide, water, and various nutrients that enrich the ecosystem. Conversely, in low-oxygen, anaerobic conditions, specific bacteria continue this decomposition process, releasing gases such as methane, which can either become trapped within the Phumdis or escape into the atmosphere. Overall, the decomposition of organic materials in Phumdis is an integral component of the ecosystem's nutritional cycle and supports ecological balance.

4.7.5. Adaptation, Succession, and Sustainability

Reeds, grasses, and various aquatic plant species that form Phumdis have evolved to thrive in wetland environments with fluctuating nutrient availability. These plants can successfully grow in submerged and emergent conditions, allowing them to adapt to diverse environmental changes. The decomposition of organic matter within Phumdis supports a range of microbial communities, which play a crucial role in nutrient cycling. These microorganisms are specifically adapted to anaerobic conditions, facilitating the breakdown of organic matter and promoting the overall health of the ecosystem. Phumdis possess resilience against environmental alterations, including human impacts and climate variability. Despite the potential dangers of drastic changes, their ability to regenerate through vegetative growth allows them to recover from disturbances.

Initially, Phumdis may originate from the accumulation of plant debris in shallow water bodies. During the early stages of Phumdis succession, a diverse plant community emerges as organic matter and sediment gradually accumulate, creating a stable foundation for the establishment of new plant species. Secondary succession can occur in areas where Phumdis have been disturbed by natural or human activi-

ties. This process enables native species to reestablish themselves and supports environmental recovery (Mubaya et al., 2021). Additionally, seed banks within the soil can promote rapid recolonization of disturbed sites. Phumdis can evolve into more complex ecosystems supporting various wildlife as succession progresses. Over time, the structure of Phumdis and the composition of plant species change, influencing the overall biodiversity and productivity of the wetland ecosystem.

4.7.6. Biodiversity Hotspot

Phumdis, fascinating floating islands formed from organic matter, play a crucial role as vibrant habitats for a diverse array of aquatic flora and fauna. These unique structures support a thriving lake ecosystem, where various fish species dart through the crystal-clear waters and colorful birds' flit above, each contributing to the dynamic balance of life. The intricate formation of Phumdis creates a nurturing environment that fosters the growth of lush aquatic vegetation, essential for the ecosystem's overall health. This rich tapestry of plant life offers refuge and breeding grounds for migratory and resident birds. It serves as a vital food source, ensuring the survival of these avian inhabitants. Thus, Phumdis stands as a testament to the interconnections within nature, providing a sanctuary that sustains and enriches countless species.

4.7.7. Mechanism and Threshold

The prolonged periods of dryness resulting from climate extremes significantly diminish the potential for biomass accumulation. Within the intricate ecosystem of Phumdis communities, a complex network of ecological interactions unfolds between various components. For instance, herbivorous fish graze on the submerged sections of the vegetation, effectively shaping the plant community. In turn, these herbivores serve as a vital food source for carnivorous species that inhabit the same waters, creating a balanced predator-prey dynamic that sustains a thriving population within the lake's ecosystem.

4.8. Function and Mechanism of Phumdis

4.8.1. Biomass Accumulation and Carbon Sink

The accumulation of biomass is subjected to a forward carbon sink zone. Carbon sink zones are important components of the Earth's carbon cycle. Carbon sink zones play a crucial role in mitigating climate change. Carbon-sequestering capacity can be improved by protecting and restoring the Carbon sink zone. Organic matter, soil, and living plant materials accumulate at the surface of Loktak Lake, creating a carbon sink zone in the form of Phumdis. The conservation and management of Phumdis are subject to ensuring a legitimate environment to achieve sustainability.

4.8.2. Seasonal Decomposition of Organic Matter

The decomposition of organic matter in the Loktak Lake ecosystem is dependent on the season. During the dry season, the lake's water area and the depth of the lake are reduced. Seasonal grass and several species die at this time due to the

unavailability of the required water for their sustainability. Seasonal grasslands produce more organic matter in the ecosystem than forests. Seasonal grass dying during the dry period decomposed just after that, in the wet period, and produced sufficient organic matter in the ecosystem.

