ASSESSMENT OF TROPHIC STRUCTURE ON SARDAR SAROVAR RESERVOIR ALONG MAHARASTRA

Dissertation submitted in partial fulfillment

of the requirements

for the degree of

M.F.Sc. (Fisheries Resource Management)

By

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DEDICATED

To

My guide, parents, family, all my teachers and friends who have helped me in achieving this milestone!

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(A University Established Under Sec. 3 of UGC Act 1956)
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Govt. of India.

Dated: 27th Sept. 2024

CERTIFICATE

Certified that the dissertation entitled **"ASSESSMENT OF TROPHIC STRUCTURE ON SARDAR SAROVAR RESERVOIR ALONG MAHARASTRA"** is a bonafide record of independent research work carried out by **Mr. Debashis Mohanta** during the period of study from December 2023 to September 2024 under our supervision and guidance for the degree of **Master of Fisheries Science (Fisheries Resource Management)** and that the dissertation has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or any other similar title.

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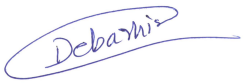
I hereby declare that the dissertation entitled **"ASSESSMENT OF TROPHIC STRUCTURE ON SARDAR SAROVAR RESERVOIR ALONG MAHARASTRA"**is an authentic record of the work done by me and that no part thereof has been presented for the award of any degree, diploma, associateship, fellowship or any other similar title.



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सारांश

यह अध्ययन सरदार सरोवर जलाशय पर केंद्रित है, जो एक महत्वपूर्ण मीठे पानी का पारिस्थितिकी तंत्र है। इसमें Ecopath मॉडल का उपयोग करके इसकी पोषण संबंधी पारस्परिक क्रियाओं, ऊर्जा प्रवाह, और पारिस्थितिकी तंत्र की गतिशीलता की जांच की गई है। खाद्य जाल में भारतीय प्रमुख कार्प, विदेशी कार्प, छोटे कार्प, ज़ोप्लवकटन, फाइटोप्लवकटन और डिट्रिटस शामिल हैं, जो प्रतिस्पर्धा और पोषक तत्वों के चक्रण का एक जटिल नेटवर्क बनाते हैं। भारतीय प्रमुख कार्प संसाधन प्रतिस्पर्धा के कारण विदेशी कार्प और ज़ोप्लवकटन पर नकारात्मक दबाव डालते हैं, लेकिन डिट्रिटस को बढ़ाकर पोषक तत्वों के चक्रण में सकारात्मक योगदान करते हैं। विदेशी कार्प, जो आक्रामक प्रवृत्ति के लिए जाने जाते हैं, ज़ोप्लवकटन और मांसाहारी मछलियों जैसी देशी प्रजातियों पर नकारात्मक प्रभाव डालते हैं। छोटे कार्प पोषक तत्वों के पुनरुत्पादन के माध्यम से प्राथमिक उत्पादन को बढ़ाते हैं, जबकि सर्वाहारी मछलियाँ पोषक तत्वों के चक्रण के माध्यम से फाइटोप्लवकटन की वृद्धि में योगदान करती हैं। मांसाहारी मछलियाँ, जो शीर्ष शिकारी हैं, शिकार प्रजातियों को नियंत्रित करती हैं और अप्रत्यक्ष रूप से निचले पोषण स्तरों का समर्थन करती हैं। ऊर्जा प्रवाह विश्लेषण से सर्वाहारी मछलियों, ज़ोप्लवकटन और मांसाहारी मछलियों के लिए उच्च इकोट्रोफिक दक्षता (EE) का पता चलता है, जो शिकार और मछली पकड़ने के दबाव से प्रेरित है। फाइटोप्लवकटन और डिट्रिटस खाद्य जाल का आधार बनाते हैं, जबकि प्राथमिक उपभोक्ता पारिस्थितिकी तंत्र को बनाए रखने में प्रमुख भूमिका निभाते हैं। प्रणाली की स्थानांतरण दक्षता (TE) 37.65% है, जो उच्च पोषण स्तरों पर ऊर्जा हानि को दर्शाते हुए अन्य जलीय पारिस्थितिक तंत्रों के अनुरूप है। 11,400 T km^2 y^{-1} की शुद्ध प्राथमिक उत्पादन और 4.32 के TPP/TR अनुपात के साथ, जलाशय का स्वचालित प्रकृति की पुष्टि की जाती है। शैनन विविधता सूचकांक 1.88 के साथ मध्यम जैव विविधता और स्थिरता परिलक्षित होती है, जबकि कनेक्टेंस और सर्वाहारिता सूचकांक एक संतुलित खाद्य जाल संरचना का संकेत देते हैं। जलाशय की मत्स्यपालन 164.216 T km^2 y^{-1} उत्पादन करती है, जिसमें 80.84 T km^2 y^{-1} का लाभ होता है, जो सतत मछली आबादी बनाए रखने के आर्थिक महत्व को उजागर करता है। रिमोट सेंसिंग विश्लेषण से उपग्रह-व्युत्पन्न और इन-सिटू जल तापमान डेटा के बीच मजबूत सहसंबंध दिखाई देता है, लेकिन ऑक्सीजन रेडॉक्स क्षमता, पीएच, और घुले हुए ऑक्सीजन जैसे जटिल मापदंडों के लिए सटीकता कम है। क्लोरोफिल-ए के लिए मध्यम सहसंबंध देखा गया, जिसमें सेंसर की सीमाओं और जल की मटमैलीपन के कारण चुनौतियाँ हैं। बड़े जलाशयों में जल गुणवत्ता की निगरानी को बढ़ाने के लिए उपग्रह डेटा को इन-सिटू मापों के साथ एकीकृत करने की सिफारिश की गई है।

ABSTRACT

This study focuses on the Sardar Sarovar Reservoir, a key freshwater ecosystem, examining its trophic interactions, energy flow, and ecosystem dynamics using the Ecopath model. The food web consists of Indian Major Carps, Exotic Carps, Minor Carps, zooplankton, phytoplankton, and detritus, forming a complex network of competition and nutrient cycling. Indian Major Carps exert negative pressure on Exotic Carps and zooplankton due to competition but contribute positively to nutrient cycling by increasing detritus. Exotic Carps, with invasive tendencies, negatively impact native species like zooplankton and carnivorous fish. Minor Carps enhance primary productivity through nutrient regeneration, while omnivorous fish promote phytoplankton growth via nutrient cycling. Carnivorous fish, as apex predators, regulate prey species and indirectly support lower trophic levels.Energy flow analysis shows high ecotrophic efficiency (EE) for omnivorous fish, zooplankton, and carnivorous fish, driven by predation and fishing pressures. Phytoplankton and detritus form the food web's base, with primary consumers playing key roles. The system's transfer efficiency (TE) of 37.65% aligns with other aquatic ecosystems, reflecting energy losses at higher trophic levels. With a net primary production of 11,400 T km^2 y^{-1} and a TPP/TR ratio of 4.32, the reservoir is confirmed as autotrophic. Moderate biodiversity and stability are reflected in a Shannon diversity index of 1.88, while connectance and omnivory indices suggest a balanced food web.The reservoir's fisheries yield 164.216 T km^2 y^{-1}, with profits of 80.84 T km^2 y^{-1}, highlighting economic importance. Remote sensing analysis shows strong correlations between satellite-derived and in-situ water temperature data, but lower accuracy for parameters like oxygen redox potential, pH, and dissolved oxygen. Moderate correlation is observed for chlorophyll-a, with challenges due to sensor limitations. Integrating satellite data with in-situ measurements is recommended for improved water quality assessments.

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1.INTRODUCTION

India's fisheries sector is known as a "sunrise sector" that is expanding swiftly, providing direct livelihoods to more than 16 million fishermen and contributing 1.03% to the national GDP. In the past few decades, inland fisheries have emerged as a substantial contributor to fish production, with their contribution increasing from 36% in the mid-1980s to approximately 70% today (DoF, 2023). The country's inland fisheries resources are extensive, spanning 201,496 kilometers and consisting of 3.52 million hectares of both small and large reservoirs, 1.2 million hectares of floodplains, and an extensive riverine network that includes tributaries and irrigation channels. The National Fisheries Policy (2020) estimates that the total inland fisheries area, excluding rivers and canals, is 8.24 million hectares. Reservoirs, which are frequently referred to as "sleeping giants" because of their fish production potential, provide varying levels of productivity depending on their size. Small reservoirs can produce approximately 500 kg/ha/year with the implementation of suitable management practices, medium reservoirs approximately 200 kg/ha/year, and large reservoirs approximately 100 kg/ha/year (Sugunan, 2015). Nevertheless, Indian reservoirs generally exhibit lower productivity in comparison to neighboring countries such as China, where fish production can reach as high as 1,200 kg/ha/year (FBMA, 2006). This discrepancy emphasizes the necessity of more effective management strategies to completely leverage the fish production capacity of Indian reservoirs.

The dynamic interactions of numerous processes within the ecosystem, such as production, consumption, decomposition, and transformation, influence aquatic productivity. The robustness of the photosynthetic (grazing) food chain and the detritus-based (heterotrophic) food chain further influences the overall functioning of aquatic ecosystems. The ultimate productivity of the ecosystem is determined by the interaction between abiotic elements and biotic factors at different trophic levels. In order to gain a comprehensive understanding of the trophic structure of these ecosystems, it is imperative to monitor the passage of energy through the food chain (Vass, 1992). The trophic interactions in a reservoir ecosystem involve the complex relationships among primary producers, consumers, and predators. The analysis of these interactions aids in the mapping out of the structure of the food web and the identification of key species that impact ecosystem production. A deeper

comprehension of these dynamics is necessary not just to improve fishery management but also to assess the general well-being of the aquatic ecosystem. The health and productivity of aquatic ecosystems are governed by a complex interplay between water quality and the trophic structureof the ecosystem. To effectively manage aquatic ecosystems and maintain ecological balance, it is essential to comprehend the intricate link between these elements.

Understanding complex interactions between reservoir communities and their effects on energy flow and community structure is essential for the effective management of reservoir systems (Vanni *et al.,* 2005). Fish play pivotal roles as drivers of food webs in reservoirs, occupying diverse trophic niches and facilitating the circulation of matter and energy from basal resources to the upper levels of the web. Studies on fish and ecosystem trophic structures are vital for establishing conservation strategies for aquatic ecosystems and conducting integrated assessments of their resources (Fauvelle *et al.,* 2017).

Ecosystem modeling has emerged as a crucial tool for ecological system assessment and reservoir management in the recent past. These models offer important insights into the composition and functioning of ecosystems and are crucial for understanding complex ecological dynamics. By simulating a range of biological processes, ecosystem modeling helps researchers and managers assess the health of ecosystems, forecast the effects of environmental changes, and direct decision-making for sustainable resource management. Because it can include a broad range of ecological data, such as species interactions, energy transfers, nutrient cycling, and habitat dependencies, ecosystem modeling is significant. With the help of this technique, important factors and stressors that affect ecosystem services and biodiversity can be identified, leading to a more thorough comprehension of the ecosystem. When evaluating how human activities, such as agriculture, fishing, and industrial development, affect ecosystems, ecosystem models are essential. They are also critical to the research of possible management actions, such as the creation of conservation plans, protected areas, and habitat restoration. Although it was first developed to examine aquatic systems, ecosystem modeling has now been used to terrestrial ecosystems (Dalsgaard *et al.,* 1995). Through the study of trophic relationships and energy flows, these models provide important insights into the resilience of ecosystems, biodiversity, and food webs. Understanding how

ecosystems respond to outside stresses like pollution, climate change, and habitat fragmentation requires this kind of analysis. By using such applications, ecosystem modeling can determine which species or processes within an ecosystem have the most influence, which is critical for maintaining ecological balance (Christensen, 1995).

Monitoring the water quality of extensive reservoirs is essential for maintaining the sustainability of aquatic ecosystems and the efficient management of water resources. The Sardar Sarovar Reservoir, situated on the Narmada River, functions as an essential resource for agriculture, potable water, hydroelectric energy, and fisheries. Preserving water quality is crucial for sustaining these processes and ensuring the reservoir's overall ecological health. Historically, water quality monitoring has depended on in-situ observations, entailing direct sampling and analysis of water at designated places. Monitoring of the water quality is an essential component of reservoir management, in addition to the ecological studies that is normally performed. It is vital to have reliable data on water quality measures in order to evaluate the state of the reservoir ecosystem (Karunakaran *et al.,* 2015). Some examples of these metrics include turbidity, dissolved oxygen, and nutrient levels for example. For a long time, the most common approach of gathering such information has been to conduct observations of the water quality in the field. Historically, water quality monitoring has depended on in-situ observations, entailing direct sampling and analysis of water at designated places. Although in-situ approaches are highly precise, they can be time-consuming, labor-intensive, and restricted in spatial and temporal scope. However, recent developments in remote sensing technology have opened up new opportunities for the monitoring of water bodies on a wide scale and in a continuous manner (Dekker *et al.,* 1990). The reliability of remote sensing in capturing key water quality indicators can be evaluated by confirming remote sensing observations with in-situ measurements. This allows for the evaluation and validation of the reliability of remote sensing. Furthermore, this validation is of utmost significance for the Sardar Sarovar Reservoir, which requires continual and extensive monitoring in order to be effectively managed.

Keeping in view, The lack of thorough research combining trophic structure analysis with remote sensing data validation regarding the Sardar Sarovar Reservoir, together with possible shortcomings in comprehending the ecological consequences

of trophic dynamics and water quality fluctuations on the reservoir's ecosystem health and functionality, this study is proposed with this objectives:

1. To study the trophic interactions in the Sardar Sarovar Reservoir

2. To validate the reliability of remote sensing observations on the water quality with the in-situ observations from Sardar Sarovar Reservoir

2.REVIEW OF LITERATURE

2.1. Ichthyofaunal diversity in reservoirs

The fish populations in reservoirs are influenced by both natural and human-induced changes, and their diversity is closely tied to the fish species from the parent rivers. The creation of a reservoir leads to modifications in fish composition, driven by changes in water flow, turbidity, fishing pressures, loss of breeding habitats, and shifts in diet. This can result in some species becoming vulnerable, leading to their decline or migration, while new species may emerge to fill the ecological gaps, forming a new trophic structure. Fish diversity in reservoirs remains strongly linked to the species of the parent river systems. According to Sarkar *et al.* (2015), Indian reservoirs host 117 fish species, with 96.5% being food fish contributing to nutritional security. In the Indo-Gangetic basin, 30 dominant species have been identified, while larger reservoirs can support up to 60 species, of which 40 are commercially significant (Jhingran, 1990, 1991).

