A Multi-index Remote Sensing Approach to Track Water Shifts in Handero Lake

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Abstract

Freshwater Wetlands are essential ecosystems but remain highly vulnerable to climate variability and human pressures. This study examines the spatiotemporal changes in the water of Handero Lake from 2001 to 2024, using Landsat satellite imagery and three water indices: the Normalized Difference Water Index (NDWI), the Modified Normalized Difference Water Index (MNDWI), and the Automated Water Extraction Index-Shadow (AWEIsh). A standardized workflow that includes cloud masking, thresholding, and multi-temporal compositing was used to analyze lake water dynamics. The lake's core remained hydrologically stable, with water extent ranging from 13.8 to 17.4 km². NDWI identified the most significant areas, although it often overestimates the extent of these areas. MNDWI provided more accurate results in semi-arid regions, while AWEIsh offered the most conservative and reliable estimates in complex terrains. This approach highlights the importance of multi-index analysis and cloud platforms in ensuring effective, long-term wetland monitoring and water management in regions sensitive to climate change.

Keywords: Remote sensing; Handero lake; Water dynamics; Water indices; Pakistan

1. Introduction

Freshwater ecosystems are essential for biodiversity and human well-being, but they are increasingly threatened by climate change, unsustainable resource use, and human activities (Igwe et al., 2023). The rapid decline of water-related biodiversity, combined with climate change, leads to increased hydrological extremes and disasters. It also helps sustain biodiversity and provides vital ecosystem services (Brauman et al., 2015). Surface water resources play a significant role in the climate system and the hydrological cycle (Tranvik et al., 2009; Collen et al., 2014). Satellite data show that global freshwater reserves have decreased sharply, losing nearly 290 cubic miles of water since 2015, mainly due to rising global temperatures and disrupted hydrological cycles (Vörösmarty et al., 2010; Rodell et al., 2018; IPCC, 2022). This decline is roughly equivalent to draining Lake Mead three times and is closely related to the

warmest years on record (Rodell et al., 2018; Wada et al., 2013). This deterioration poses serious ecological risks, with nearly one-quarter of freshwater species at risk of extinction (Dudgeon et al., 2025). An integrated approach is especially important in ecologically fragile and data-scarce areas, such as Sindh Province, located in Pakistan's climatically sensitive lower Indus Basin. This region is home to numerous freshwater and brackish ecosystems that support both biodiversity and agriculture. However, these ecosystems face growing threats from transboundary hydrological imbalances, unregulated land use, and rapidly increasing population (Hannan et al., 2024). Sindh's wetlands are recognized as environmentally and socioeconomically vital sites. Still, despite improvements in surface water analysis, climate-sensitive and ecologically critical wetlands such as Hadero Lake in Pakistan continue to be underrepresented in long-term monitoring studies (Aslam et al., 2024; Mahessar et al., 2015).

Remote sensing is a crucial tool for studying wetland ecosystems, which often cover large and inaccessible areas (Rokni et al., 2014). Satellite sensors, including both optical and microwave types, are used to map water bodies and wetland boundaries. Spectral indices such as the Normalized Difference Water Index (NDWI), Modified Normalized Difference Water Index (MNDWI), and Automated Water Extraction Index – Shadow (AWEIsh) have become vital for monitoring surface water dynamics on a large scale (Adam et al., 2010; McFeeters, 2013; Pekel et al., 2016). Integrating remote sensing with cloud-based platforms, such as Google Earth Engine (GEE), has revolutionized hydrological research by enabling scalable, efficient, and long-term surface water monitoring across broad geographic regions (Feyisa et al., 2014; Gorelick et al., 2017; Zhao et al., 2021; Amani et al., 2020). This study conducts a spatiotemporal analysis of Handero Lake water changes over 24 years (2001-2024), using multi-sensor Landsat imagery (Landsat 7, 8, and 9) processed through the GEE platform (Yang et al., 2003; Rokni et al., 2014; Asfaw et al., 2020). Following established methods (Wang et al., 2018; Mugiraneza et al., 2020), the study employs a standardized workflow that includes cloud and shadow masking, radiometric normalization, and the calculation of water indices (AWEIsh, MNDWI, and NDWI) to improve water body detection under different environmental conditions. The analysis is divided into five specific periods (2001-2005, 2006-2010, 2011-2015, 2016-2020, and 2021-2024). This approach offers a transparent and reproducible workflow for assessing hydrological variability in wetlands within arid regions. The findings provide important insights to support wetland conservation, ecosystem restoration, and sustainable water management, particularly in response to increasing environmental pressures and human impacts.