4.8.3. Rainfall: Occurrence, Intensity, and Duration

The vibrant ecosystem of Loktak Lake flourishes with adequate rainfall, which maintains the delicate water levels necessary for the Phumdis—floating islands of vegetation—to remain buoyant and healthy. However, when the rains are insufficient, the water recedes, causing these unique formations to settle on the lake bed. This grounding effect disrupts their natural beauty and can compromise their structural integrity, threatening the biodiversity that depends on this unique habitat. 24.1 percent of the water received from the rain seeps into the soil as groundwater (Singh, 2010).

4.8.4. Temperature in Hydrosphere and Atmosphere

The favorable climatic conditions in the Loktak Lake region, characterized by a humid environment, significantly enhance the growth and development of various living species. The high humidity levels contribute to a rich biodiversity, as the lake's moist air and regular moisture create an ideal habitat for aquatic plants and animals. This thriving ecosystem supports a diverse range of species, from various fish populations to unique flora, enabling them to flourish and adapt to this vibrant environment. The combination of warmth and humidity not only sustains these species but also plays a crucial role in maintaining the health and ecological balance of Loktak Lake. The mean annual temperature of the Loktak region ranges from 12.6˚C to 26˚C (Singh, 2010).

4.8.5. Humidity and Dryness

Humidity and dryness collectively contribute to the origin, development, mechanism, dynamic nature, and maintenance of Phumdis in Loktak Lake. Humidity and dryness are the two most important climatic factors that play a crucial role in the ecosystem of Loktak Lake. The lake is considered a vital habitat for several species. Humidity and dryness are two principal habitat factors in the Loktak Lake ecosystem. The peak southwest monsoon rain occurred in June-July in the basin with an average rainfall of 24.78cm and 24.71 cm, respectively, in June and July (Singh, 2010).

4.8.6. Growth and Decay of Aquatic Plants

Organic matter is associated with different stages of decay. This dynamic system produced buoyancy and thickness of Phumdis. Partial decomposition of plants promotes the floatability of Phumdis throughout the year. The current, movement, and flow of lake water play a significant role in the fragmentation of the Phumdis. The surface of Phumdis is associated with dense vegetation (grasses, shrubs, small trees, etc.) that helps stabilize the Phumdis by holding the structure together.

4.8.7. Endemic Species

Certain endemic plant species thrive and sustain the Phumdis ecosystem. They adopted the unique eco-hydrological condition that thrives on Phumdis. Mechanism and growth of endemic species enhance the structural integrity of Phumdis.

4.8.8. Fluctuation of Lake Water Level

The water level of Loktak Lake is deeply related to the health and status of Phumdis. Phumdis are highly sensitive to changes in seasonal water levels in Loktak Lake. During the Monsoon season, lake water levels remain high due to the availability of adequate rainwater. The high-water level in Loktak Lake provides excellent floating conditions for Phumdis (**Figure 22**). Dryness in the Loktak Lake ecosystem from November to May due to the absence of adequate rainfall grounded Phumdis almost in the lake bed. Loktak is a sub-basin of the Manipur River (Singh, 2010). Mass degradation of Phumdis happened due to a flood in 2016 (**Figures 23-25**).

4.8.9. Quality of Lake Water

Home sewage, industrial effluents, and agricultural runoff have contaminated the freshwater ecology of Loktak Lake. This pollution adversely affects aquatic life, which can also upset the food chain. Parts of the lake's water depth have decreased due to silt buildup from nearby catchment areas, impacting habitat quality and navigation. By outcompeting native flora, introducing non-native plant species has changed local water ecosystems. Weather patterns can change hydrological cycles, which can impact the quality and availability of water.