The key reservoir fish species in India include mahseers (*Tor putitora*, *T. mosal*, *T. tor*, *Neolissochilus hexagonolepis*), snow trout (*Schizothorax plagiostomus*), Indian major carps (*Labeo catla*, *L. rohita*, *Cirrhinus mrigala*), and other carps such as *L. calbasu*, *L. dero*, *L. gonius*, *L. bata*, *L. boga*, *Puntius sarana*, and *Chagunius chagunio*. Major catfish species include *Wallago attu*, *Silonia silondia*, *Bagarius bagarius*, *Pangasius pangasius*, *Rita rita*, *Sperata aor*, and *S. seenghala*, while smaller catfish species consist of *Clupisoma garua*, *Eutroplichthys vacha*, *Mystus cavasius*, *M. tengara*, and *Ompok bimaculatus* (Sugunan, 1995). Common fish species found in reservoirs include catfish, featherbacks, air-breathing fishes, murrels, and minnows. However, over 300 exotic fish species have been introduced into India, some of which have invaded the Ganga basin, posing threats to reservoir and wetland ecosystems. Although exotic species can boost fish production and support local livelihoods, they often displace native species and disrupt ecosystems. For example, in Sathanur Reservoir in Tamil Nadu, *Catla catla* accounts for 80-90% of the total catch, leading to the decline of the indigenous species *Labeo fimbriatus*, once dominant in the 1960s. Similarly, the introduction of silver carp in Gobindsagar, common carp in Krishnarajasagar, and Tilapia in Amaravathy has resulted in the dominance of non-native species. The introduction of common carp in Girma and

Krishnasagar reservoirs has led to the decline of native species such as *Cirrhinus cirrhosus*, *C. reba*, and *C. mrigala*. The African catfish (*Clarias gariepinus*) has also been reported in Kelavarapalli Reservoir, Tamil Nadu, and Karapuzha Reservoir, Kerala (ICAR-CIFRI, 2016).

Nevertheless, some native species, such as *Salmostoma phulo* and *Osteobrama vigorsil*, continue to thrive in reservoirs like Nagarjunasagar and Tungabhadra (Sugunan, 1995). In Nagarjunasagar, the catadromous catfish *Pangasius pangasius* has become a resident population, contributing significantly to the commercial catch. Reservoirs also serve as sanctuaries for species like *Barilius bola* in Tilaiya (Damodar), *Mystus krishnensis*, *Osteobrama vigorsii*, and *Pseudeutropius taakree* in Nagarjunasagar (Krishna), *Thynnichthys sandkhol* in Nizamsagar (Godavari), *Tor khudree* and *T. sussala* in Shivajisagar (Krishna), and *Aorichthys seenghala* and *Tor putitora* in Pong (Beas) and Vallabhsagar (Tapti). As a result, introducing exotic carp species in reservoirs is discouraged due to the potential negative effects on native fish communities and ecosystem balance.

Naik *et al*. (2013) reported that the fish diversity in Karanja Reservoir was dominated by cyprinids, while introduced catfish negatively impacted indigenous fish species. Bera *et al*. (2014) recorded high fish diversity (26 species) in Kangsabati Reservoir and found that temperature played a significant role in affecting fish diversity. Rongsenkumzuk *et al*. (2019) studied the biodiversity of Doyang Reservoir, Nagaland, and found 64 fish species inhabiting the reservoir. They observed that the introduction of Indian major carp reduced endemic fish populations, with the upper stretch of the reservoir having a higher concentration of endemic species than the lower stretch near the dam. Bedajit *et al.* (2013) reported 45 fish species in the Thoubal River, with 23 species found near the Maphou Dam, although the study was conducted before the dam's commissioning.

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2.2. Mass balance ecosystem modelling approach in reservoir's ecosystem

The mass-balanced Ecopath model has seen extensive global application in studying trophic interactions and ecosystem dynamics within aquatic systems, contributing to ecosystem-based management approaches (Jarre-Teichmann, 1998; Christensen *et al.,* 2000; Walters, 2011; Coll and Libralato, 2012) Its development began in 1984, in the Northern and Central Atlantic Ocean. Initially, the modelling focused on the trophic functioning of tropical marine ecosystems. However, over the last two decades (1994-2014), its utility has been extended to polar regions and terrestrial ecosystems. A quantitative analysis shows that 80% of the models are concentrated in tropical ecosystems, with the remaining 20% representing temperate systems. Fisheries-related models have significantly increased from 10% in 1984-1993 to 30% in 1994-2003. Ecopath with Ecosim models are now considered as the promising tools for fisheries management because they provide a clear snapshot of the entire ecosystem. In peninsular India, there is a growing trend of using mass balance ecosystem modelling approaches to examine the effects of exotic fish in reservoir ecosystems. The first study to assessed the effect of invasive species in a reservoir ecosystem using ecosystem modelling was conducted by Khan and Panikkar (2009) in Kelavarapalli reservoir, Tamil Nadu. This study revealed both direct and indirect effects of predation among ecosystem components, with Nile tilapia and pearl spot competing heavily for similar food sources. Khan *et al.* (2015) later used a mixed trophic impact routine of ecosystem modelling in Hemavathy reservoir Karnataka and found that the presence of exotic carp had a positive impact on gobies but negatively impacted the major carp. Another mass balance modelling study was conducted in Karapuzha reservoir, Kerala, which revealed that *Orechromis mossambicus* had no negative effect on other species in the reservoir, while *Clarias gariepinus* did. Similar results were obtained in Wyra reservoir, Telangana, where *O. mossambicus* had a neutral effect on coexisting fish fauna, but showed a slightly positive impact on India major carp. Dutta *et al.* (2017) conducted an assessment of the ecosystem structure and trophic dynamics of the Sunderban estuary in India and found it to be detritus- dependent, highly exploited, and highly efficient. Behera *et al.* (2020) similarly evaluated the Chilka lagoon ecosystem and identified Elopiformes as the top predator and zooplankton as the most utilized group in a developing but stable

ecosystem. Panikkar and Khan (2008) used ecosystem modelling to assess the impact of management measures aimed at conserving fish stocks in tropical reservoirs of India and found that the Wyra reservoir was more resilient in the pre-band phase than in the post-band phase. Villanueva *et al.* (2006) investigated the grazing food web structure of the Bagre reservoir and determined that detritus had less importance in the ecosystem. Conversely, the Ria Formosa reservoir in southern Portugal has a detritus-based food chain.

2.3. Water quality Parameters

Water is the unique component of nature the liquid of life and plays an important role in the life of all living processes from molecules to man. The quality of water is described by its physical, chemical and biological characteristics. It is essential for agriculture, industry and human existence. The healthy aquatic ecosystem is depended on the physico-chemical and biological characteristics (Venkatesharaju *et al.,* 2010). Significant amount of information can be obtained from the quality of water of an ecosystem about its available resources for supporting life in that ecosystem. Thirupathaiah *et al.* (2012) stated that assessment of physico-chemical parameters and biological characteristics can identify certain condition for the ecology of living organisms and suggest appropriate conservation and management strategies. Many researchers have done studies on physico- chemical parameter on reservoirs, dams and tank water (Hulyal and Kaliwal 2008; Manjare *et al.,* 2010a; Lubal *et al.* 2012: Makode 2012; Thirupathaiah *et al.,* 2012; Janeshwar *et al.,* 2013) to name a few.

2.3.1 Temperature

Water temperature plays an important part in influencing the productivity of an ecosystem. Prasad (1956) stated that temperature affects the chemical and biological processes of an ecosystem. Makode (2012) observed that during summer, water temperature was high due to low water level, high temperature and clear atmosphere. Water temperature plays an important factor which influences the chemical, biochemical and biological characteristics of water body (Salve and Hiware, 2008). Kar (2007) reported that temperature of water influences water chemistry e.g. dissolved oxygen, pH, conductivity etc.

2.3.2 pH

The factors like air temperature bring about changes in the pH of water and most of bio- chemical and chemical reactions are influenced by the pH (Makode, 2012). Kamble et al. (2009) reported that the reduced rate of photosynthetic activities reduces the assimilation of carbon dioxide and bicarbonates which are ultimately responsible for increase in pH, the low oxygen values coincided with high temperature during the summer month. Karanth (1987) and Tiwari *et al.* (2009) observed higher pH values which suggests that carbon dioxide, carbonate- bicarbonate equilibrium is affected more due to change in physico-chemical condition.

2.3.3 Dissolved Oxygen

Oxygen whether as free oxygen (O) or as dissolved (DO) is needed for respiration for most aquatic organisms. It is one of the important factors in water, as many metabolic processes of aquatic organisms are regulated by it. The oxygen content in water samples depends on a number of physical, chemical, biological and microbiological processes. DO values also show lateral, spatial and seasonal changes depending on industrial, human and thermal activity. DO levels below 1 ppm will not support fish; levels of 5 to 6 ppm are usually required for most of the fish population (Venkatesharaju *et al.,* 2010). The average value of DO levels (6.5mg 1^{1}) indicates the average quality of river water (APHA, 2005). Hutchinson (1957) has remarked that a series of oxygen determinations along with knowledge of turbidity and colour of water could provide more information about the nature of water than any other chemical data. Sugnnan (1995) stated that in small reservoir, oxygen is derived from photosynthesis and while in large reservoir, oxygen is derived from both photosynthesis as well as significant wave action.

2.3.4 Chlorophyll-a

The health of a particular water body can be assessed by using phytoplankton as an indicator organism. Chlorophyll is essential to the existence of phytoplankton. Chlorophyll-a content (chl-a) can be used as the standard measure for phytoplankton biomass and the trophic state of a water body (Schiemer *et al.,* 2000; Schiemer 2008).

Silva (2001) mentioned about the water quality of some selected oxbow lakes of southwestern Bangladesh with special emphasis on chlorophyll-a.

2.3.5 Oxidation-reduction potential

Oxidation-reduction potential (ORP) is a critical parameter in aquatic chemistry, reflecting the redox state of an environment and influencing various biological and chemical processes. ORP measures the tendency of a solution to gain or lose electrons, thus indicating its oxidizing or reducing nature. In aquatic systems, ORP is pivotal for understanding nutrient cycling, pollutant degradation, and the overall health of ecosystems. Elevated ORP values generally indicate oxidative conditions, which can enhance the breakdown of organic matter and pollutants, while low ORP values suggest reducing conditions, potentially leading to the accumulation of toxic substances such as hydrogen sulfide (H2S) (Wetzel, 2001). ORP is also crucial in assessing the impact of anthropogenic activities, such as wastewater discharge, on aquatic environments (Reddy *et al.,* 2008). Accurate monitoring of ORP using advanced multiparameter meters has become essential for effective water quality management and ecological research.

2.4. Remote sensing

Remote sensing technique offers a number of important advantages over the subjective view of the human. It provides a synoptic view of the earth's features. With the development of modern satellite systems and improvements in image transmission and ground receiving station technology, remote sensing imagery can now be obtained rapidly and repeatedly over large areas. Satellite remote sensing can serve as a fast and relatively cost-effective tool for early and expeditious assessment of the spatial and temporal variability of lake water quality conditions (Zilioli and Brivio, 1997).

It is also a very cost effective tool for rapid and effective assessment of large area of the earth's features. Imageries are not very expensive and in some cases they are even freely available. These imageries are helpful to monitor fisheries habitats, rivers, reservoirs and wetlands. Many researchers assessed water quality parameters using the optical remote sensing since 1970s. Ritchie *et al.* (1974) developed an early empirical approach to estimate the suspended sediments. Various

workers reported that remote sensing is a powerful tool which could be applied to regional water quality monitoring and assessment (Ritchie and Charles, 1988; Schalles *et al.,* 1998; Chopra *et al.* 2001; Dekker *et al.,* 2002; Gupta *et al.,* 2003).

Studies have demonstrated stable/significant reliable relationships between water quality parameters, such as total phosphorus, total nitrogen, dissolved oxygen, pH, salinity, secchi depth, sodium, potassium, and radiance data from the satellites (Dewidar and Khedr 2001; Alparslan *et al.,* 2007). The econometric tool of regression technique has strong potential for the application of Remote Sensing (RS) data in monitoring water quality of inland waters in estuaries (Choubey, 1997). Several authors found correlations between remotely sensed data and turbidity, although they are unique for a specific water body (Fraser, 1998). In one study Gupta *et al.,* (2003) found primary production and remote sensing data have good corelation. This advantage has been widely exploited to monitor and map shallow coastal waters also (Bierwirth *et al.,* 1993).

Karunakaran *et al.* (2015) assessed water quality parameters and chlorophyll concentration in the water bodies of Purulia and Bankura districts of West Bengal, Jhansi district of Utter Pradesh, Mandya and Hassan districts of Cauvery basin in Karnataka both during pre-monsoon and post-monsoon period. They conclude that IRS P6 LISS III band Near Infrared (0.77- 0.86 µm) is useful to assess the water quality parameters like depth, specific conductivity and turbidity. Similarly, short wave infrared band (1.55-1.70 µm) is useful for assessing chlorophyll-a after the images are atmospherically corrected. Their models are region specific and they have the potential for monitoring water qualities of large water bodies in regular interval by use of Liss-III images. Using the landscape matrices, water quality parameters like specific conductivity and salinity can also be assessed.

Satellite remote sensing using Landsat satellite series has been explored in several studies as an economic measure in terms of reducing the expenditure and effort of sampling water in the field (Cheng and Lei, 2001; Olmanson *et al.,* 2002, 2008; Mishra and Garg, 2011; Jally *et al*., 2016). Landsat has been used successfully in aquatic studies for the remote sensing of Secchi Disk Transparency (SDT), Trophic State Index (TSI) and suspended sediments (Allee and Johnson, 1999; Tebbs *et al.,*

2013). Sheela *et al*. (2011) has succeeded in estimating Trophic state index of a lake system using IRS(P6-LISS III) satellite imagery.

Patra *et al.* (2016) estimated Chlorophyll-a Concentration and Trophic States for an Inland Lake from Landsat & OLI from Nalban Lake of East Kolkata wetland. This empirical study showed that Landsat 8 OLI imagery can be effectively applied to estimate Chl-a levels and trophic states for inland lakes. Jally *et al.* (2016) successfully developed site specific algorithm for estimation of Trop Index from Landsat-8 OLI data lata and and Secchi disk transparency collected from Chilka Lake synchronous to satellite pass. The analysis has shown that the lake water is in eutrophic condition from the year 2013 to 2015.

