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Geo-Spatial Tools for Science-Based Management of Inland Aquatic Habitats and Conservation of Fish Genetic Resources

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Inland fisheries resources are vital for the human community and contribute to the development of a particular region. However, inland water bodies are highly dynamic, surrounded by terrestrial ecosystems, and face multiple threats from various anthropogenic stressors. Hence, the conservation and management of aquatic resources are becoming formidable which require the use of geo-spatial technologies for evidence-based scientific management of their habitats and fish genetic resources. The applications of geo-spatial tools are well acknowledged in data-scarce regions and in the field of natural resource management where the decision can be made based on the outputs arising from limited scientific assumptions. The remote sensing (RS) and Geographical Information System (GIS) based habitat characterization of inland water bodies, *viz.,* inventory, monitoring of water spread and quality, habitat risk and suitability mapping, habitat prediction, and connectivity assessment is getting momentum in recent times, and incorporation of field exploration data with landscape information derived from geo-spatial tools enhance our understanding on aquatic habitats. The applications of geo-spatial models enhanced the potential of ecosystem service quantification and conservation planning in inland aquatic habitats. The demonstration of RS and GIS applications at a larger landform scale in inland open water bodies is necessary to illustrate its potential for science-based management of inland aquatic habitats for the conservation of fish genetic resources.

Introduction

Inland fisheries resources are vital for the human community as they not only act as food source and livelihood options but also contribute to the development of the entire region. The dependence of the human community on these resources has gradually increased due to growing demand from exploding populations around the world (Lynch *et al.,* 2016). The mismatch between the demand and supply from the natural inland water bodies led to the over-exploitation of its fishery resources. The inland water bodies are highly dynamic, surrounded by terrestrial ecosystems, and broadly classified into a lotic and lentic system based on the nature of the flow. Hence, the conservation and management of aquatic genetic resources are becoming formidable as they face multiple threats from various anthropogenic sources. The combined effect of these factors leads to the extirpation of certain fish species from a particular range of their distribution or even extinction.

The traditional habitat survey involves the inventory of resources, collection, recording, and analysis of multiple parameters at selected locations to understand the overall ecosystem status and health. Integration and compilation of such datasets are mandatory for the extraction of information related to the spatio-temporal trend in habitat conditions and its association with other biological components. Further, visualising the scientific evidence at a spatial scale will help in convincing the policymakers for making the effective decision regarding fish genetic resource management.

The geo-spatial technologies play an important role in ecology, biodiversity, and conservation studies at large spatial and/or long-term temporal scales. Remote Sensing (RS) is the process of detecting and monitoring the physical features of an area at a distance and the Geographic Information System (GIS) is a computer system that analyses and visualises information that is attached to a particular location (https://www.usgs.gov). GIS effectively addresses problems that are inherent to a spatial analysis by effectively collating, archiving, displaying, and modelling spatio-temporal data. These tools are essential for inventory and mapping of the biological resources and monitoring the ecosystem components and health due to their simplicity and ability to answer user-defined queries (Ingole *et al.,* 2015). The applications of geo-spatial tools are well acknowledged

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in data-scarce regions where the decision can be made based on the outputs arising from limited scientific assumptions (Anand *et al.,* 2020). The limited data on habitat, fish diversity and distribution information from field surveys and published literature linked with open source landform data such as Digital Elevation Model (DEM) are helpful for characterisation of an aquatic ecosystem from a regional to global scale.

The availability of open-source remote sensing imageries accelerated the applications of geo-spatial tools in environmental management studies and led to a better understanding of the structure and functions of natural resources (Chaminé *et al*., 2021). With the introduction of high spatio-temporal resolution datasets, the contiguous monitoring of the aquatic ecosystem is possible at various scales. This facilitated the evidence-based scientific management of the ecosystem for its conservation and sustainable utilisation. This paper reviews the potential applications of RS and GIS in the context of habitat characterization of inland aquatic systems for the conservation and management of fish genetic resources.