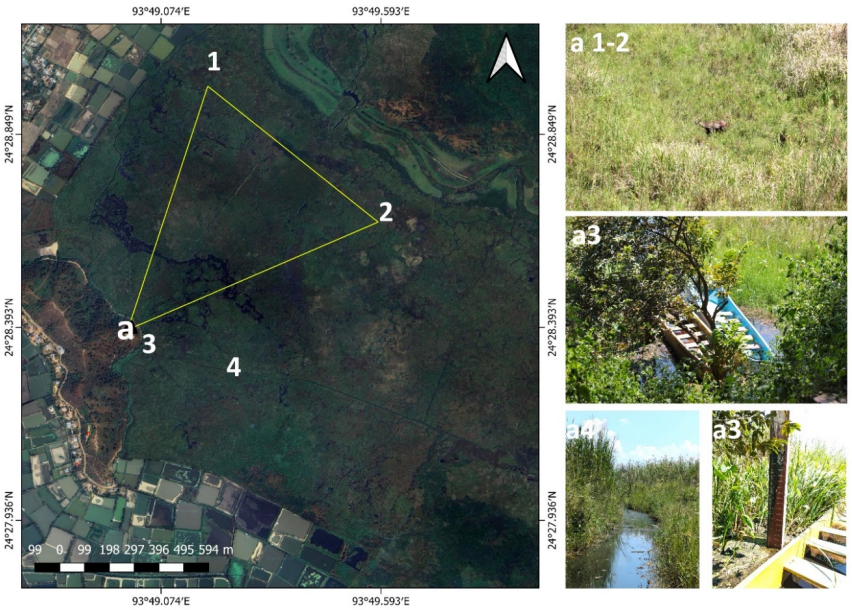

Figure 22. Phumdis is located in the northwestern part of Keibul Lamjao National Park. (a) is the watch tower where the photograph (a1-2) was taken. Triangle a-1-2 is the focus zone of the picture. In this photo, the Dancing Deer or Sangai Deer is spotted. Picture of the boat (a3, a4) indicating the place from where the survey was conducted (a3). In this picture (a3), a gauging station is spotted. That is used to measure lake water levels.

Figure 23. A devastating flood occurred at the Loktak Lake catchment area during 2016. Significant hydro-geomorphologic and ecological change has occurred due to the flood.

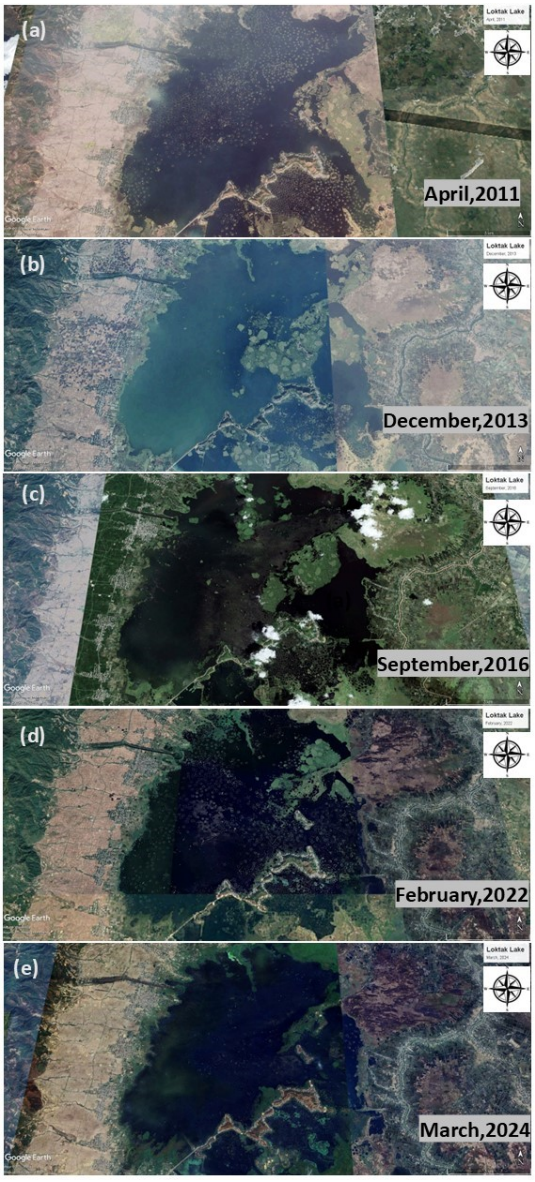

Figure 24. Loktak lake landscape during 2011-2024. Chronological maps have been collected from the Google Earth historical maps section.