Kabiri and Moradi (2016) examined the advantages of incorporating the new band of Landsat-8OLI imagery (band): Coastal/Aerosol, 435-451nm) to a model for estimation of Secchi disk depth (SDD) values in near-shore coastal waters of Chahahar Bay in the southern part of Iran. Mushtaq *et al.* (2022) derived Trophic State Index for freshwater Himalayan Lake (TSIFHL) from Landsat & OLI to determine the aquatic health of the lake ecosystem.

3. MATERIAL AND METHODS

3.1. Study area

The Narmada is a large west-flowing Indian peninsular river with a 1333 km long mainstream channel covering a catchment area of 92,672 km^2. The basin is predominantly characterized by agricultural land (57%) with forest cover comprising 33%. Its climate is characterized as humid and tropical (Gupta *et al*., 2021), with nearly 90% of its annual rainfall occurring during the monsoon months from June to October. The monsoon contributes significantly, ranging from 70% to 92%, to the water discharge in the Narmada basin (Gupta & Chakrapani, 2005).Originating near Amarkantak at approximately 1050 m above Mean Sea Level in the Maikaley highlands, the river traverses westward through the rugged terrain and highlands of Madhya Pradesh before descending into the plains of Gujarat, ultimately merging with the Gulf of Cambay along the West coast. The comprehensive development of the entire Narmada basin is underway through a river valley project program, facilitated by a network of dams (Bhaumik *et al.,* 2017).

The Narmada basin is home to five mega-dams and numerous large dams. Within the basin, plans for irrigation and hydroelectric power generation include 30 major, 135 medium, and 3000 minor projects. The Sardar Sarovar Dam stands as the largest among them, followed by the Indira Sagar and Bargi dams along the main channel. The Sardar Sarovar Reservoir, which spans a total water spread area of 37,000 hectares, includes a significant portion of 6,000 hectares within Maharashtra. The project affects several regions, specifically the talukas of Akkalkua and Dhadgaon in the Nandurbar district. In Maharashtra alone, 33 villages have been impacted by the project, with a total submerged length of 117 km, of which 73 km falls within the state. The fisheries in this area are supported by 26 registered Fishermen's Cooperative Societies, located in villages such as Manibeli (Tal. Akkalkua), Chimalkhedi (Tal. Akkalkua), Chichkhedi (Tal. Akrani), Shelgada (Tal. Akrani), and Khardi (Tal. Akrani). These societies collectively represent 1,099 registered fishermen. This data has been sourced from the Fisheries Department of Nadurbar, Maharashtra.

Sampling was conducted during January 2024 to August 2024. Fiften sampling locations were selected to study the variations in the physico-chemical parameters and fish composition of the reservoir. Following are the list of sampling satation of Sardar sarovar reservoir along with their cordiantes:

Table 1: Location of sampling sation of Sardar sarovar reservoir.

	Sampling Site	Latitude (DMS)	Longitude (DMS)
1.	Danel	21°52'20.71"N	73°56'57.92"E
2.	Gaman	21°51'19.54"N	73°55'11.20"E
3.	Chimalkhadi	21°51'0.60"N	73°54'17.84"E
4.	Bhamani	21°51'49.76"N	73°56'8.88"E
5.	Mukhadi	21°52'39.64"N	73°58'3.05"E
6.	Pimpalchop	21°54'42.78"N	74°2'41.46"E
7.	Thuwani	21°56'5.95"N	74°6'17.62"E
8.	Bharad	21°56'29.38"N	74°7'42.02"E
9.	Shikka	21°56'47.73"N	74°8'3.67"E
10.	Chitkhedi	21°54'43.31"N	74°9'57.05"E
11.	Bhusha	21°55'31.58"N	74°17'50.00"E
12.	Warwali	21°57'49.42"N	74°17'58.06"E
13.	Sadri	21°58'47.11"N	74°21'21.20"E
14.	Bhadal-1	22°1'12.08"N	74°23'26.13"E
15.	Bhadal-2	22°1'43.11"N	74°25'54.66"E

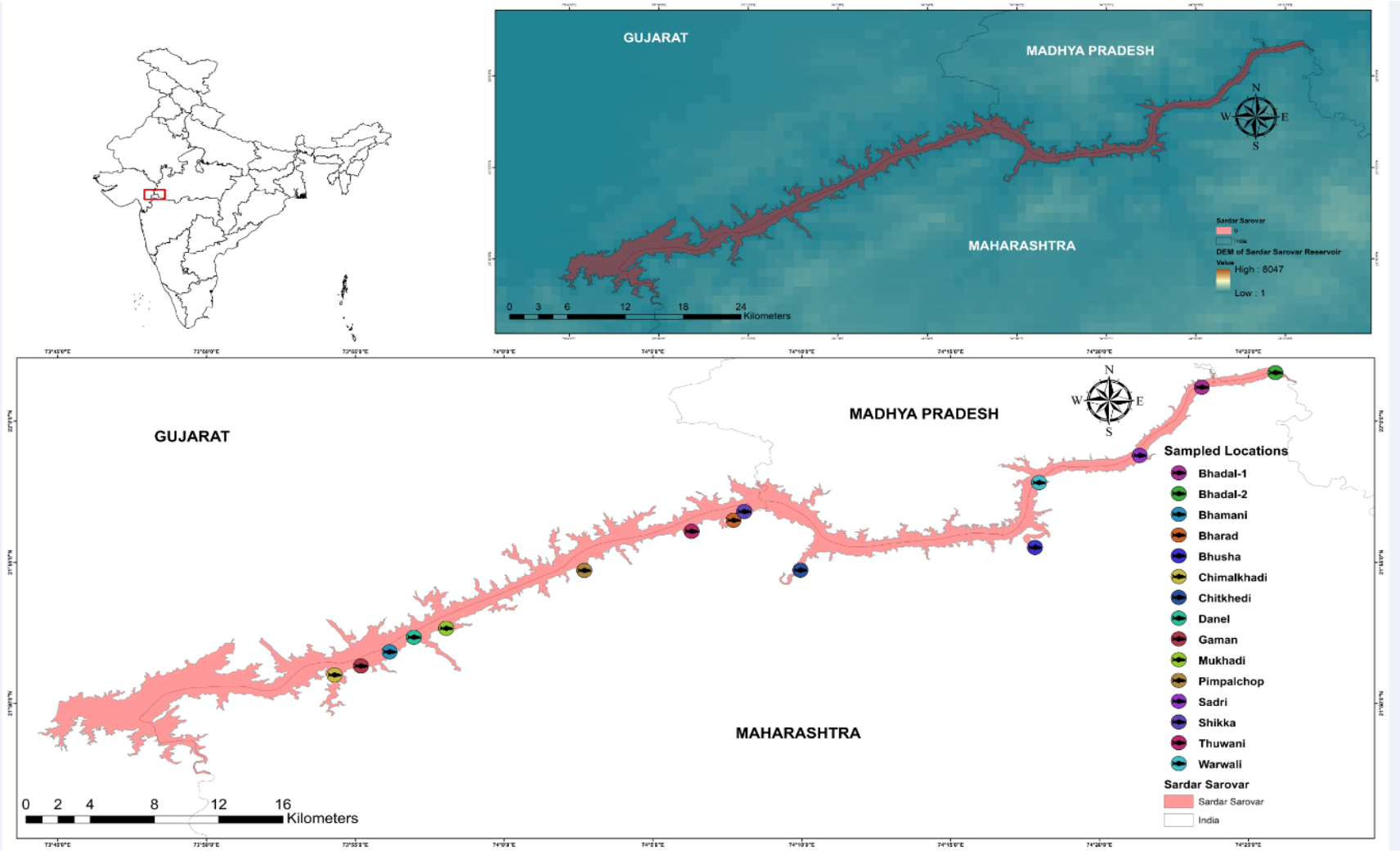


Fig 1. Map showing sampling points and location of the study area.

3.2 Trophic structure and Ecosystem Modelling

The ecosystem model of the Sardar sarovar reservoir was develop using Ecopath with Ecosim software (EwE) (version 6.6.5.17207) which illustrated the flow of the energy amongst the different functional groups and their interactions, and to identify the ecological properties and key biological components governing the Sardar sarovar reservoir ecosystem. The model represents all the ecosystem major components and feeding interactions and readily lend themselves to answering the ecosystem wide questions about the ecosystem dynamics and response to anthropogenic changes. Therefore, the model will be an important tool to proposed suitable strategies for effective sustainable management of the reservoir. The ecopath parametizes model based on two master equations. The first equation described how the production term for each group' can be split onto components. Such as

Production=Catch+Predation mortality+Biomass accumulation +Net migration and other mortality.

Consumption= Production+Respiration+Unassimilated food

$$B_i.\ (P/B)_i.EE_i - \Sigma^{n}_{j=1} B_j\ (Q/B)_j.DC\text{-}Ex_{ji} - EX_i = 0$$

Where B, is the Biomass of group, "(P/B), is the production/Biomass.

3.2.1 Fish sampling

Experimental fishing was done in the four sampling sites using gill net of different mesh size 25 mm, 30 mm, 80 mm and 120 mm. Fishes were also caught and brought to laboratory for further analysis. Fishes were identified by referring the original description papers and standard manuals (Geetakumari and Basudha, 2012, Talwar and Jhingran, 1991).

3.2.2 Functional Groups

Functional groups were classified based on the feeding habits Khan and Panikkar, (2007) and grouping of heterogeneous group is also acceptable (Godinot and Allian, 2000). Thirty fish species were grouped into 7 groups i.e., Indian Major

carp (IMC), Exotic carps, Carnivorous fishes. Omnivorous fishes, Herbivorous fishes, Minor carps and *Corica soborna* were kept separately being dominant biomass fish.

1) Indian Major carp (*Labeo catla, Labeo rohita, Cirrhinus mrigala*)
2) Exotic Carps (*Hypophthalmichthys molitrix, Ctenopharyngodon idella*)
3) Minor Carps (*Labeo calbasu, Cirrhinus reba*)
4) Corica soborna (*Corica soborna*)
5) Herbivorous (*Salmostoma bacaila, Amblypharyngodon mola, Cabdio morar, Barilius barila, Barilius bendelisis, Puntius sophore, Tor tor*)
6) Omnivorous (*Xenetodon cancila, Osteobrama cotio cotio, Aplocheilus panchax, Chanda nama, Parambassis ranga, Glossogobius giuris, Macrognathus pancalus, Systomus sarana*)
7) Carnivorous (*Ompok bimaculatus, Mystus cavasius, Sperata aor, Sperata seenghala, Wallago attu, Eutropiichthys vacha, Notopterus notopterus*)
8) Zooplankton
9) Phytoplankton
10) Detritus

3.2.3 Fish Biomass estimation

Fish catch data during January 2024 to August 2024 were collected from the local fisherman and fisheries department nadurbar maharashtra . Most of the fishes were caught with gill net . The fish biomass was estimated using the equation given by Ryder (1965) and Haputhantri *et al.* (2008)

$$\text{Annual Biomass (ton/km)} = \frac{\text{Annual Yield}}{\text{Fishing Mortality}}$$

Fishing mortality values were taken from other literatures (Ahmed *et al.,* 2003; Abdolmaleki, 2004; Mustafa and Graaf, 2008; Palamnishwami *et al.,* 2011).

3.2.4 Zooplankton Biomass estimation

According to the method outlined by McCauley (1984); Abdul and Adekoya, (2016). The biomass of zooplankton was estimated by using species- specific correlations between the length and dry weight of individual species (Kumar *et al.,* 2022).

3.2.5 Phytoplankton Biomass estimation

Phytoplankton biomass were estimated based on the Chl-a (Gebre- Mariam and Desta, 2002). The Chl-a (2.05 mg m^3) and euphotic depth in meter (2.36 m) were used and the mean biomass was calculated using the conversion factor of 0.3 mg chl-a per 100 mg phytoplankton (Zhang and He, 1991; Lui, *et al.,* 2007; (Xu *et al.,* 2011).

3.2.6 Detritus Biomass Estimation

By utilizing the correlation proposed by Christensen and Pauly (1993), the biomass of detritus was estimated based on primary production and euphotic depth.

$$\text{LogD}=0.954\ \text{logPP} + 0.863\ \text{logE}-2.41$$

where, D is the standing stock of detritus in gCm^2, PP represents primary productivity (annual average GPP) and E stands for average depth of reservoir in meter.

3.2.7 Diet Composition matrix

Diet compositions are the basic essential input parameters required to determine of the trophic level (Pauly *et al.,* 2000). The fraction of one ecological group by another is expressed as a fraction of the total diet. Diet compositon matrix were prepared referring other models of Gomito and Erzini, (2005); Lui *et al.,* (2007); Behra *et al.,* (2020), Khatun, (2020) and Prajna, (2020); and Fishbase. Diet composition of Phytoplankton and zooplankton were taken from Dutta *et al.,* (2017) and Mensah *et al.,* (2019) respectively.

Table 2 . Diet matrix of functional groups of Sardar sarovar reservoir.

	Prey \ predator	1	2	3	4	5	6	7	8
1.	Indian Major Carps	0	0	0	0	0	0	0.0556	0
2.	Exotic Carps	0	0	0	0	0	0	0.0556	0
3.	Minor Carps	0	0	0	0	0	0	0.0556	0
4.	*Corica soborna*	0	0	0	0	0	0.125	0.111	0
5.	Herbivorous	0	0	0	0.132	0	0.25	0.167	0
6.	Omnivorous	0	0.05	0.05	0.268	0	0	0.278	0
7.	Carnivorous	0	0.1	0.1	0	0	0.125	0	0
8.	Zooplankton	0.353	0.4	0.25	0.277	0.2	0.25	0.222	0
9.	Phytoplankton	0.412	0.3	0.4	0.185	0.2	0.125	0.0556	0
10.	Detritus	0.235	0.15	0.2	0.138	0.6	0.125	0	0.9
	Import	0	0	0	0	0	0	0	0.1
	Sum	1	1	1	1	1	1	1	1
	(1 - Sum)	0	0	0	0	0	0	0	0

3.2.8 Production/biomass ratios (P/B) estimation

All the inputs parameters were taken up from other literatures with little modification to balance the model. Liu *et al.,* (2007); Khan and Panikkar, (2007); Panikkar, (2008); Khan and Panikkar, (2009); Panikkar *et al.,* (2014); Regi *et al*., (2020).