2. Materials and Methods

2.1 Study Area

Lake Handero, located in the Thatta District of Sindh Province, Pakistan (24°49′42″N, 67°51′37″E), is a freshwater body situated within the ecologically important Indus River Delta (Figure 1). This delta system is characterized by a semi-arid climate, with low annual rainfall (150–250 mm), high evapotranspiration rates, and significant seasonal water fluctuations, mainly driven by the southwest monsoon and irregular upstream water releases (Khan et al., 2020). The region experiences hot summers with high temperatures and mild winters. Rainfall is infrequent

and inconsistent, mostly occurring during the monsoon season, which is vital for replenishing the lake's hydrological cycle. Despite being close to the Arabian Sea, Lake Handero remains freshwater due to continuous inflows from inland sources. The surrounding landscape includes a mix of agricultural land and natural wetlands, which enhances the lake's role as a key water resource. Hydrologically, Lake Handero is sustained by water from the Indus River system, primarily through a complex network of irrigation canals. These canals divert water for farming and recharge natural depressions and freshwater lakes. The lake's water levels fluctuate throughout the year, affecting its ecology and resource availability. It provides water for domestic use, livestock, and local fisheries. However, increasing human activities and climate change raise concerns about its long-term future. Understanding the hydrological processes, ecological significance, and human impacts on Lake Handero is crucial for developing effective conservation and water management strategies.
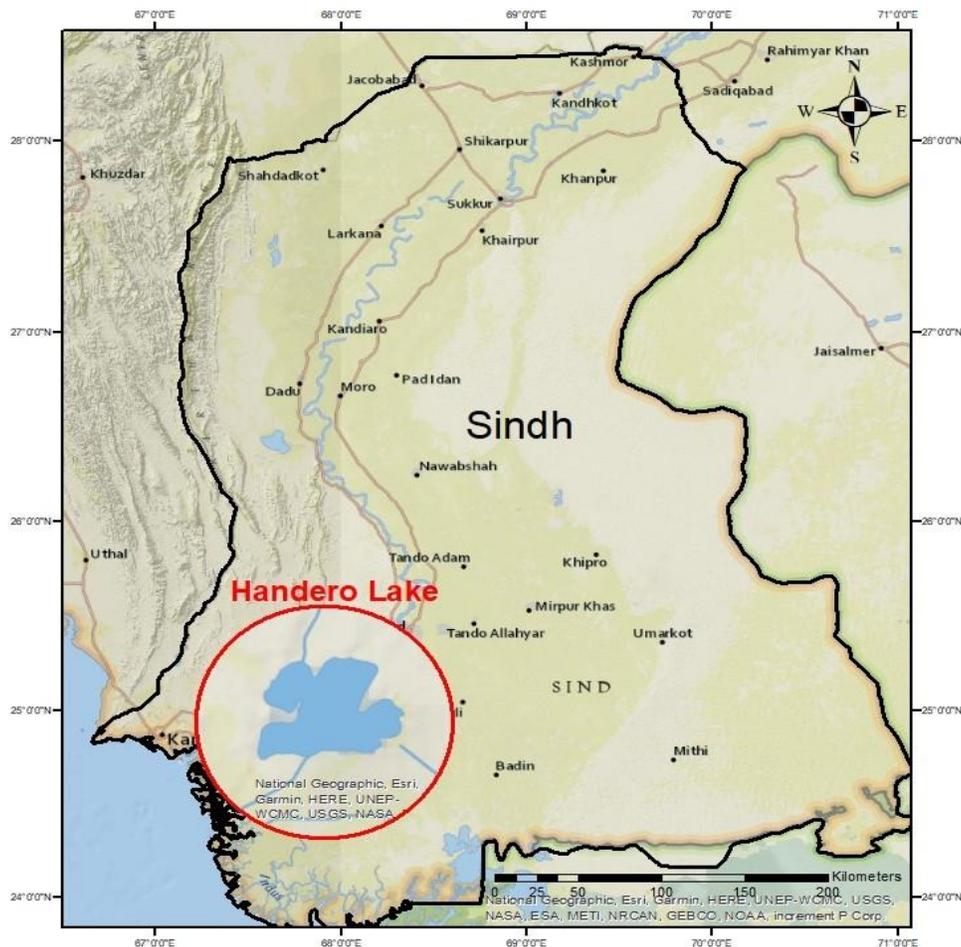