This image (Figure 24) provides a time-series satellite view of Loktak Lake, illustrating changes in water coverage and surrounding land from April 2011 to March 2024 through Google Earth imagery. Each sub-image corresponds to a specific year and month. In the first image (a), April 2011, the lake appears relatively full, with darker water indicating depth. Several scattered patches of vegetation or Phumdis (floating biomass) are visible, especially along the shores. Image 2 (b), December 2013, shows extensive water coverage and a greener appearance, possibly due to seasonal effects or algal bloom. Phumdis are concentrated in certain areas, with more open water in the center. Image 3 (c), September 2016, shows denser, darker patches, suggesting increased vegetation or sediment buildup. Some cloud cover partially blocks the view, but the expansion of vegetated zones is evident. In image 4 (d), February 2022, a significant increase in floating vegetation or Phumdis has been observed, reducing open water areas. Dark patches are more widespread, indicating ongoing biomass encroachment. In image 5 (e), March 2024, water coverage remains lower than in previous years, with extensive vegetation coverage. The boundary between open water and vegetated patches is less distinct, reflecting ongoing ecological changes. The sequence highlights both seasonal and long-term shifts in Loktak Lake's hydrology and ecology, driven by natural cycles, sediment inflow, vegetation growth, and possibly human activities such as land use change, water diversion, and fishing. Over time, open water has decreased, while vegetation and Phumdis coverage have expanded, potentially affecting biodiversity, water quality, and local livelihoods. Based on the map pixels (Figure 24), we performed a detailed change detection analysis, quantifying percentage changes in water and vegetation areas for each year, which clearly illustrates these trends (Table 1).

Table 1. Detailed change detection analysis table for Loktak Lake, showing the percentage coverage of water, vegetation, and other land types for each observation year 2011-2024.

Year	Water (%)	Vegetation (%)	Others (%)
2011	22.2904	23.0593	54.6501
2013	63.2788	11.1001	25.6210
2016	13.1299	42.4246	44.4453
2022	20.0426	30.3837	49.5736
2024	44.2773	11.086	44.6539

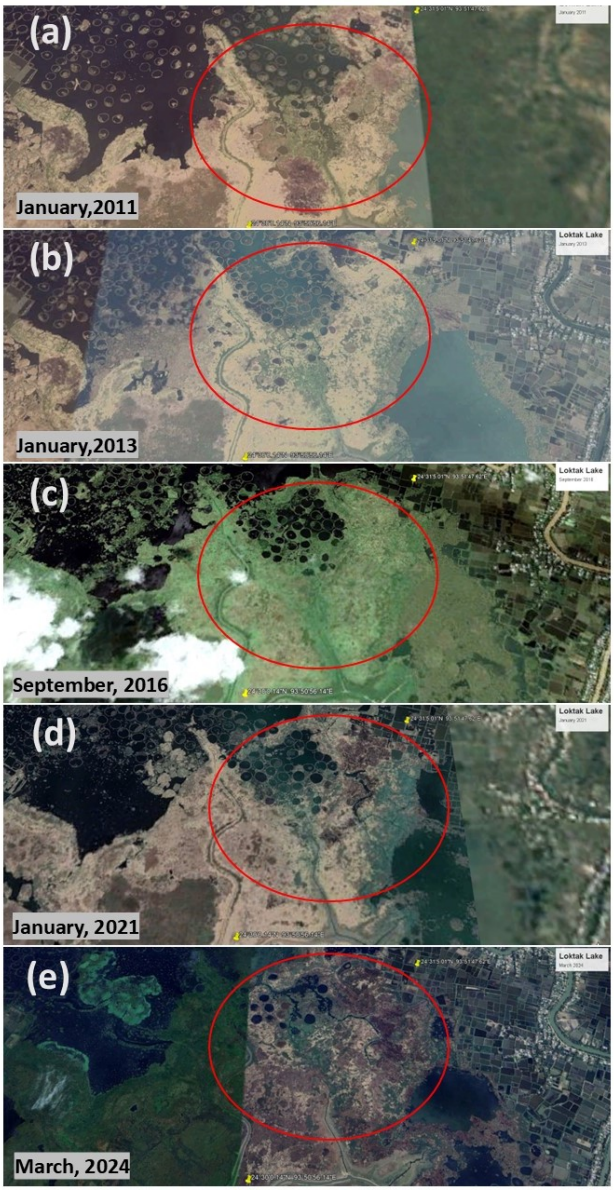

Figure 25. Dynamic change and exposure of Phumdis and surrounding area over time (2011-2024).