3.2.9 Model Balancing and Uncertainties

The value of EE should lesser than 1 and P/Q value lies within the 0.05-0.3 for all the functional groups. So, modification of input parameters can be done to balance the model (Christensen *et al.,* 2005) and a minor modification in diet matrix is also acceptable (Chea *et al.,* 2016).

3.3 Estimation of environmental parameters

Water samples were obtained from the selected sampling location along with data on latitude and longitude. The parameters such as temperature, pH, oxidation-reduction potential and dissolve oxygen were measured onboard by Multiparameter water quality meter. For the estimation of Chlorophyll-a, water samples were collected in 1L polyethylene bottles, transported in individual sample boxes to the laboratory and stored at 4°C and further analyses was done in the laboratory according to standard protocol (APHA, 2005). For each parameter triplicates were used to reduce the error.

3.3.1 Temperature

The measurement of water temperature was conducted using a Multiparameter Water Quality Meter. This device was calibrated according to the manufacturer's guidelines prior to use. The probe was submerged at various depths in the water to record temperature data, ensuring consistent contact with the water column. The temperature readings were taken at different locations within the study area to account for spatial variations. Data were recorded in real-time and stored for subsequent analysis. Multiparameter meters are known for their precision in environmental monitoring, providing reliable temperature measurements essential for understanding water quality dynamics (Smith *et al.,* 2020).

3.3.2 pH

The measurement of pH was performed using a Multiparameter Water Quality Meter with a calibrated pH probe. Before use, the meter was calibrated with standard buffer solutions (pH 4, 7, and 10) to ensure accuracy. The probe was submerged in the water at designated sampling points, allowing for equilibrium before recording the pH value. Measurements were taken at various depths to capture vertical variations in pH levels. The data were logged for further analysis. Multiparameter meters are widely utilized for their precision and efficiency in field studies, providing reliable pH measurements critical for water quality assessments (Jones *et al.,* 2019).

3.3.3 Dissolved oxygen

Dissolved oxygen (DO) levels were measured using a Multiparameter Water Quality Meter equipped with a DO probe. Prior to field deployment, the meter was calibrated according to the manufacturer's instructions using air-saturated water for optimal accuracy. The DO probe was submerged at various depths in the water column at each sampling location, allowing the sensor to stabilize before recording the measurements. Readings were taken at multiple points to assess spatial variability. Multiparameter meters are well-suited for providing accurate and real-time measurements of dissolved oxygen, which is critical for assessing aquatic ecosystem health (Brown et al., 2021).

3.3.4 Oxidation-reduction potential

Oxidation-reduction potential (ORP) was measured using a Multiparameter Water Quality Meter with an ORP electrode. The meter was calibrated according to the manufacturer's guidelines, using standard ORP calibration solutions. The electrode was immersed in the water sample, allowing it to stabilize before recording the ORP values. Measurements were taken at various depths and locations to account for potential variations. Multiparameter meters are highly effective for providing accurate and consistent ORP readings, which are crucial for assessing redox conditions in aquatic environments (Johnson *et al.,* 2022).

3.3.5 Chlorophyll-a estimation

Chl-a was extracted using acetone extraction method (APHA, 2005) Spectrophotometer was used for taking the absorbance reading at 664 nm and 750 nm before acidification and at 665 nm and 750 nm after acidification. Chl-a was calculated using the formula,

$$Ca = [11.85(OD * 664nm) - 1.54(OD * 647nm) - 0.08(OD * 630nm)]$$

$$\text{Chl-a } (\mu g\ L^{1}) = [(Ca*v)/V*L)]$$

Where,

OD = optical density

nm = nano meter

v = amount of aceton (ml)

V = volume of water filtered (L)

L= cuvette length (mm)

Table 3: Water quality parameter and analytical methods used for the water qualithy estimation.

S. No.	Water Parameters	Abbreviations	Analytical method	Instruments/Methods	Unit
1	Water Temperature	WT	Instrumental	Multiparameter Water Quality Meter	°C
2	pH	pH	Instrumental	Multiparameter Water Quality Meter	pH Unit
3	Dissolved Oxygen	DO	Instrumental	Multiparameter Water Quality Meter	mg/l
4	Chlorophyll-a	Chl-a	Spectrophotometry	UV-Vis Spectrophotometer	mg/l
5	Oxidation-reduction potential	ORP	Instrumental	Multiparameter Water Quality Meter	mV

3.4. Remote sensing information

Satellite-derived environmental parameters were collected from Internet. based Earth Observation portals like (https://earthexplorer.usgs.gov/) . Landsat 8 data, available through the USGS EarthExplorer, is a valuable resource for monitoring environmental parameters such as dissolved oxygen (DO), temperature, and chlorophyll-a in aquatic ecosystems. The thermal infrared bands (Band 10 and Band 11) are used to estimate water temperature, while the red (Band 4) and near-infrared (Band 5) bands help derive chlorophyll-a concentrations through indices like the Normalized Difference Chlorophyll Index (NDCI) (USGS, 2024).

The value was extracted for each fishing geo-location by using Sentinel Application Platform (SNAP) software. These data were tabulated in Excel sheet making it compatible for analysis.Five environmental parameters Temperature , Chlorophyll-a concentration (Chl-a), oxidation-reduction potential, dissolved oxygen (DO) and Ph were used to assess the quality of Satellite-derived environmental data with in-situ information.

Table 4: Landsat & Operational Land Imager (OLI) bands.

Band	Name	Wavelength (μm)	Resolution (m)
Band 1	Coastal/Aerosol	0.433 - 0.453	30
Band 2	Blue	0.450 - 0.515	30
Band 3	Green	0.525 - 0.600	30
Band 4	Red	0.630 - 0.680	30
Band 5	Near Infrared (NIR)	0.845 - 0.885	30
Band 6	Shortwave Infrared 1 (SWIR 1)	1.560 - 1.660	30
Band 7	Shortwave Infrared 2 (SWIR 2)	2.100 - 2.300	30
Band 8	Panchromatic	0.500 - 0.680	15
Band 9	Cirrus	1.360 - 1.390	30
Band 10	Thermal Infrared 1 (TIRS 1)	10.60 - 11.19	100 (resampled to 30)
Band 11	Thermal Infrared 2 (TIRS 2)	11.50 - 12.51	100 (resampled to 30)

Table 5: Regression equations for the water quality models for the Land sat-8.

Dependent variable	Equation	Author
Chl-a	15.717 + (-1247.530 * B2) + (192.236 * B3) + (846.290 * B4)	Yadav *et al*. (2019) and Watanabe *et al.* (2018)
Temperature	-147.6961 + (0.5924 * B10)	Mushtaq, Nee Lala (2017)
pH	9.9977 + (-110.1097 * B1) + (17.4231 * B3) + (49.6782 * B5)	Mushtaq, Nee Lala (2017)
DO	9.5867 + (-127.1909 * B2) + (115.4625 * B4) + (-223.5492 * B6) + (227.0583 * B7)	Gonzalez- ´ Marquez ´ *et al.* (2018), Mushtaq, Nee Lala (2017)
ORP	316.16 + (7054.50 * B1) + (-903.87 * B4) + (-3313.56 * B5)	Karaoui *et al.* (2019) , Gonzalez- ´ Marquez ´ *et al.* (2018)

Table 6: Landsat 8 OLI bands used in the present study.

Sr. No	Date	Landsat 8 image id
1	09-01-2024	LC08_L2SP_147045_20240111_20240123_02_T1
2	14-02-2024	LC08_L2SP_147045_20240212_20240222_02_T1
3	17-04-2024	LC08_L2SP_147045_20240416_20240423_02_T1

4. RESULTS

4.1. ECOPATH basic estimates

The basic estimates from the Ecopath model provide detailed parameters for each functional group, including the Ecotrophic Efficiency (EE), which represents the portion of the functional group utilized within the ecosystem. For a balanced model, EE values should be below 1. Based on the given data, the EE values range from 0.049 (Indian Major Carps) to 0.993 (Omnivorous fishes). The highest EE is observed in omnivorous fishes (0.993), followed by zooplankton (0.991), carnivorous fishes (0.985), herbivorous fishes (0.976), and phytoplankton (0.156). The production/consumption (P/Q) ratios for the functional groups vary from 0.255 (*Corica soborna*) to 5 (Omnivorous fishes).

4.2. Trophic Structure of reservoir

In the present study, the Ecopath model was used to determine the trophic levels (TL) and Ecotrophic Efficiency (EE) of various functional groups, as shown in Table 7. The trophic interactions among the 10 functional groups were classified into three distinct trophic levels (TL-1, TL-2, and TL-3). The highest trophic level (TL-3) was occupied by carnivorous fishes with a TL of 3.4, indicating their position as top predators in the food web. The lowest trophic level (TL-1) was represented by phytoplankton and detritus, both with a TL of 1, as they are primary producers and decomposers, respectively.

The remaining seven functional groups were classified under TL-2, indicating their intermediate position in the food web. Zooplankton occupied TL-2.0, while herbivorous fishes, Indian major carps, and exotic carps were placed slightly higher at TL-2.2 to TL-2.7. Omnivorous fishes occupied TL-3.1. The estimated geometric mean energy transfer from primary producer is 27.07%, from detritus is 39.60% and the total transfer efficiency estimated to be 37.65% (Table 8).

4.3. The energy flow and transfer efficiency (TE)

The energy flow and transfer efficiency (TE) within the ecosystem, based on the Ecopath with Ecosim (EwE) model, show how energy is transferred through ten trophic levels (TL-I to TL-X), with diminishing energy as it moves upward in the system. The Lindeman spine diagram provides a clear illustration of these trophic interactions, particularly highlighting the efficiency of energy transfer between successive trophic levels (Fig.2). The following breakdown outlines the transfer efficiencies (TE) for each trophic transition: From TL-II to TL-III, the TE is 0.495, indicating a substantial transfer of energy at this level, mainly involving primary consumers. From TL-III to TL-IV, the TE is 0.338. From TL-IV to TL-V, the TE is 0.319,. From TL-V to TL-VI, the TE is 0.322, maintaining similar efficiency at this level.

4.4. The Mixed Trophic Impact (MTI)

The Mixed Trophic Impact (MTI) analysis for the Sardar sarovar reservoir, represented in the diagram, illustrates the complex interactions between various functional groups within the ecosystem. In this figure 3, the impacted groups are arranged horizontally, while the impacting groups are arranged vertically. Positive impacts are shown in blue, while negative impacts are indicated in red. The intensity of each color reflects the strength of the impact. *Corica soborna* exhibit a strong negative impact on most of the other groups, particularly on herbivorous, omnivorous, and Phytoplankton groups. However, their interaction with Carnivorous is strong positive impact. Detritus has a significant positive impact on various groups, including omnivorous fishes, exotic carps, and Indian major carps. However, it strong positive impacts herbivorous and zooplankton . Phytoplankton positively influences most of the other groups , significant negative impact on zooplankton. Indian major carps has a significant positive impact on various groups including herbivorous, omnivorous and Carnivorous. Carnivorous exhibit a strong negative impact on minor carp and slightly negative impact on Indian major carps. Other interactions among the groups are relatively weak, with only minor positive or negative impacts, indicating less significant or indirect trophic interactions.

4.5. The ecosystem properties of the Sardar sarovar reservoir

The ecosystem properties of the Sardar sarovar reservoir are summarized in Table 9. The sum of all consumption, sum of all exports, sum of all respiratory flows, sum of all flows into detritus, and total system throughput were 12035.08 T km^{-2} y^{-1}, 9140.696 T km^{-2} y^{-1}, 2637.304 T km^{-2} y^{-1}, 13893.35 T km^{-2} y^{-1}, and 37706.43 T km^{-2} y^{-1}, respectively. The sum of all production was 18390.76 T km^{-2} y^{-1}, while the calculated total net primary production amounted to 11400 T km^{-2} y^{-1}.The ratio of total primary production to total respiration (TPP/TR) was 4.322596, and the total primary production to total biomass ratio stood at 34.47775 T km^{-2} y^{-1}. The total biomass, excluding detritus, was 330.648 T km^{-2} y^{-1}, with a total biomass to total system throughput (B/TST) ratio of 0.008769 T km^{-2} y^{-1}. The mean trophic level of the catch was 1.853572, while the gross efficiency of the catch relative to net primary production was 0.014405. The connectance index (CI) and system omnivory index (SOI) were 0.54321 and 0.3557, respectively. Economically, the total market value and total value of the catch were both estimated at 164.216 T km^{-2} y^{-1}, with a total profit of 80.8432 T km^{-2} y^{-1}.The Ecopath pedigree index was calculated as 0.441861 and the Shannon diversity index was 1.88. The system's measure of fit (t*) was 1.30317. The overall follow of energy in the Sardar sarovar is depicted in fig 4. .

Table 7: Basic parameters of the mass balanced trophic model and transfer efficiency among different functional groups of reservoir.

	Group name	TL	B	P/B	Q/B	EE	P/Q
1.	**Indian Major Carps**	2.3	29.33	10	35	0.049	0.286
2.	**Exotic Carps**	2.7	15	2	7	0.319	0.286
3.	**Minor Carps**	2.6	12	2.5	3	0.286	0.833
4.	***Corica soborna***	3.0	112.3	14	55	0.057	0.255
5.	**Herbivorous**	2.2	32.5	29	15	0.976	1.933
6.	**Omnivorous**	3.1	17	100	20	0.993	5
7.	**Carnivorous**	3.4	7.5	8	11	0.985	0.727
8.	**Zooplankton**	2.0	45	52.5	84	0.991	0.625
9.	**Phytoplankton**	1	60	190		0.156	
10.	**Detritus**	1	100			0.35	

Note: TL= Trophic level; B= Biomass (T km^{-2} y^{-1}.); P/B= Production/Biomass (yr^{-1}); Q/B= Consumption/Biomass (yr^{-1}); EE= Ecotrophic efficiency; P/Q= Production/consumption or gross efficiency of food conversion (yr^{-1})

Table 8: Transfer efficiency among different trophic levels of the Sardar sarovar reservoir.