Habitat Inventory and Monitoring of Water Spread

The inland water bodies are known for their complex geographical settings, varying sizes, and high level of interaction with surrounding terrestrial ecosystems compared to their marine counterparts. Hence, the use of geospatial technologies is necessary for the identification of remotely located inland water bodies (Ingole *et al.,* 2015). Additionally, due to the availability of high spatial resolution imageries, the resource inventory and mapping of small-sized pools and water bodies with an extent <5 ha is achievable (Anand *et al.,* 2020). Surface water monitoring is possible due to the repetitive mapping of these waterbodies at selected time intervals which is also important to understand the ecological and hydrological processes in any water body. Understanding the water spread dynamics in lotic water through RS and GIS helps in identifying the permanent water bodies which act as refugia for fish genetic resources, especially during the non-monsoon months (Kantharajan *et al.,* 2022). The Sentinel-2 imagery (10 m resolution) based water map of Godavari and Pranhita River confluence generated using the 'Normalized Difference Water Index' is shown in Fig. 1. The RS and GIS-based monitoring of the anthropogenic degradation of lentic and lotic water bodies provides meaningful insight for the development of regional or national environmental management plans.

Monitoring of Habitat Quality

The habitat quality of inland waterbodies, *viz.,* wetlands, lakes, and rivers depend on multiple factors which include geographical, hydrological, and socio-economic development (Joshi *et al.,* 2022). For instance, the downstream habitat quality of the riverine ecosystem is linked to its upstream catchments. Further, the degraded habitat conditions at one segment along the river affect the flow of benefits to the downstream. Identification of such strategic locations through manual monitoring is cumbersome and involves engagement of lot of manpower and money. Further, the source identification of such degradation process requires a thorough understanding of the interaction between topography, land use, flow hydrology, and socio-economic settings of the region. The mapping of vegetation in open water bodies through spectral indices is essential to quantify the extent of spread and initiate appropriate measures. Likewise, qualitative assessment of siltation mapped through spectral index, *i.e.,* Normalised Difference Turbidity Index (NDTI) helps in prioritising sub-watershed for land-use management. The NDTI based qualitative assessment performed to assess the temporal variation in turbidity before and after lockdown associated with COVID-19 in river Ganga revealed a drastic reduction post lockdown (Garg *et al.,* 2020).

Mapping of deep pools based on consistent water presence

Deep pools are the unique habitats in the riverine ecosystem which are abode to fish species round the year and act as essential habitats for feeding and breeding activities. Traditionally, these habitats are identified with the help of information obtained from local fishermen and by conducting intensive habitat exploratory surveys. However, through RS and GIS techniques the area which holds water for the selected time period can be mapped through 'Water Presence Frequency' (WPF) approach (Kantharajan *et al.*, 2022).

The monthly water map of a selected eco-region is generated for twelve months using 'Normalized Difference Water Index' which are overlaid to delineate 'deep pools' with 100% WPF. These deep pools are expected to hold water throughout the year and can be monitored efficiently to ensure their habitat provision services to fish genetic resources.