Figure 25 illustrates a time-series analysis of satellite imagery for a specific section of Loktak Lake, Manipur, India, focusing on the red-circled region over 13 years from January 2011 to March 2024. The images are sourced from Google Earth. In the first panel (a), January 2011, the red-circled area shows a mix of open water and numerous circular fish culture enclosures (athaphums) surrounded by floating vegetation (Phumdis). The water spread is relatively extensive compared to later years. In the second panel (b), January 2013, the number and density of circular enclosures increase, with some areas showing less open water, being replaced by vegetation or sediment. Agricultural fields to the east (right side) are clearly visible. In the third panel (c), September 2016, there is a notable expansion of greenish tones indicating increased vegetation

coverage. The circular enclosures become more distinct and concentrated, though cloud cover partially obscures the western part. Open water decreases during this period. In the fourth panel (d), January 2021, water coverage slightly improves compared to 2016, but vegetated areas remain prominent. Many circular fish enclosures still exist, though some may have shifted positions due to the movement of Phumdis. In the fifth panel (e), March 2024, the water area appears more fragmented, with vegetation dominating much of the circled zone. Several enclosures remain, but fewer are visible compared to 2011-2013. Surrounding land shows increased agricultural activity. Noticing how vegetation and Phumdis are spreading more over time, especially after 2013, it's interesting to see the reduction of open water areas in the circled region. Fish farming continues in the area, although its locations are shifting slightly. These patterns change with the seasons and years, influenced by water cycles, sediment flow, and human activities.

4.8.10. Anthropogenic Activity

Sometimes, Phumdis has been used by the local people for farming, especially vegetables. Growing crops on Phumdis affects their formation and composition. Local peoples also construct huts and use Phumdis as a base for fishing (**Figure 8**, **Figure 13**, **Figures 16-18**). What are influencing the composition, health, size, and floatability of Phumdis? Fisherman of Loktak Lake is very familiar with demarcating their fishing area into the lake ecosystem through encircling by Components of Phumdis.

4.9. Threats of Phumdis

4.9.1. Human Encroachment

As a result of the increased population, human encroachment in the Loktak catchment area become a burning concern. Catchment areas have been occupied by humans for agriculture, construction of households, and grazing grounds. Human encroachment in Phumdis is also a significant environmental concern (**Figure 7**, **Figure 8**). The construction of the Ithai barrage is another big issue in this area (**Figure 10**). All the encroachment disrupts the natural balance of the lake ecosystem and causes a loss of biological diversity.

4.9.2. Occurrence of Flood and Drought

Floods due to excessive rainfall during monsoon are common in the Loktak Lake catchment area. Floods and inundation generally occur from June to September when the water level of the Manipur River remains high (**Figure 2**, **Figure 23**). The groundwater table also reached a high point during this time. The percentage of soil moisture remains high during July and August. The saturated soil in the Loktak catchment area has a lower water-holding capacity. All these factors increase the likelihood of flooding during September.

4.9.3. Climate Change Driving Mechanism

Climate change poses a significant threat to the Phumdis ecosystem and overall

health. The Lake ecosystem is adversely affected by temperature changes, rainfall intensity, and water availability in the Loktak catchment area. The natural growth of Phumdis has been impacted by climate change over the last 200 years. The breeding pattern of fish in the Loktak Lake ecosystem has been altered due to climate change. A significant change in the character and association of Phumdis occurred between 2011 and 2024 (**Figure 24**, **Figure 25**).

4.9.4. Deforestation in the Catchment

Hills and dense to moderate forest surround Loktak Lake. Due to the increase in population and the advancement of society, deforestation has become an essential concern in the last 15 - 20 years. Rapid and unauthorized deforestation leads to excessive soil erosion in the Loktak Lake area. Deforestation leads to surface runoff, which is subjected to the loss of surface soil from topsoil. Eroded soil is associated with less nutrient availability, which does not provide a sufficient environment for the growth and development of further vegetation.

4.9.5. Water Pollution

The primary sources of water pollution in Loktak Lake are agricultural land through agricultural runoff, the discharge of domestic waste into the lake ecosystem through sewage lines, and the release of industrial waste. Those all have negative environmental impacts on the lake ecosystem. Excessive nutrients (nitrogen, phosphorus, etc.) from all the sources of pollution in Loktak Lake enhance the process of eutrophication. Eutrophication in the lake ecosystem leads to the overgrowth of algae and reduces the water level in the lake water.