Source \ Trophic level	II	III	IV	V	VI	VII	VIII	IX	X
Producer	1.779	393.6	28.32	25.26	38.44	25.15	35.44	27.54	32.11
Detritus	59.47	32.58	32.06	32.4	27.99	32.95	28.8	31.81	29.5
All flows	49.54	33.76	31.91	32.15	28.27	32.67	28.99	31.66	29.58
Proportion of total flow originating from detritus: 0.67									
Transfer efficiencies (calculated as geometric mean for TL II-IV)									
From primary producers: 27.07%									
From detritus: 39.60%									
Total: 37.65%									

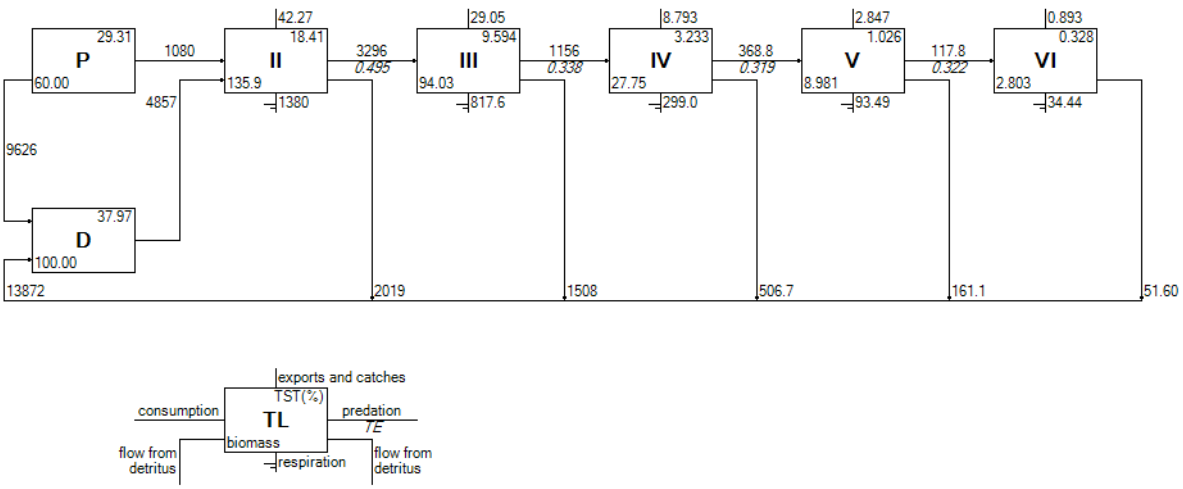


Figure 2: Lindeman spine flow network showing the trophic flows through discrete trophic levels (TL). Note: Trophic level 1 has two components: Primary producers (PP) and detritus (D). TE= transfer efficiency (%); TST=Total system throughput. Values are in T km^{-2} y^{-1}.

Table 9: Summary statistics of the ecosystem parameters of the Sardar sarovar reservoir.

Parameters	Value	Units
Sum of all consumption	12035.08	T km^{-2} y^{-1}
Sum of all exports	9140.696	T km^{-2} y^{-1}
Sum of all respiratory flows	2637.304	T km^{-2} y^{-1}
Sum of all flows into detritus	13893.35	T km^{-2} y^{-1}
Total system throughput	37706.43	T km^{-2} y^{-1}
Sum of all production	18390.76	T km^{-2} y^{-1}
Mean trophic level of the catch	1.853	T km^{-2} y^{-1}
Gross efficiency (catch/net p.p.)	0.0144	T km^{-2} y^{-1}
Calculated total net primary production	11400	T km^{-2} y^{-1}
Total primary production/total respiration	4.322	
Net system production	8762.69	T km^{-2} y^{-1}
Total primary production/total biomass	34.47	
Total biomass/total throughput	0.0087	T km^{-2} y^{-1}
Total biomass (excluding detritus)	330.64	T km^{-2}
Total catch	164.21	
Connectance Index	0.54	
System Omnivory Index	0.35	
Total market value	164.21	
Total value	164.21	
Total variable cost	83.37	
Total cost	83.37	
Profit	80.84	% of total throughout
Ecopath pedigree	0.44	
Measure of fit, t*	1.30317	%
Shannon diversity index	1.889931	%

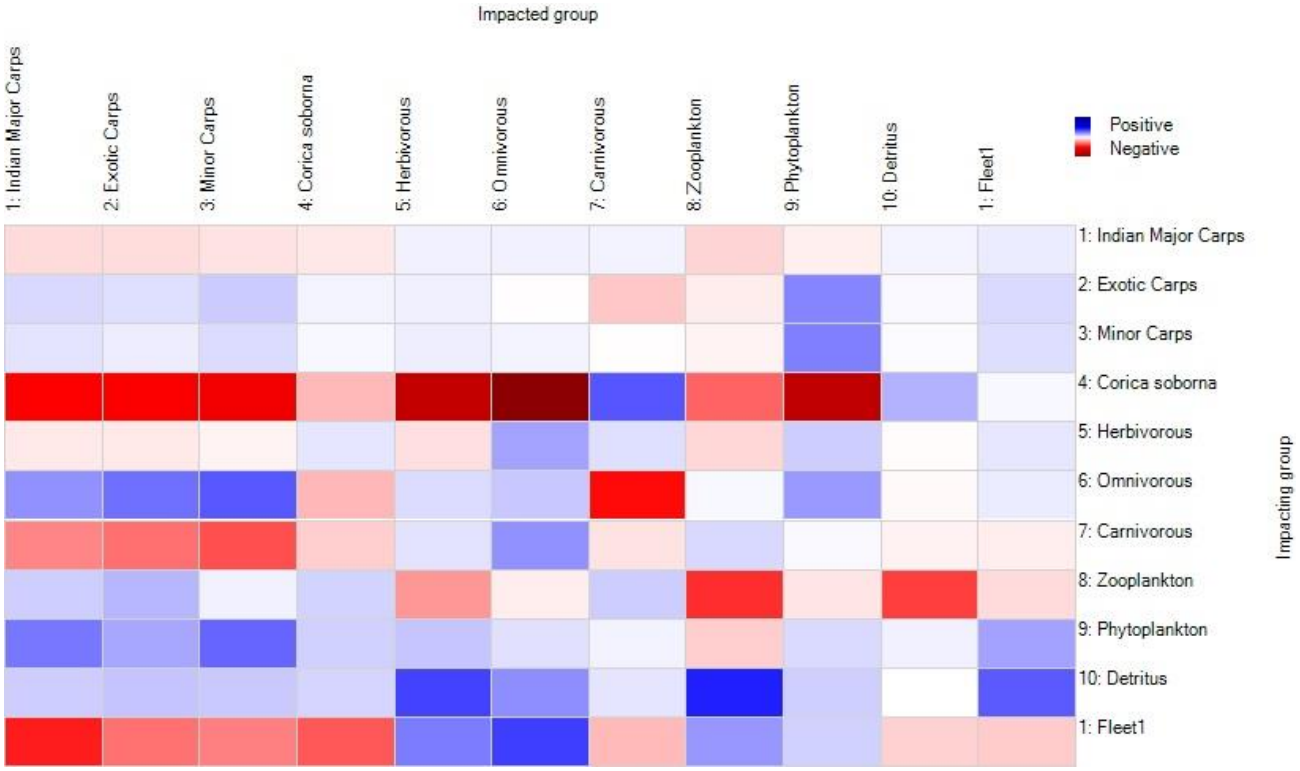


Figure 3: Mixed trophic impacts of the food web model of Sardar sarovar reservoir.

Note: The blue colour depicts the positive impact and red colour depicts negative impacts. The intensity of the colour indicated the degree of impact.

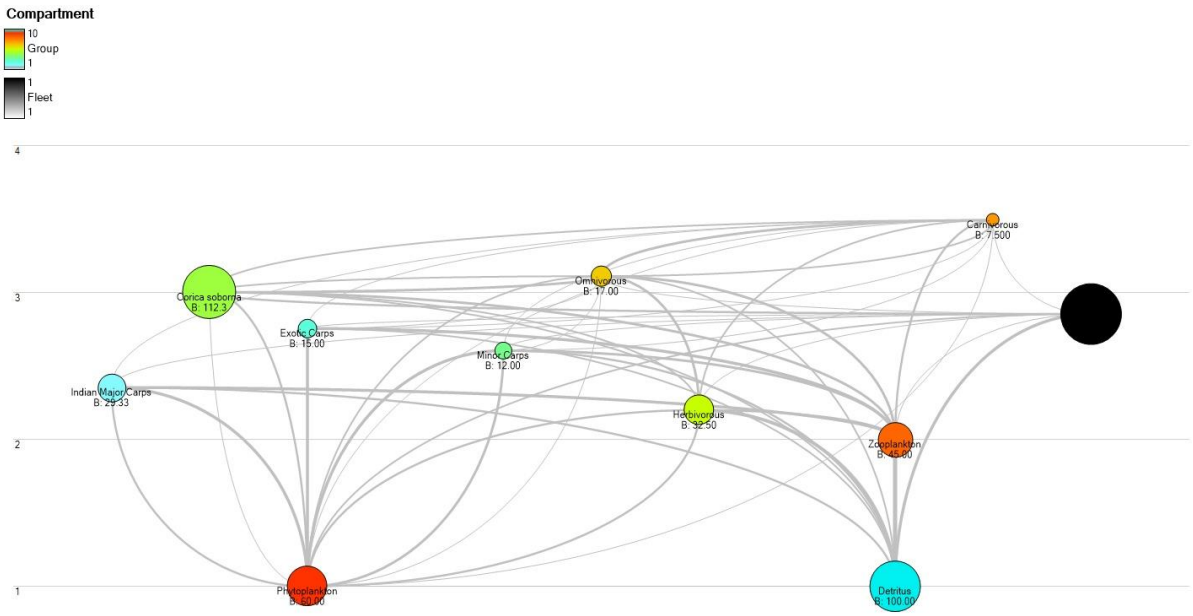
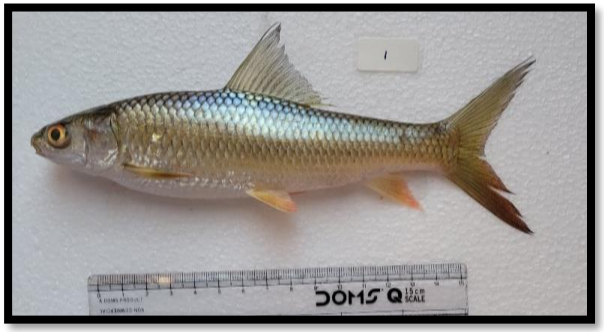


Figure 4: Energy Flow diagram of the Sardar Sarovar reservoir.

Table 10 : List of identified fish species from Sardar sarovar resevoir.

Family	Order	Fish Species
Cypriniformes	**Cyprinidae**	*Labeo catla* (Hamilton, 1822)
		Cirrhinus mrigala (Hamilton, 1822)
		Labeo rohita (Hamilton, 1822)
		Hypophthalmichthys molitrix (Valenciennes, 1844)
		Ctenopharyngodon idella (Valenciennes, 1844)
		Cirrhinus reba (Hamilton, 1822)
		Labeo calbasu (Hamilton, 1822)
		Salmostoma bacaila (Hamilton, 1822)
		Amblypharyngodon mola (Hamilton, 1822)
		Cabdio morar (Hamilton, 1822)
		Barilius barila (Hamilton, 1822)
		Barilius bendelisis (Hamilton, 1822)
		Puntius sophore (Hamilton, 1822)
		Tor tor (Hamilton, 1822)
		Osteobrama cotio cotio (Hamilton, 1822)
		Systomus sarana (Hamilton, 1822)
Siluriformes	**Siluridae**	*Ompok bimaculatus* (Bloch, 1794)
		Wallago attu (Bloch & Schneider, 1801)
	Bagridae	*Mystus cavasius* (Hamilton, 1822)
		Sperata aor (Hamilton, 1822)
		Sperata seenghala (Sykes, 1839)
	Schilbeidae	*Eutropiichthys vacha* (Hamilton, 1822)
Clupeiformes	**Clupeidae**	*Corica soborna* (Hamilton, 1822)
Beloniformes	**Belonidae**	*Xenetodon cancila* (Hamilton, 1822)
Cyprinodontiformes	**Aplocheilidae**	*Aplocheilus panchax* (Hamilton, 1822)
Perciformes	**Ambassidae**	*Chanda nama* (Hamilton, 1822)
		Parambassis ranga (Hamilton, 1822)
Gobiiformes	**Gobiidae**	*Glossogobius giuris* (Hamilton, 1822)
Synbranchiformes	**Mastacembelidae**	*Macrognathus pancalus* (Hamilton, 1822)
Osteoglossiformes	**Notopteridae**	*Notopterus notopterus* (Pallas, 1769)



Cirrhinus mrigala

(Hamilton, 1822)

Notopterus notopterus

(Pallas, 1769)

Systomus sarana

(Hamilton, 1822)

Cirrhinus reba

(Hamilton, 1822)

Labeo rohita

(Hamilton, 1822)

Tor tor

(Hamilton, 1822)

Plate 1a: Identified fish species from Sardar sarovar reservoir.

Parambassis ranga

(Hamilton, 1822)

Macrognathus pancalus

(Hamilton, 1822)

Xenentodon cancila

(Hamilton, 1822)

Chanda nama

(Hamilton, 1822)

Glossogobius giuris

(Hamilton, 1822)

Salmostoma bacaila

(Hamilton, 1822)

Plate 1b: Identified fish species from Sardar sarovar reservoir.

Mystus cavassius

(Hamilton, 1822)

Sperata aor

(Hamilton, 1822)

Labeo catla

(Hamilton, 1822)

Ompok bimaculatus

(Bloch, 1794)

Labeo calbasu

(Hamilton, 1822)

Corica soborna

(Hamilton, 1822)

Plate 1c: Identified fish species from Sardar sarovar reservoir.

4.6 Comparative assessment of water parameters

4.6.1 Water Temperature

Satellite-derived water temperatures range from 23.70°C to 32.77°C, while in-situ measurements range from 16.60°C to 34.95°C. The median temperature recorded by satellites (25.80°C) is lower than the in-situ median (29.16°C), indicating a notable discrepancy. The mean temperatures are similar, but the satellite data shows a narrower range and lower minimum value. The satellite data for water temperature shows a reasonable level of accuracy compared to in-situ observations, with an R^2 value of 0.74 indicating a good fit between the two datasets. The RMSE of 3.46 and MAE of 3.07 reflect some discrepancy, but the moderate MAPE of 12.23% suggests that the satellite measurements are close to the actual values.

Table 11: Descriptive statistics of Water Temperature In-situ and satellite derived data study (°C).