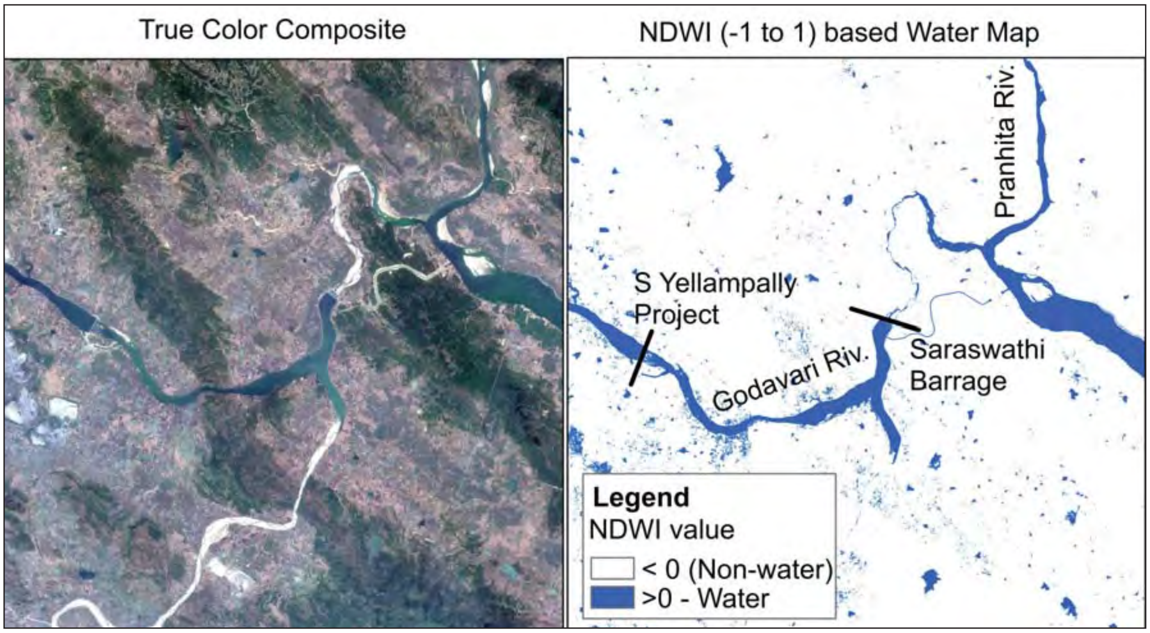

Fig. 1. Sentinel-based NDWI map depicting the water pixels along the Godavari-Pranhita River confluence at Kaleshwaram, Telangana

Further, the RS and GIS tools are also useful in evaluating the impact of invasive species on habitat degradation and the progress of restoration activities for improving the water quality. For instance, Choudhary *et al.* (2021) mapped the deteriorated habitat quality for bird species in Keoladeo National Park, India, a Ramsar Wetland, due to the land cover changes and spread of an invasive plant, *Prosopis juliflora* in the wetland.

Mapping of Habitat Risk

The inland water bodies are threatened by multiple anthropogenic stressors which affect their ecosystem structure and functioning. The quantification of risk arising from such stressors is essential for prioritising areas for restoration by considering their spatio-temporal exposure, intensity, and consequences (Sharp *et al.,* 2020). The RS-based data-driven geo-spatial models are in use for the risk assessment of such habitats by considering various aspects, *viz.,* water flow obstruction, land-use pattern, inflow from agriculture landscape, developmental activities, destruction of riparian vegetation cover, the spread of non-native invasive species, and the extent of fishing.

Mapping of Habitat Suitability

Fish species require optimum environmental conditions for their survival and growth thus, they choose habitats with stable environmental conditions and confine their distribution to that particular geographical range. Though these factors which govern the suitability of habitats are often considered complex, it broadly covers topography, hydrology, water quality, and riparian features. Apart from this, the co-occurrence of niche species and non-native species also determines the habitat suitability for fish species. Thus, habitat suitability of any open water body including rivers can be mapped spatially considering the optimum physico-chemical habitat parameters required for fish species. Based on the suitability ranking and scores, the selected waterbody can be classified into different zones which enable easy monitoring and management. Further, the simulations of a particular parameter foresee the habitat supporting ability of the aquatic ecosystem in accordance with climate change and ongoing habitat degradation. Further, the species-specific environmental preference datasets coupled with geo-spatial models lead to mapping the specific habitat suitability map.

Vyas *et al.* (2013) performed the physical habitat assessment of river Denwa in Narmada Basin, India and developed a Habitat Suitability Map based on assigned scores to demonstrate its suitability to sustain aquatic biota. The habitat suitability of Pengba fish (*Osteobrama belangeri*) in Loktak lake, India, was evaluated for water quality parameters through geo-spatial models (Khwairakpam *et al.,* 2020).

Spatial Habitat Prediction and Assessment

The fish diversity and abundance data collected through exploratory surveys and field sampling from selected locations reveal partial information on fish distribution patterns at the landscape level. However, bringing this information into GIS platform along with other associated habitat data, *viz.,* topography, climate, flow hydrology, and other environmental factors is helpful in predicting the expected distribution range of the fish species through modelling tools. This is essential for the management of threatened or endangered fish species which are on the verge of extinction to bring back their populations to their original state.

On the other hand, the habitat prediction framework of Meixler and Bain (2012) classifies the river habitat based on stream size, stream quality in terms of land-use pattern, and optimum range of selected water quality parameters which are required for the survival of fish species and accordingly classify the rivers into different categories. Further, the fish species reported in the particular geographical area were classified based on stream size, stream quality, and water quality preferences and tolerance so that to predict the fish diversity in a classified river segment. The validated habitat prediction map generated through this framework revealed the potential of such framework in categorising fish habitat classes and predicting fish distributions at the landscape scale to facilitate better-informed management decisions.