Figure 1. Specific map location of Handero Lake in Sindh, Pakistan.

2.2 Data Sources

To analyze the lake water extent within the lake, a series of multi-temporal satellite images from Landsat 7 ETM (Enhanced Thematic Mapper Plus), Landsat 8 OLI (Operational Land Imager), and Landsat 9 OLI-2 (Operational Land Imager 2) sensors were used (Table 1). All datasets were obtained as Collection 2, Tier 1 Level 2 Surface Reflectance products, which offer radiometric and geometric corrections to ensure consistency and comparability over time. To improve the reliability of water detection, cloud and shadow contamination were mitigated by applying pixel quality masks. Specifically, pixels marked as clouds, cloud shadows, or cirrus within the QA_PIXEL band were excluded. The processed datasets, resampled at a spatial resolution of 30 meters, were exported using the GEE platform to support detailed spatial and temporal assessments of water changes.

Table 1. Datasets used in the study.

Period	Sensor	Source
2001-2013	Landsat-7 (+ ETM)	https://developers.google.com/earth-engine datasets/catalog/LANDSAT_LE07_C02_T1_RT
2014-2020	Landsat-8 (OLI)	https://developers.google.com/earthengine/ datasets/catalog/LANDSAT_LC08_C02_T1_RT
2021-2024	Landsat 9 (TIRS-2)	https://developers.google.com/earth-engine/ datasets/catalog/LANDSAT_LC09_C02_T1_TOA

2.3 Water Indices

Lake water delineation was performed using three spectral indices (Table 2), based on the distinct reflectance of water in the visible, NIR, and SWIR regions. The NDWI, which uses green and NIR bands, improves the detection of open water but may misclassify urban features (McFeeters, 2013). To address this, the Modified NDWI (MNDWI) replaces the NIR with SWIR1 to reduce spectral confusion in built-up areas (Xu, 2006). Additionally, AWEIsh was applied to minimize shadow-related false positives in complex terrains and low-light conditions, outperforming other indices in shadowed regions (Feyisa et al., 2014). All indices were calculated from median composites of cloud-free Landsat images, and a threshold of zero was used to generate binary water masks (McFeeters, 2013; Xu, 2006).

Table 2. Water indices used in the study.