Algorithms	Range(°C)	Q1	Q3	Mean±SE	Median	SD	IQR	CV%
In-situ	16.60-34.94	23.15	29.15	27.80±1.50	29.15	5.81	11.33	20.92
Landsat8	23.7-32.77	24.05	30.64	26.77±0.83	25.8	3.24	6.59	12.13

Table 12: Validation statistics of the matchups of Water Temperature (°C).

Parameter	$WT^{landsat8}$ vs $WT^{In\text{-}situ}$
RMSE	3.469043
MAE	3.072872
Bias	-1.024449
MAPE	12.23 %
R^2	0.745164

Table 13: comparison between in-situ and Landsat-8 derived Water Temperature for different sampling sites.

	Sampling site	Latitude (DMS)	Longitude (DMS)	WT (°C)	
				In-situ	Landsat-8
1.	Danel	21°52'20.71"N	73°56'57.92"E	29.15	26.1
2.	Gaman	21°51'19.54"N	73°55'11.20"E	29.36	25.8
3.	Chimalkhadi	21°51'0.60"N	73°54'17.84"E	29.37	25.5
4.	Bhamani	21°51'49.76"N	73°56'8.88"E	29.25	25.9
5.	Mukhadi	21°52'39.64"N	73°58'3.05"E	29.12	26.2
6.	Pimpalchop	21°54'42.78"N	74°2'41.46"E	25.65	25.69
7.	Thuwani	21°56'5.95"N	74°6'17.62"E	23.15	24.05
8.	Bharad	21°56'29.38"N	74°7'42.02"E	18.90	23.93
9.	Shikka	21°56'47.73"N	74°8'3.67"E	16.60	23.7
10.	Chitkhedi	21°54'43.31"N	74°9'57.05"E	25.78	23.8
11.	Bhusha	21°55'31.58"N	74°17'50.00"E	21.73	24.05
12.	Warwali	21°57'49.42"N	74°17'58.06"E	34.49	30.64
13.	Sadri	21°58'47.11"N	74°21'21.20"E	34.69	31.13
14.	Bhadal-1	22°1'12.08"N	74°23'26.13"E	34.75	32.38
15.	Bhadal-2	22°1'43.11"N	74°25'54.66"E	34.94	32.77

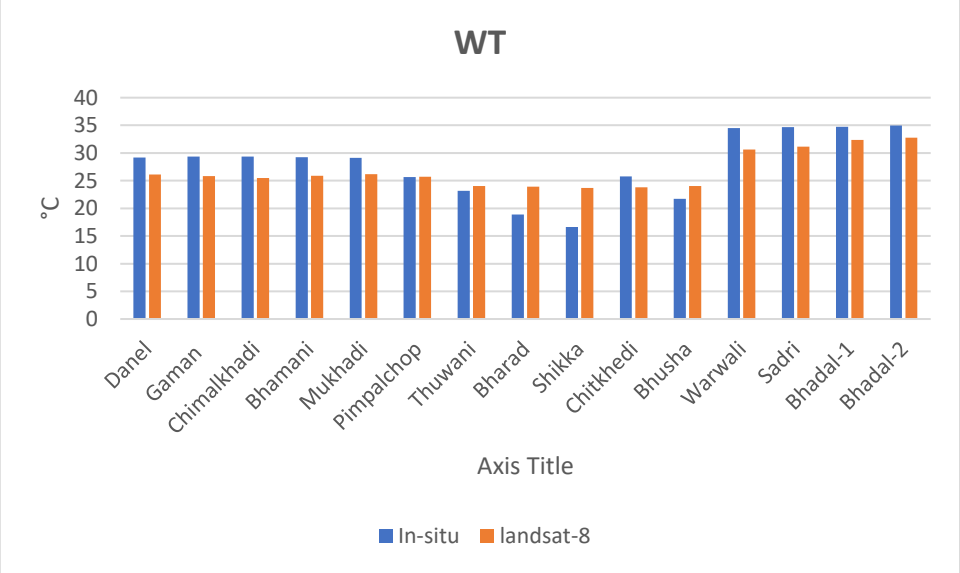


Figure 5: Water Temperature distribution bar graph for sampling sites.

4.6.2 Oxidation-reduction potential

Satellite ORP measurements range from 59.03 mV to 345.96 mV, while in-situ measurements range from 70.0 mV to 202.2 mV. The median satellite ORP (233.18 mV) is substantially higher than the in-situ median (105.1 mV), suggesting significant discrepancies in ORP readings between the two methods. The accuracy metrics for oxidation-reduction potential indicate a moderate level of correlation between satellite and in-situ measurements, with an R^2 of 0.61. However, the RMSE of 152.9 and MAE of 135.4 suggest significant variability in the satellite data, and the high MAPE of 124.9% indicates considerable discrepancies relative to in-situ observations.

Table 14: Descriptive statistics of Oxidation-reduction potential In-situ and satellite derived data study.

Algorithms	Range (mV)	Q1	Q3	Mean±SE	Median	SD	IQR	CV%
In-situ	70-202.2	100.4	200.01	144.09±13.89	105.1	53.80	99.61	37.34
Landsat8	59.03-345.96	105.37	289.80	217.20±23.98	233.18	92.90	184.42	42.77

Table 15: Validation statistics of the matchups of Oxidation-reduction potential.

Parameter	$ORP^{Landsat8}$ VS $ORP^{In\text{-}situ}$
RMSE	152.9484
MAE	135.406
Bias	73.1105
MAPE	124.97 %
R^2	0.6104476

Table 16: comparison between in-situ and Landsat-8 derived Oxidation-reduction potential (ORP) for different sampling sites.

	Sampling site	Latitude (DMS)	Longitude (DMS)	ORP(mV)	
				In-situ	Landsat-8
1.	Danel	21°52'20.71"N	73°56'57.92"E	101.6	217.38
2.	Gaman	21°51'19.54"N	73°55'11.20"E	102.2	230.32
3.	Chimalkhadi	21°51'0.60"N	73°54'17.84"E	200	216.25
4.	Bhamani	21°51'49.76"N	73°56'8.88"E	101.6	259.23
5.	Mukhadi	21°52'39.64"N	73°58'3.05"E	188.8	233.18
6.	Pimpalchop	21°54'42.78"N	74°2'41.46"E	105.1	253.24
7.	Thuwani	21°56'5.95"N	74°6'17.62"E	200.01	98.18
8.	Bharad	21°56'29.38"N	74°7'42.02"E	200.05	105.37
9.	Shikka	21°56'47.73"N	74°8'3.67"E	201.4	59.03
10.	Chitkhedi	21°54'43.31"N	74°9'57.05"E	202.2	233.28
11.	Bhusha	21°55'31.58"N	74°17'50.00"E	200	71.64
12.	Warwali	21°57'49.42"N	74°17'58.06"E	70	313.76
13.	Sadri	21°58'47.11"N	74°21'21.20"E	88.4	331.33
14.	Bhadal-1	22°1'12.08"N	74°23'26.13"E	100.4	289.80
15.	Bhadal-2	22°1'43.11"N	74°25'54.66"E	99.6	345.96

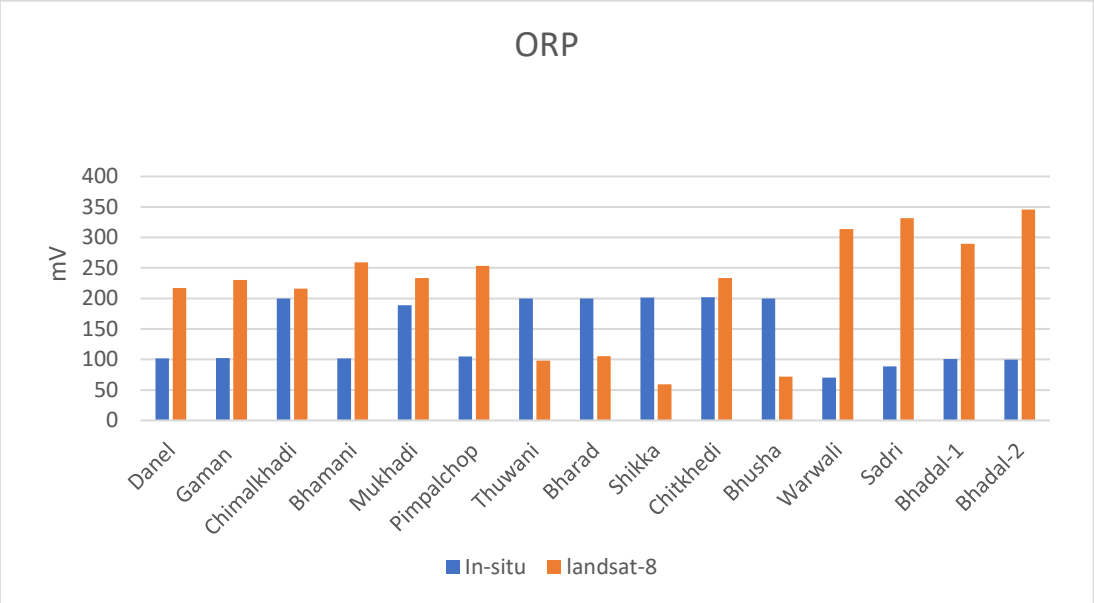


Figure 6: Oxidation-reduction potential distribution bar graph for sampling sites.

4.6.3 Water pH

Satellite pH measurements range from 9.84 to 14.27, while in-situ measurements range from 4.38 to 9.08. The median satellite pH (11.60) is substantially higher than the in-situ median (7.63), suggesting significant discrepancies in pH readings between the two methods. For water pH, the correlation between satellite and in-situ measurements is relatively poor, with an R^2 value of 0.15. The RMSE of 4.97 and MAE of 4.43 reflect a substantial level of error, and the MAPE of 68.07% further suggests that satellite data may not be a reliable proxy for in-situ pH measurements.

Table 17: Descriptive statistics of pH In-situ and satellite derived data study.

Algorithms	Range	Q1	Q3	Mean±SE	Median	SD	IQR	CV%
In-situ	4.38-9.08	6.72	8.71	7.41±0.35	7.63	1.37	1.99	18.60
Landsat8	9.84-14.27	10.73	13.60	11.84±0.36	11.60	1.43	2.86	12.09

Table 18. Validation statistics of the matchups of pH.

Parameter	$Ph^{Landsat8}$ VS $ph^{In\text{-}situ}$
RMSE	4.97823
MAE	4.431273
Bias	4.31273
MAPE	68.07%
R^2	0.1559892

Table 19: comparison between in-situ and Landsat-8 derived pH concentrations for different sampling sites.

	Sampling site	Latitude (DMS)	Longitude (DMS)	pH	
				In-situ	Landsat-8
1.	Danel	21°52'20.71"N	73°56'57.92"E	6.01	11.84
2.	Gaman	21°51'19.54"N	73°55'11.20"E	6.72	11.63
3.	Chimalkhadi	21°51'0.60"N	73°54'17.84"E	7.63	11.86
4.	Bhamani	21°51'49.76"N	73°56'8.88"E	7.63	11.18
5.	Mukhadi	21°52'39.64"N	73°58'3.05"E	7.61	11.60
6.	Pimpalchop	21°54'42.78"N	74°2'41.46"E	4.97	11.18
7.	Thuwani	21°56'5.95"N	74°6'17.62"E	4.38	13.60
8.	Bharad	21°56'29.38"N	74°7'42.02"E	7.65	13.76
9.	Shikka	21°56'47.73"N	74°8'3.67"E	7.68	14.27
10.	Chitkhedi	21°54'43.31"N	74°9'57.05"E	7.6	11.58
11.	Bhusha	21°55'31.58"N	74°17'50.00"E	7.82	13.99
12.	Warwali	21°57'49.42"N	74°17'58.06"E	9.08	10.37
13.	Sadri	21°58'47.11"N	74°21'21.20"E	8.83	10.11
14.	Bhadal-1	22°1'12.08"N	74°23'26.13"E	8.85	10.73
15.	Bhadal-2	22°1'43.11"N	74°25'54.66"E	8.71	9.847

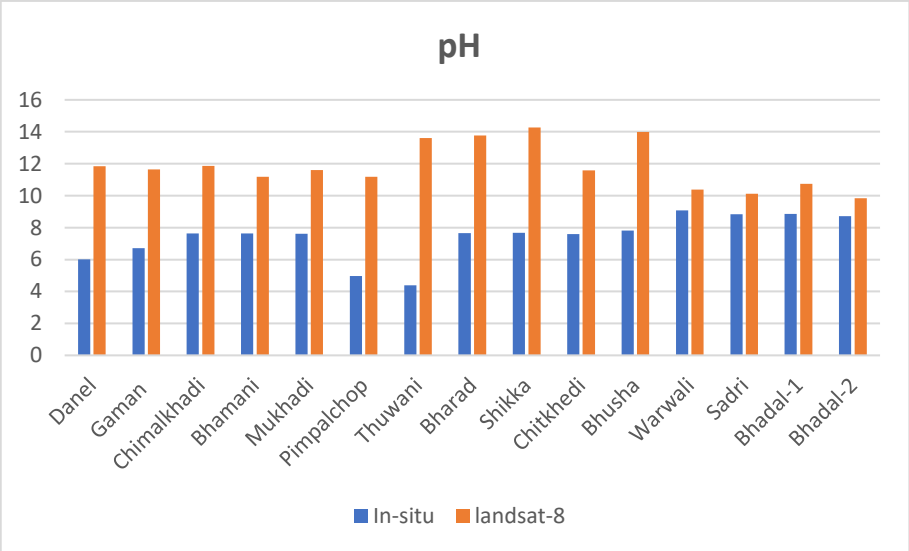


Figure 7: pH distribution bar graph for sampling sites

4.6.4 Dissolved Oxygen

Satellite measurements of dissolved oxygen range from 8.252 mg/l to 11.067 mg/l, whereas in-situ measurements range from 4.150 mg/l to 7.800 mg/l. The median satellite DO (9.076 mg/l) is much higher than the in-situ median (5.40 mg/l), indicating that satellite sensors may overestimate DO levels. The results for dissolved oxygen show very low correlation, with an R^2 value of 0.011. The RMSE of 3.92 and MAE of 3.67 indicate a noticeable level of error, and the high MAPE of 72 % implies significant discrepancies between satellite and in-situ measurements.

Table 20. Descriptive statistics of Dissolved Oxygen In-situ and satellite derived data study (mg/lit).