4.9.6. Degradation of Land

Deforestation, soil erosion, pollution in lake water, agricultural activities, and overgrazing are the major mechanical factors causing land degradation in the Loktak catchment area. Degradation of land in the lake catchment leads to less productive soil and agricultural productivity.

4.9.7. Invasive Species

A direct negative relationship exists between introducing new invasive species and the existing flora and fauna into the lake ecosystem. Water Hyacinth (Eichhornia crassipes) has become a significant threat to the existing species in Loktak Lake since the early 20th century (**Figure 26**). It can spread rapidly and clog up large areas quickly due to its high rate of growth. This leads to insufficient penetration of light and depleting oxygen levels into the lake's depth.

4.9.8. Lake Impoundment

The maximum and minimum depths of Loktak Lake are 4.58 meters and 0.50 meters (Singh, 2010). Encircled floating biomass in the Loktak Lakeis not Phumdis (**Figure 8**). Local fishermen use biomass collected from the Phumdis area to demarcate their fishing territory in Loktak Lake to make this encircled floating fea-

ture. These are also important causes of the depletion of the Phumdis area and its health.

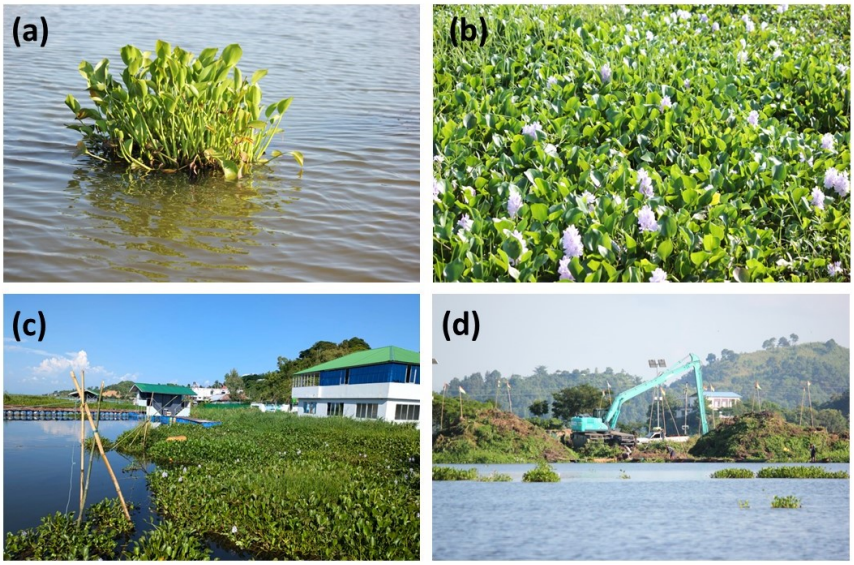

Figure 26. Human intervention in the lake hydrological system, like constructing the Ithai barrage on the lower catchment of the lake (Manipur River), creates favourable conditions for the growth and development of water hyacinths into the lake ecosystem (a, b, c). Colonization of water hyacinths has a significant effect on Lake biodiversity. Fishing was also affected by that colonization. The lake authority has continuously removed water hyacinths (d).

4.9.9. River Impoundment Through the Hydroelectricity Project

The Ithai barrage (Figure 10) has been constructed southeast of the Loktak Lake on the Manipur River to produce hydroelectricity and maintain the water level in the lake throughout the year. The construction has adversely affected the entrainment of sediment and discharge.

4.9.10. Removal of Earth Materials and Sand Mining

Unauthorized, unscientific, and unregulated sand mining and removal of bank materials from rivers related to Loktak Lake, as well as around the shores of Loktak Lake have caused significant destruction of the fragile lake ecosystem, degradation of land, damage of habitat and loss of biodiversity