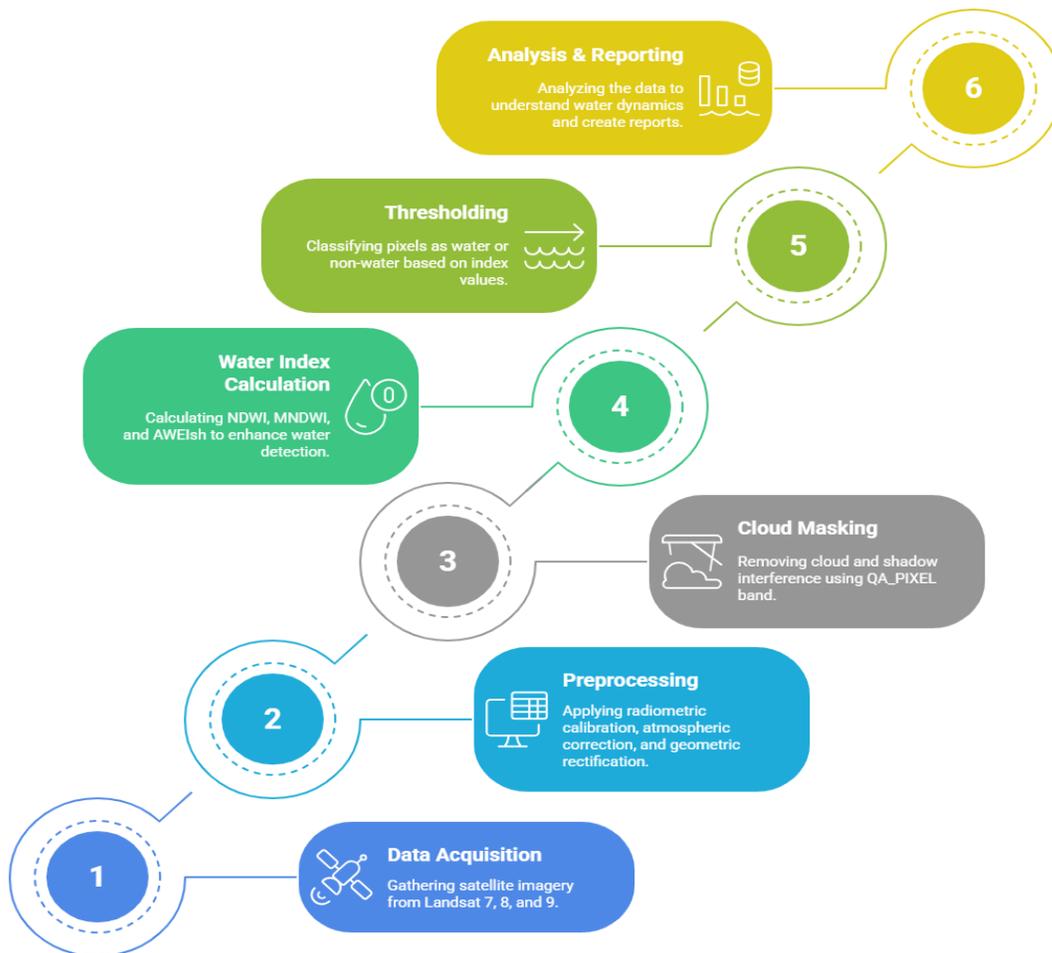| Index	Name	Formula
AWEIsh	Automated Water Extraction Index – Shadow	Blue+2.5×Green-1.5×(NIR+SWIR1)-0.25×SWIR2
MNDWI	Modified Normalized Difference Water Index	$\dfrac{(Green - SWIR1)}{(Green + SWIR1)}$
NDWI	Normalized Difference Water Index	$\dfrac{(Green - NIR)}{(Green + NIR)}$

Figure 2. Methodological framework of the study.