Algorithms	Range (mg/l)	Q1	Q3	Mean±SE	Median	SD	IQR	CV%
In-situ	4.15-7.8	4.66	7.21	5.64±0.32	5.4	1.27	4.66	22.55
Landsat8	8.25-11.06	9.00	9.64	9.32±0.21	9.07	0.81	0.64	8.76

Table 21. Validation statistics of the matchups of Dissolved Oxygen (mg/l).

Parameter	$DO^{Landsat8}$ VS $DO^{In\text{-}situ}$
RMSE	3.927567
MAE	3.673447
Bias	3.673447
MAPE	72.00%
R^2	0.01125229

Table 22. comparison between in-situ and Landsat-8 derived Dissolved Oxygen (DO) concentrations for different sampling sites.

	Sampling site	Latitude (DMS)	Longitude (DMS)	DO(mg/l)	
				In-situ	Landsat-8
1.	Danel	21°52'20.71"N	73°56'57.92"E	4.15	9.03
2.	Gaman	21°51'19.54"N	73°55'11.20"E	4.77	9.01
3.	Chimalkhadi	21°51'0.60"N	73°54'17.84"E	4.66	9.07
4.	Bhamani	21°51'49.76"N	73°56'8.88"E	6.4	8.41
5.	Mukhadi	21°52'39.64"N	73°58'3.05"E	4.77	8.51
6.	Pimpalchop	21°54'42.78"N	74°2'41.46"E	4.18	8.25
7.	Thuwani	21°56'5.95"N	74°6'17.62"E	4.38	9.00
8.	Bharad	21°56'29.38"N	74°7'42.02"E	5.4	10.22
9.	Shikka	21°56'47.73"N	74°8'3.67"E	5.4	11.06
10.	Chitkhedi	21°54'43.31"N	74°9'57.05"E	5.43	9.25
11.	Bhusha	21°55'31.58"N	74°17'50.00"E	5.35	10.83
12.	Warwali	21°57'49.42"N	74°17'58.06"E	7.52	9.33
13.	Sadri	21°58'47.11"N	74°21'21.20"E	7.8	9.12
14.	Bhadal-1	22°1'12.08"N	74°23'26.13"E	7.32	9.64
15.	Bhadal-2	22°1'43.11"N	74°25'54.66"E	7.21	9.03

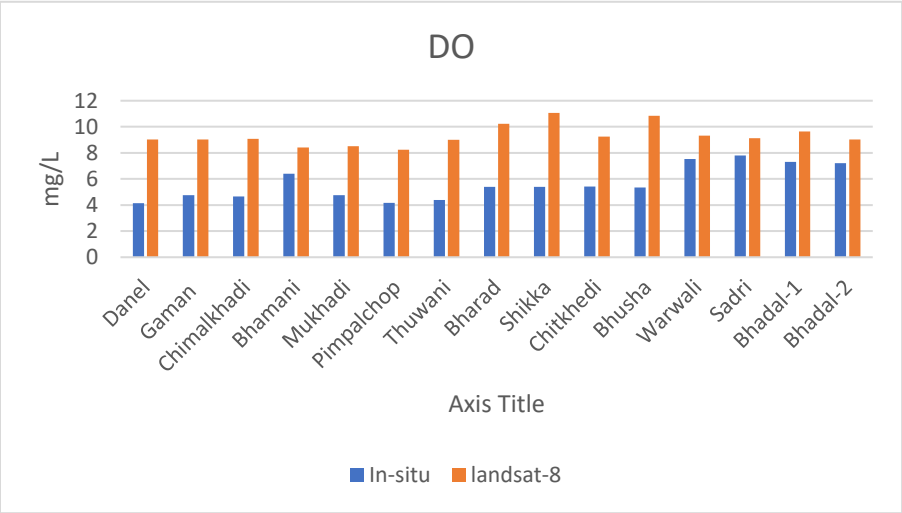


Figure 8: Dissolved oxygen distribution bar graph for sampling sites.

4.6.5 Water Chlorophyll-a

Satellite measurements of chlorophyll-a range from 0.02063 mg/l to 0.04747 mg/l, while in-situ measurements range from 0.01320 to 0.58700 mg/l. The median satellite Chl-a (0.02664 mg/l) is lower than the in-situ median (0.07800 mg/l). The satellite data for chlorophyll-a exhibits a moderate correlation with in-situ observations (R^2 = 0.33). While the RMSE of 0.28 and MAE of 0.18 indicate some error, the MAPE of 80.3% suggests that there are notable differences between satellite and in-situ measurements.

Table 23. Descriptive statistics of Chlorophyll-a In-situ and satellite derived data study (mg/l) .

Algorithms	Range (mg/l)	Q1	Q3	Mean±SE	Median	SD	IQR	CV%
In-situ	0.01-0.58	0.02	0.48	0.20±0.06	0.078	0.23	0.45	114.14
Landsat8	0.02-0.04	0.023	0.034	0.029±0.002	0.026	0.009	0.011	30.49

Table 24. Validation statistics of the matchups of Chlorophyll-a (mg/l)

Parameter	Chlorophyll-a ^{Landsat8} VS Chlorophyll-a $^{In-situ}$
RMSE	0.289338
MAE	0.1857163
Bias	-0.1757138
MAPE	80.33%
R^2	0.3363411

Table 25. comparison between in-situ and Landsat-8 derived chlorophyll-a (Chl-a) concentrations for different sampling sites

	Sampling site	Latitude (DMS)	Longitude (DMS)	Chl-a(mg/l)	
				In-situ	Landsat-8
1.	Danel	21°52'20.71"N	73°56'57.92"E	0.095	0.028
2.	Gaman	21°51'19.54"N	73°55'11.20"E	0.0132	0.025
3.	Chimalkhadi	21°51'0.60"N	73°54'17.84"E	0.097	0.027
4.	Mukhadi	21°52'39.64"N	73°58'3.05"E	0.057	0.037
5.	Thuwani	21°56'5.95"N	74°6'17.62"E	0.016	0.031
6.	Shikka	21°56'47.73"N	74°8'3.67"E	0.02	0.023
7.	Chitkhedi	21°54'43.31"N	74°9'57.05"E	0.031	0.022
8.	Bhusha	21°55'31.58"N	74°17'50.00"E	0.061	0.025
9.	Warwali	21°57'49.42"N	74°17'58.06"E	0.524	0.020
10.	Sadri	21°58'47.11"N	74°21'21.20"E	0.493	0.028
11.	Bhadal-1	22°1'12.08"N	74°23'26.13"E	0.473	0.025
12.	Bhadal-2	22°1'43.11"N	74°25'54.66"E	0.587	0.020

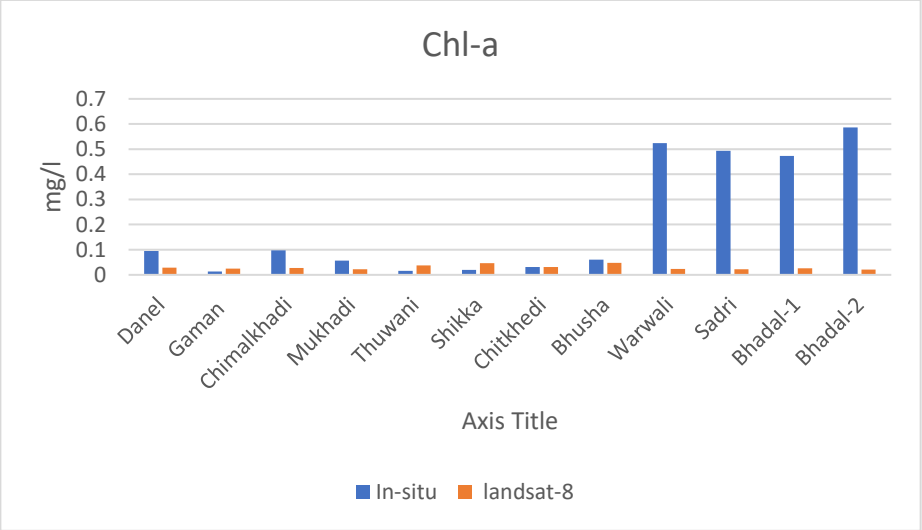


Figure 9: Chlorophyll-a distribution bar graph for sampling sites.

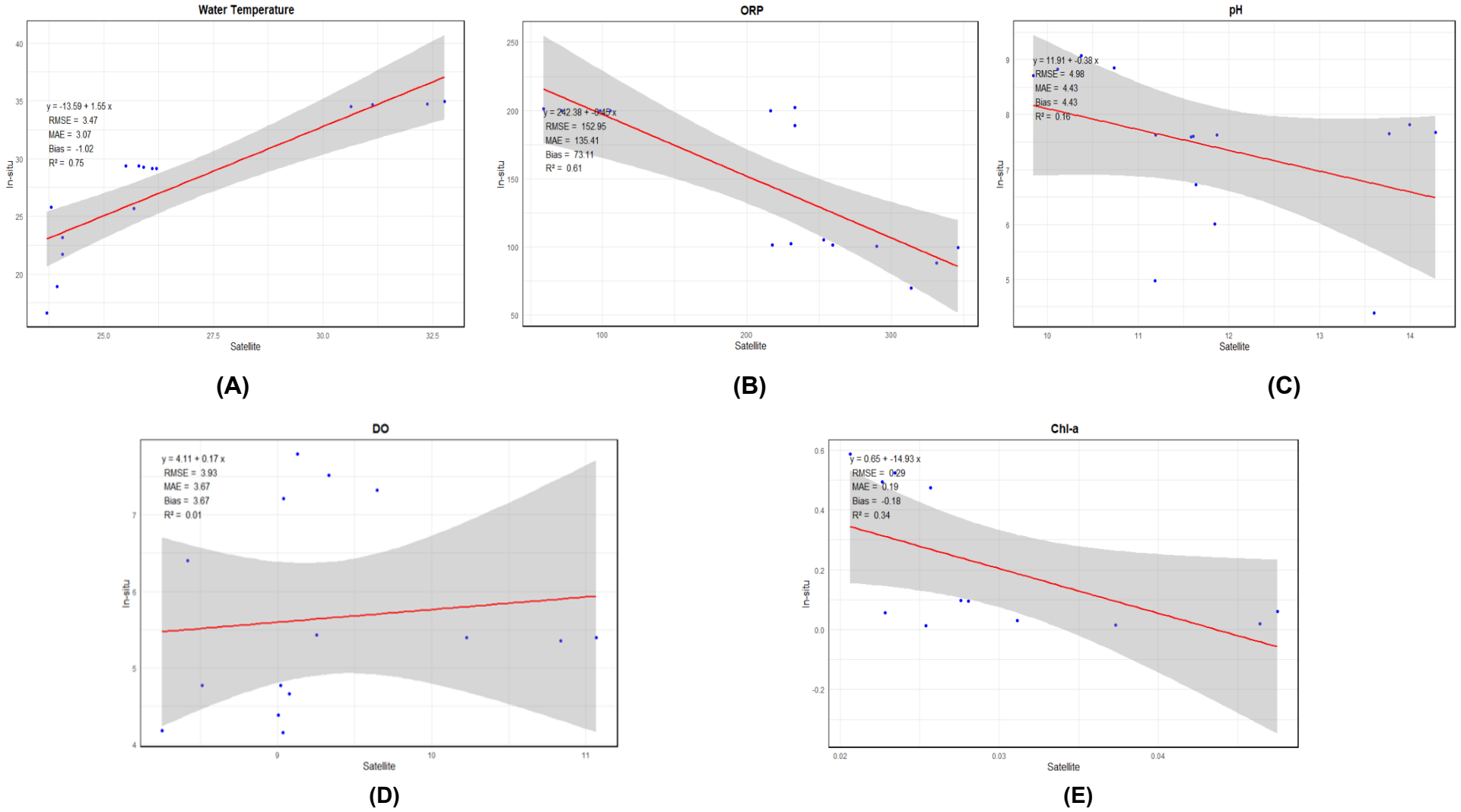


Figure 10: In-situ vs Satellite-derived reading (A) Water temperature, (B) ORP, (C) pH, (D) DO, and (E) Chl-a.

5.DISCUSSION

5.1. Mix Trophic Impact

The intricate network of relationships between Indian Major Carps, Exotic Carps, Minor Carps, zooplankton, phytoplankton, detritus, and the impact of fishing activities, is revealed by the analysis of trophic impact. Intensity of these relationships are indicated by the interaction coefficients. Positive values indicate mutual benefits or co-dependencies, while negative values reflect competition or predation pressures.

Indian Major Carps have a moderately negative impact on groups such as Exotic Carps, Minor Carps, and Zooplankton, which may indicate competition for resources. Positive impact on herbivorous fish and detritus is indicative of their function in nutrient cycling, potentially through the breakdown of organic matter. This is corroborated by studies that describe carps' influence on nutrient dynamics in freshwater ecosystems (Weber and Brown, 2009). Exotic Carps shown a positive self-reinforcing interaction, which may be as a result of improved reproductive success. This phenomenon is frequently observed in invasive species under favorable conditions (Bunn and Arthington, 2002). Nevertheless, they have a detrimental effect on Zooplankton and Carnivorous fish, which is consistent with the discovery that invasive species can disrupt native food webs, indicating predation pressure or resource competition (Gallardo *et al.,* 2016). The significance of the Detritus pool in organic matter recycling, a critical function in nutrient-poor ecosystems, is underscored by their positive contribution (Wilden, *et al.,* 2024).

Minor Carps, promote primary productivity, as demonstrated by their beneficial influence on phytoplankton. This suggests that they are involved in nutrient regeneration through bioturbation and excretion, similar to the nutrient enhancement functions observed in other carps (Khan *et al.,* 2003). Their minor adverse impacts on carnivorous fish and zooplankton suggest that resource competition is occurring on a smaller scale. Potentially as a result of competitive exclusion or habitat overlap, *Corica soborna* demonstrates robust negative interactions with itself, Indian Major Carps, and Exotic Carps (Smale, 1992). The adverse effects on Phytoplankton may suggest overgrazing or environmental perturbation, while the substantial negative impact on Omnivorous fish may suggest intense competition for shared resources.