4.10. Conservation, Management, and Sustainability

Loktak Lake and its associated Phumdis have excellent environmental, socio-cultural, and economic significance. Preserving Phumdis and the lake's natural ecosystem and introducing sustainable management practices in the Loktak catchment area are essential. The indigenous Sangai deer and other resources that provide a living for the locals are among the lake's unique biodiversity. However, the lake is endangered by pollution, resource depletion, wetland encroachment, and hydrological modification, mainly due to the development of Ithai Barrage. Conservation strategies for the Loktak Lake include the designation of this lake as a

protected area to control illegal hunting, restrict most economic activities such as fishing, and empower communities to undertake proactive wildlife surveillance. Conservation efforts must ensure the integrity and sustainability of these atypical floating islands by controlling their erosion, removing excessive development of Phumdis that obstructs water movement, and managing the health of Phumdis. The primary objective of environmental education is to achieve sustainable development goals for the people, by the people. Surrounding local inhabitants must be aware of the lake's ecology, its significance and potential, the ecosystem services it provides, and the harmful impacts of overutilizing resources related to the lake ecosystem. People need to know how to manage the ecosystem properly. To begin with, agricultural runoff is primarily responsible for polluting the lake waters, as it carries away artificial hazards, chemicals, fertilizers, and pesticides from adjacent farms.

Concerns about the ecological health of water bodies have grown, particularly in light of the environment's increasing pollution and degradation. Sustainable fishing methods are encouraged to address this issue (**Figure 13** and **Figure 16**). These include implementing a fishing quota system, temporarily closing fishing during the peak reproductive season, and creating designated stock enhancement zones. Programs designed for Community-based conservation and management to allow the engagement of local fishers, farmers, and indigenous people, and strengthen the framework of care for the environment. It is essential to promote green tourism when one's aim is sustainable growth, environmental conservation, and improved quality of life for people. Ecotourism, in this case, is referred to as a means to develop the economy without harming the environment around Loktak Lake, which draws people in from across the globe, but clouds knowledge about the deteriorating factors concerning the area's ecology. Encouraging Sustainable Practices for the Health of Loktak Lake and Phumdis should have been the case. Restoring the lake's surface is not only important, but also urgent. It is a key factor in enhancing flood management, improving water quality, and promoting increased biodiversity. The areas that have been altered should be restored by planting trees. A proper buffer zone must be constructed to prevent sediment from entering the lake system. The Loktak Development Authority (LDA) manages one of Manipur's signature water bodies, which is also home to diverse biosphere reserves. This agency focuses on conservation work to preserve the lake's beauty and ecological integrity. Additionally, the LDA conducts awareness programs to promote the sustainable use and conservation of resources.

Several legal instruments, including the enactment of the Wildlife Protection Act, the Wetlands Conservation Rules, and the provisions of the Ramsar Convention, ensure consistency in environmental governance for most conservation activities. This legal and regulatory framework protects endangered plants and animals, as well as their habitats, and regulates the use of wetlands to prevent their depletion and destruction for future generations. The ecological setting of Loktak Lake is susceptible to various climatic changes from its geographic position, in-

cluding irregular precipitation increases, elevated thermal conditions, and water level fluctuations. Adaptation strategies include preparing for flood or drought conditions as extremes of climate, protecting species of plants and animals adapted to changing environments, and developing flood-proof and drought-proof structures. Building and restoring ecosystems, such as wetlands and forests adjacent to Loktak Lake, can be a natural shield from the adverse impacts of climate. These shields, built by nature, help to hold excess rain, control soil loss, and support biological life.

5. Outcomes of the Research

Loktak Lake is the largest freshwater lake in Manipur, India. It has undergone a complex geological evolution, and its unique geological formation was influenced by tectonic uplift and volcanic activity. The lake forms part of an endorheic basin and is situated in a super-volcanic caldera, making its geological context critical for understanding its formation and ongoing evolution. The landscape of the Loktak catchment is characterized by rugged hills, escarpments, lacustrine and fluvial sediment sinks, and a biologically diverse ecosystem. Phumdis is a floating island composed of organic matter. Seasonal fluctuations in water levels, resulting from monsoon rains and anthropogenic interventions such as the construction of the Ithai barrage, impact the hydrology and geomorphology of the area. Phumdis biomass is considered an essential carbon sink globally. Phumdis are habitats of diverse aquatic flora and fauna. Phumdis play a significant role in nutrient cycling, water purification, and carbon sequestration. Phumdis are dynamic.