Mapping Spatial Habitat Connectivity

Maintaining the connectivity between and within the inland water bodies is essential to preserve the fish diversity and to ensure the sustainable livelihood of the associated community in the eco-region (Kantharajan *et al.,* 2022). For instance, the water level, nutrient dynamics, and fish diversity of a wetland along the riparian corridor depend on its associated riverine ecosystem to which it is connected (Joshi *et al.,* 2022). Failure to protect this habitat connectivity, as well as the inability of fishes to move freely in them, may have a significant impact on fish populations, which will eventually disturb the socio-economics of dependent local communities.

Fish species, such as Hilsa, migrate from coastal regions to the river streams to complete their life cycle. Apart from this, there are numerous local migratory fish species, *viz.,* Mahseers and Catfishes which migrate from one stream to another stream for several purposes, and especially for breeding and feeding. The free-swimming larvae originating from spawning habitats must reach productive nurseries to maximize survival. The spatial mapping of fragmentation, and connectivity assessment between habitat patches aid in the development of possible migration maps for fish species conservation.

The spatial data on landscape variables play an important role in 'Landscape Genetics', to derive meaningful conclusions by integrating with the population genetics of a fauna (Storfer *et al.,* 2008). This explores the possible influence of habitat fragmentations on the gene flow of a particular organism, intra- and inter-specific speciation and genetic diversity.

Mapping Ecosystem Services

The concept of ES is essential for justifying the arguments regarding the conservation and restoration of any natural ecosystem. The inland open waterbodies provide multiple ES, grouped under provisioning, supporting, regulation and cultural services. The GIS-enabled models are widely used for ES quantification and help the resource managers to visualise the spatio-temporal pattern and estimate the impact of projected LULC change, climatic conditions, and extent of management measures on the provision of services (Sharp *et al.,* 2020).

The geo-spatial model-based study conducted in the lake Hawassa watershed in Ethiopia revealed that the sediment export to the lake was mainly contributed by the cultivable lands while vegetation cover in the watershed retains sediment thus, maintaining the water quality in the lake (Degife *et al.,* 2021). The sediment retention potential of riparian vegetation shall be converted into monetary value to fix a 'payment for ecosystem services' to encourage farmers to carry out Best Management Practices in their cultivable lands.

Conservation and Restoration Planning

The purpose of designating 'Protected Areas (PAs)' is to conserve representative species, and habitats of importance from threat factors to ensure their persistence (Margules and Pressey, 2000). This process should be performed holistically coupled with habitat and anthropogenic factors. For instance, prioritisation of wetlands for implementing management measures requires integration of geospatial data from various sources including hydrology, topography, diversity and abundance of flora and fauna, surface water coverage, farming period, existing management factors and level of protection and anthropogenic stressors. Spatial datasets on these factors can be overlaid on the GIS platform for prioritisation and the weightage of each factor can be decided based on its importance as per the policymaker's opinion and expert consultation. Further, RS and GIS offer scope for monitoring and evaluating the progress of conservation targets set for a particular species/habitat and track how these actions progress over time.

Another important role for GIS in fisheries resource management is involving the public in decision-making. Participatory GIS (P-GIS) aims to involve the public to generate and convert cognitive spatial knowledge into cartographic and descriptive information for spatially informed management decisions (Herlihy and Knapp, 2003). For instance, the capture of local and traditional knowledge on fish migration path, and behaviour and ecosystem services through P-GIS help in designating conservation measures.

Conclusion

The geographical setting and increased dependence of the human community on freshwater resources make them highly vulnerable and also disturb the equilibrium. Hence, spatial knowledge on their habitat characteristics, inherited biodiversity, and associated risk factors are immensely required for their conservation and management. The geo-spatial tools help in the analysis and visualisation of datasets which are essential for evidence-based resource management. Incorporation of field exploration data with landscape information derived from remotely sensed imageries in the GIS platform enhances our understanding of aquatic habitats. Further, the demonstration of RS and GIS at a larger landform scale is necessary to illustrate its potential for science-based management of inland aquatic habitats for the conservation of fish genetic resources.

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