By contributing to nutrient cycling and supporting higher trophic levels, herbivorous fish play a stabilizing function, positively influencing Phytoplankton and Carnivorous fish (Heymans *et al.,* 2016). Their grazing behaviors, which reduce detritus accumulation, are likely the cause of their detrimental impact on Detritus. Omnivorous fish exhibit a diverse array of interactions, which have a detrimental effect on carnivorous fish as a result of competition for dietary resources. It is observe that they encourage phytoplankton development, a phenomenon that is observed in systems where omnivores improve nutrient cycling (Fernando and Súarez, 2021). Their substantial influence on *Corica soborna* implies either competition or predation. Carnivorous group shown adverse effects on prey species, including Indian Major Carps and Minor Carps, in accordance with their status as apex predators within the system (Thompson *et al.,* 2007). Nevertheless, they exhibit a positive interaction with Zooplankton, which underscores their indirect support of lower trophic levels, which are essential for the maintenance of their populations (Christensen *et al.,* 2005). Zooplankton play a critical role in the ecosystem, interacting positively with Phytoplankton and Carnivorous fish. However, they are significantly affected by Exotic Carps and fishing pressure, suggesting that they are susceptible to both predation and anthropogenic influences (Walters *et al.,* 1997). The significance of primary producers in sustaining trophic dynamics is underscored by the interactions between phytoplankton, the foundation of the aquatic food web, and Minor Carps, Herbivorous fish, and Omnivorous fish (Hindle and Hutchinson, 1967). Nevertheless, they are adversely affected by *Corica soborna*, which may be indicative of overgrazing (Keramidas *et al.,* 2023). Indian Major Carps and Exotic Carps exhibit positive relationships with detritus, an essential component of the nutrient cycle. This suggests that these species contribute to the organic matter reservoir, thereby increasing the availability of nutrients for other groups (Vincent, 2001).

5.2. Trophic Structure and Energy Flow

The Ecopath model for the Sardar Sarovar reservoir provides critical insights into the energy dynamics and trophic structure. Ecotrophic efficiency (EE) values, which quantify the extent to which each functional group is varied from 0.049 for Indian Major Carps to 0.993 for omnivorous fishes. A balanced system is indicated by EE values below 1, as per Christensen and Pauly (1992). The high EE values for omnivorous fishes (0.993), zooplankton (0.991), and carnivorous fishes (0.985) indicate that these groups are extensively utilized, likely as a result of predation or fishing pressures. The primary consumers and producers of the ecosystem are underscored by herbivorous fishes and phytoplankton, which have EE values of 0.976 and 0.156, respectively. *Corica soborna* has the lowest P/Q ratio (0.255), which suggests that its production is minimal in comparison to its consumption, which may be a result of predation. The high biomass production of omnivorous fishes, which is indicative of their dietary flexibility, is suggested by a P/Q ratio of 5 (Geary *et al.,* 2020). In accordance with the typical predator-prey dynamics in freshwater systems, carnivorous fishes occupy the highest position at TL-3.4 (Huang, *et al.,* 2021). Phytoplankton and detritus are the foundation of the food web at TL-1, while intermediate groups, such as herbivorous fishes and zooplankton, are located within TL-2. A variety of dietary habits is exhibited by omnivorous fish at TL-3.1. The overall system TE is 37.65%, with transfer efficiencies (TE) of 27.07% from primary producers and 39.60% from detritus, as indicated by the energy flow analysis report. These values are consistent with the results of other aquatic ecosystems, which have demonstrated that energy transfer decreases as trophic levels increase (Pauly & Christensen, 1995). The significant retention of energy within primary consumers is reflected in the energy transfer from TL-II to TL-III (0.495). This is consistent with Lindeman's (1942) ecological efficiency model, as progressively lower TE values are observed between higher trophic transitions.

5.3. Ecosystem Maturity and Resilience

A net primary production of 11,400 T km² y^{-1} and a sum of all production reaching 18,390.76 T km² y^{-1} are indicative of the extensive energy processing that is evident in the total system throughput 37,706.43 T km² y^{-1}. An autotrophic system with robust primary production that exceeds respiration demands is indicated by a total primary production to respiration (TPP/TR) ratio of 4.32 (Christensen & Walters, 2004). The biomass-to-system throughput ratio (B/TST) was 0.008, indicating efficient energy turnover, and the total biomass, excluding detritus, was 330.6 T km² y^{-1}. The catch's mean trophic level of 1.85 indicates a predominance of lower trophic species, which is indicative of balanced reservoir fisheries (Winemiller & Jepsen, 2002). The fishery's economic significance is evidenced by a total catch value of 164.216 T km² y^{-1} and a profit of 80.84 T km² y^{-1}, as revealed by economic analysis. Dunne *et al.* (2002) hypothesize that the moderately omnivorous food web, as indicated by the connectance index (CI) of 0.54 and system omnivory index (SOI) of 0.35, contributes to system stability. The reservoir's moderate biodiversity, which is crucial for long-term ecological resiliency, is preserved by its Shannon diversity index of 1.88 (Panikkar *et al.,* 2015). The pedigree index (0.44) and fit (t* = 1.30) of the model indicate a satisfactory level of confidence in the ecosystem model (Couce-Montero *et al.,* 2015).

5.4. Water Temperature

The satellite-derived water temperature data demonstrated a strong correlation with in-situ measurements ($R^2 = 0.745$), with relatively low RMSE (3.469) and MAE (3.073). This aligns with findings from Korver et al. (2024), who observed that satellite-based temperature measurements are highly reliable due to their ability to capture large-scale temperature patterns in surface waters. Similarly, Philippus *et al.* (2024) reported effective temperature estimations for small rivers using satellite data, reinforcing the accuracy of remote sensing for this parameter.

5.5. Oxidation Redox Potential

The accuracy of satellite measurements for oxidation redox potential was less robust, with a moderate R^2 (0.610) and high RMSE (152.948) and MAE (135.406). Friedrich *et al.* (2014) and Mouw *et al.* (2015) emphasize the challenges in remotely sensing redox potential due to its dependence on complex environmental factors and the limitations of satellite sensors in capturing this parameter accurately. This finding reflects the inherent difficulties in obtaining reliable remote sensing data for redox potential, consistent with the high variability observed in this study.

5.6. Water pH

The results for water pH showed a poor correlation ($R^2 = 0.156$) between satellite and in-situ data, with high RMSE (4.978) and MAE (4.431). This is in line with the findings of Gholizadeh *et al.* (2016) and Zhou *et al.* (2024), who highlighted the limitations of remote sensing for accurately measuring pH, primarily due to the challenges in capturing optically complex water environments and the lack of precise sensors for pH estimation in satellite missions.

5.7. Dissolved Oxygen

Dissolved oxygen measurements from satellites showed a very low R^2 (0.011) and high RMSE (3.928) and MAE (3.673). This aligns with recent studies by Dong *et al.* (2024) and Beal *et al.* (2024), which noted significant challenges in using remote sensing for dissolved oxygen due to its complex nature and the high variability in data captured by satellite sensors. The difficulties in accurately monitoring dissolved

oxygen from space are well-documented, underscoring the need for improved methodologies and models, as discussed by Tiyasha *et al.* (2021) and Shi *et al.* (2024).

5.8. Water Chlorophyll-a

For chlorophyll-a, the satellite data showed a moderate correlation with in-situ measurements (R^2= 0.336), with a relatively lower RMSE (0.289) and MAE (0.186). Mondal *et al.* (2024) and Joshi *et al.* (2024) have similarly reported that while satellite imagery can effectively estimate chlorophyll-a concentrations, there are still challenges related to the accuracy of these measurements due to water turbidity and sensor limitations. Kuhn *et al.* (2019) also noted that while Landsat-8 and Sentinel-2 sensors perform well for chlorophyll-a retrievals, improvements are still needed to enhance the precision of remote sensing data.

6. SUMMARY

The trophic interactions in the Sardar Sarovar Reservoir present a complex web of relationships between various species, including Indian Major Carps, Exotic Carps, Minor Carps, zooplankton, phytoplankton, detritus, and the pressures exerted by fishing activities. Indian Major Carps show moderately negative impacts on Exotic Carps, Minor Carps, and Zooplankton, most likely due to competition for shared resources. This competition for food and habitat demonstrates how species at similar trophic levels can adversely affect one another. However, Indian Major Carps exhibit a positive influence on herbivorous fish and detritus, suggesting their role in nutrient cycling and the breakdown of organic matter within the ecosystem. These interactions highlight their dual role in both competing for resources and promoting nutrient recycling, which is vital for maintaining ecosystem balance.

Exotic Carps, often invasive in nature, show self-reinforcing behaviors, likely due to enhanced reproductive success in a favorable environment. While their presence strengthens their own population, they exert a negative impact on zooplankton and carnivorous fish. This negative influence suggests competition for food or direct predation, reflecting the disruptive nature of invasive species in local ecosystems. Exotic Carps' dominance in certain environments can destabilize native food webs, underscoring the need for careful monitoring and potential management strategies to mitigate their impact. The detritus pool, critical for recycling organic matter in nutrient-poor ecosystems like the Sardar Sarovar Reservoir, plays a significant role in maintaining the overall productivity of the ecosystem by facilitating the flow of nutrients back into the food web.

Minor Carps also contribute positively to primary productivity, particularly through their influence on phytoplankton populations. This suggests that they play a key role in nutrient regeneration, possibly through processes such as bioturbation or excretion, which can enhance the availability of nutrients in the water. However, Minor Carps show minor competition with carnivorous fish and zooplankton, which may indicate localized competition for habitat or food resources. Corica soborna demonstrates strong negative interactions with itself, Indian Major Carps, and Exotic Carps, possibly due to competitive exclusion or overlap in habitat preferences. This

species' adverse effect on phytoplankton suggests that overgrazing may occur, affecting the balance of primary producers in the system.

Herbivorous fish play a stabilizing role in the ecosystem, contributing positively to both phytoplankton and carnivorous fish populations. Their feeding behaviors help to regulate detritus accumulation, reducing excess organic matter and promoting nutrient cycling. By stabilizing the primary producers, herbivorous fish support the structure of the food web, ensuring that energy flows efficiently through the system. Omnivorous fish display a wide range of interactions, negatively impacting carnivorous fish due to competition for similar food resources. However, omnivores also encourage phytoplankton growth through nutrient cycling, showing how species can have complex and sometimes contradictory roles within an ecosystem.

Carnivorous fish, as top predators, exert predation pressure on prey species such as Indian Major and Minor Carps, which aligns with their role as apex predators. This predation helps control the population of lower trophic groups, maintaining balance within the food web. At the same time, carnivorous fish have an indirect positive effect on zooplankton, as their predation on mid-level species reduces competition for zooplankton, allowing their populations to flourish. Zooplankton are vital to the ecosystem's structure, interacting positively with phytoplankton and carnivorous fish. However, their populations are significantly influenced by Exotic Carps and fishing activities, highlighting their vulnerability to both biological and human-induced pressures. Primary producers like phytoplankton are essential for maintaining the base of the food web, but overgrazing by species such as Corica soborna negatively affects their abundance, disrupting energy flow.

The Ecopath model for the Sardar Sarovar Reservoir offers key insights into the system's trophic structure and energy flow dynamics. The high ecotrophic efficiency values for omnivorous fishes, zooplankton, and carnivorous fishes indicate that these groups are heavily utilized, either through predation or fishing. This suggests that these species face significant pressure, which could have long-term implications for the ecosystem if not managed properly. Herbivorous fishes and phytoplankton serve as central components of the ecosystem, acting as primary consumers and producers, respectively.

The model shows that energy transfer efficiency across trophic levels is moderate, with a significant amount of energy retained within primary consumers. This retention aligns with classical ecological models, where energy diminishes as it moves up the food chain due to metabolic losses at each stage.

The reservoir's overall energy turnover is efficient, with a balanced primary production-to-respiration ratio that indicates a healthy ecosystem capable of sustaining itself. The concentration of biomass at lower trophic levels, particularly in primary consumers, further supports the system's stability. This balanced energy distribution is crucial for maintaining the long-term viability of the reservoir's fisheries. The economic importance of the fishery is underscored by substantial catch values and profits, which highlight the need for sustainable management practices to preserve this valuable resource. The reservoir’s moderate omnivory and biodiversity contribute to system stability, while the model's pedigree and fit indices suggest a high level of confidence in its findings.

Satellite-derived water quality data offer mixed results in comparison with *in-situ* measurements. Water temperature data show a strong correlation, demonstrating the reliability of remote sensing for this parameter. Satellite imagery effectively captures large-scale temperature patterns in surface waters, making it a valuable tool for ongoing environmental monitoring. However, measurements for oxygen redox potential display moderate accuracy, reflecting the challenges of capturing this complex parameter remotely. Oxidation redox potential depends on numerous environmental variables, and current satellite technologies may lack the precision needed for accurate remote sensing of this parameter.

Water pH measurements show a poor correlation with in-situ data, suggesting that remote sensing may not be well-suited for this parameter, particularly in optically complex water environments like the reservoir. Similarly, dissolved oxygen measurements exhibit very low correlation with in-situ data, emphasizing the difficulties in monitoring this parameter through satellite technology. The variability of dissolved oxygen levels, influenced by numerous biological and chemical processes, makes it challenging to capture accurately from space. Chlorophyll-a measurements, on the other hand, show moderate correlation with in-situ data, indicating that satellite

imagery can provide useful estimates, though factors such as water turbidity and sensor limitations still affect accuracy.

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ABBREVIATION

1. °C : Celsius
2. µm :Micrometer
3. B : Biomass
4. B/TSS: Biomass/Total System Throughput
5. C/B : Consumption/ Biomass
6. Chl-a :Chlorophyll-a
7. Chl-a: Chlorophyll-a
8. CI : connectance index
9. DMS :Degrees, Minutes, and Seconds
10. DO : Dissolved Oxygen
11. DO :Dissolved oxygen
12. EE : Ecotrophic Efficiency
13. GDP :Gross domestic product
14. GPP : Gross Primary Productivity
15. kg/ha/year :kilograms per hectare
16. mg/l :Milligrams per liter
17. Mv :Millivolts
18. NPP : Net Primary Productivity
19. OLI :Operational Land Imager
20. ORP :Oxidation-reduction potential
21. P/B : Production/Biomass
22. P/Q : Production/Consumption
23. PH : Potential of Hydrogen
24. PP : Primary Productivity
25. SOI : System Omnivory Index
26. T km^{-2} y^{-1} :Tones per kilometer square per year
27. T km^2 y^1: Tones per kilometer square per year
28. T km^2: Tones per kilometer square
29. TL : Trophic Level
30. TL: Trophic level

31. TPP/TB: Total Primary Productivity/Total Biomass
32. TPP/TR: Total Primary Productivity/Total Respiration
33. TSI : Trophic State Index
34. TST : Total System Throughput