Environmental factors, such as temperature and rainfall, significantly influence the expansion and fragmentation of Phumdis. Loktak Lake supports a rich biodiversity, including the endangered Sangai deer. It provides numerous ecosystem services, including provisioning services (water, fish, and agricultural resources), regulating services (flood control, water quality management), and cultural services (recreation and spiritual connection). The ecological balance of the lake ecosystem has been interrupted by several anthropogenic threats, like pollution from agricultural runoff, deforestation, invasive species, and overfishing. The construction of the Ithai barrage and the resulting alteration of the natural water regime have had detrimental effects on the lake's ecosystem. The Loktak Development Authority (LDA) plays a crucial role in managing the lake and promoting conservation efforts through awareness programs and regulatory frameworks. Promoting ecotourism is a viable alternative livelihood that can benefit local communities economically while fostering environmental conservation.

6. Conclusions

The health and sustainability of Loktak Lake's ecosystem are closely linked to its unique geological features, the dynamic nature of the Phumdis, and the interaction between ecological and human factors. Effective management and conservation strategies rooted in community engagement and supported by robust policy

frameworks are essential to preserve this vital freshwater ecosystem for future generations.

6.1. Innovation and Path-Breaking Aspects of the Research

This Holistic Ecosystem Service Assessment, by integrating ecological data with socio-economic factors, can lead to a better understanding of ecological and economic interdependencies. The research identifies Phumdis as critical components of ecosystems and aims to enhance their role in biodiversity and community livelihoods through adaptive management strategies. This objective focuses on identifying specific local problems related to Loktak Lake and its catchment area. The research can gain a deeper understanding of the area's unique socio-cultural and environmental context by addressing localized issues, leading to more tailored and effective interventions. Studying how local communities depend on the lake ecosystem helps us understand the link between environmental health and community well-being, leading to policies that support ecological sustainability and economic resilience. The research introduces a feedback mechanism to inform future policy-making by assessing the impact and progress of current governmental policies. It suggests a community-based management system that prioritizes local knowledge and participation, leading to more effective and culturally appropriate management practices. The emphasis on long-term policy-making allows for flexibility and adaptability in ecosystem management, addressing future challenges posed by climate change and socio-economic shifts. The interdisciplinary approach fosters a more comprehensive understanding of Loktak Lake's complexities, encouraging stakeholder collaboration.

6.2. Relevance of the Study for Policy-Making

The study assesses the impact of current policies on Loktak Lake, identifying both its strengths and weaknesses in governance. This information is crucial for informing stakeholders, such as policymakers and local communities, about the effectiveness of current management strategies. By pinpointing significant problems related to the lake, the study provides a focused approach to environmental challenges, facilitating targeted interventions and resource allocation to the areas that need it most. Additionally, the study suggests community-based ecosystem management models to emphasize the importance of local participation in policy development. Policymakers can utilize these recommendations to develop inclusive policies that empower communities and ensure their active involvement in resource management.

Furthermore, the study proposes models for long-term policy-making, contributing to a proactive approach to environmental management. This is especially important in addressing emerging challenges such as climate change and encouraging adaptive management practices. The study encourages collaborative policy-making involving various stakeholders, including government agencies, local communities, and NGOs, by highlighting the intersection of ecological, economic, and

social factors. This approach promotes a holistic approach to environmental management. Lastly, the study assesses Loktak Lake's ecosystem services, providing policymakers with valuable information on the lake's natural capital. This enables decisions that consider not only economic factors but also environmental sustainability.

6.3. Relevance of the Study for Society

The community-based ecosystem management system proposal emphasizes the importance of local knowledge and involvement in ensuring culturally suitable solutions that are more likely to be accepted by local communities. The study aims to evaluate the ecosystem services provided by Loktak Lake, which are essential for understanding its ecological functions and contributions to biodiversity, water quality, and habitat provision, underscoring their significance in regional ecological well-being. By examining the lake's significance to local communities, the research delves into the socio-cultural aspects, emphasizing the interconnectedness between the environment and the livelihoods of nearby populations, which can raise awareness about the potential impacts of environmental degradation on local communities.

Comprehending the relationship between the lake ecosystem and the economy can guide economic policies that promote sustainable livelihoods. The findings can illustrate how ecosystem health directly influences economic opportunities, such as fisheries, tourism, and agriculture. Understanding the formation and dynamics of Phumdis can inform adaptive management practices, enabling policymakers to develop flexible and responsive strategies for ecosystem changes and enhancing resilience against challenges such as climate change. The study focuses on sustainable development, aligning with global agendas such as the SDGs. Policymakers can utilize the findings to prioritize ecological integrity while fostering economic growth.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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