3. Results

3.1 Spatiotemporal Lake Water Shifts

First, consider the three well-established water detection indices: NDWI, MNDWI, and AWEI. Each row in the figure shows lake water delineation based on one of these indices, while the columns represent five-year intervals from 2001 to 2024. These indices utilize the unique spectral reflectance properties of water in the visible, near-infrared (NIR), and shortwave infrared (SWIR) bands to distinguish open water from surrounding land features. Using multiple indices is methodologically important. Although all three are designed to improve water visibility, usually displaying water bodies in blue and non-water features in grayscale, their strengths differ in various contexts (Figure 3). NDWI, despite its widespread use, tends to overestimate water extent in built-up or moist areas because it relies on green and NIR bands. MNDWI, which replaces the NIR band with SWIR1, reduces such false positives and offers a more conservative and accurate detection, especially in urban or heterogeneous environments. AWEI, specifically developed to address misclassification caused by shadows and mixed land cover pixels, provides the most restrained water mapping, making it exceptionally reliable in complex terrains or under variable lighting conditions. Over the two-decade observation period, all three indices consistently identify the lake's core water body, indicating a relatively stable hydrological regime.
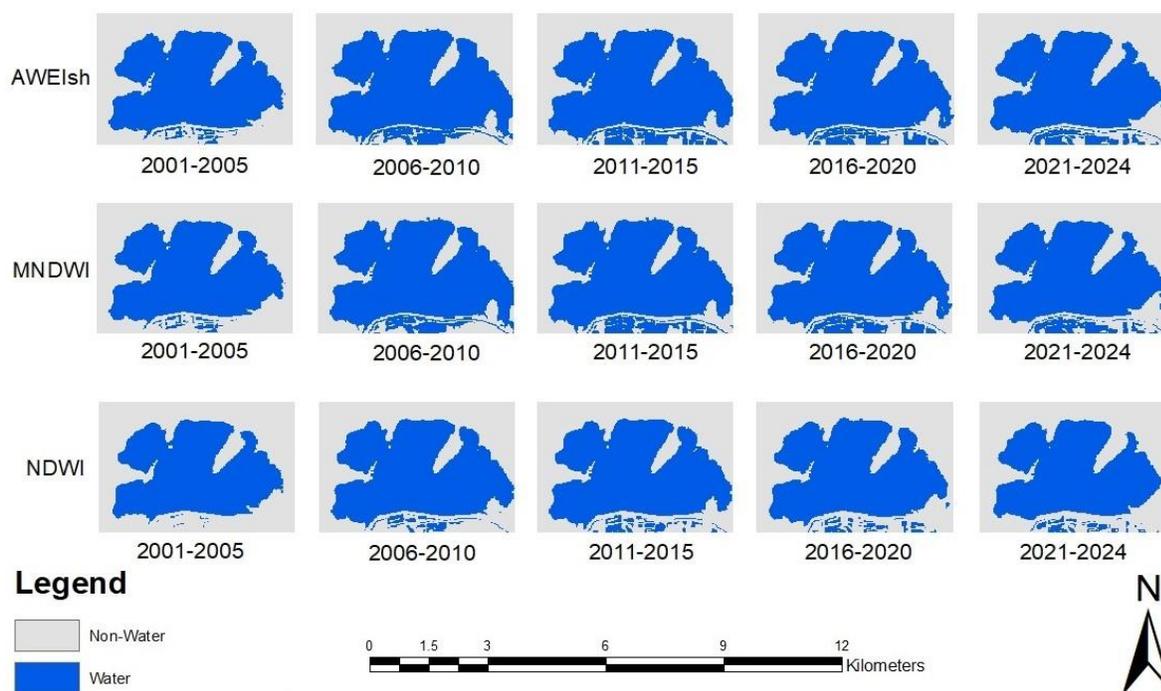

Figure 3. Spatial variation of Handero Lake extent from 2001 to 2024 derived using NDWI, MNDWI, and AWEIsh indices.

Despite observable interannual variability, the overall spatial extent of the primary water body has remained essentially unchanged, reflecting consistent water input likely associated with steady monsoonal inflows and irrigation connectivity. However, a closer look at peripheral areas reveals subtle temporal shifts, such as slight expansions or contractions of water patches, which may result from seasonal flooding, evaporation cycles, or localized water management efforts. Quantitatively, NDWI generally reports the most significant water extent, sometimes exceeding 17 km², followed by MNDWI with slightly more conservative estimates (Figure 4). This pattern underscores NDWI's sensitivity but also its susceptibility to misclassification. In contrast, AWEI consistently provides the lowest water area measurements, often aligning more closely with ground conditions due to its improved ability to distinguish non-water features under shadows or reflectance interference. These findings confirm that while all three indices effectively capture seasonal and interannual hydrological variations, their use must be tailored to the context. AWEI appears to be the most reliable for areas with complex land cover, whereas NDWI and MNDWI remain useful for large-scale monitoring, particularly where high temporal resolution is crucial.
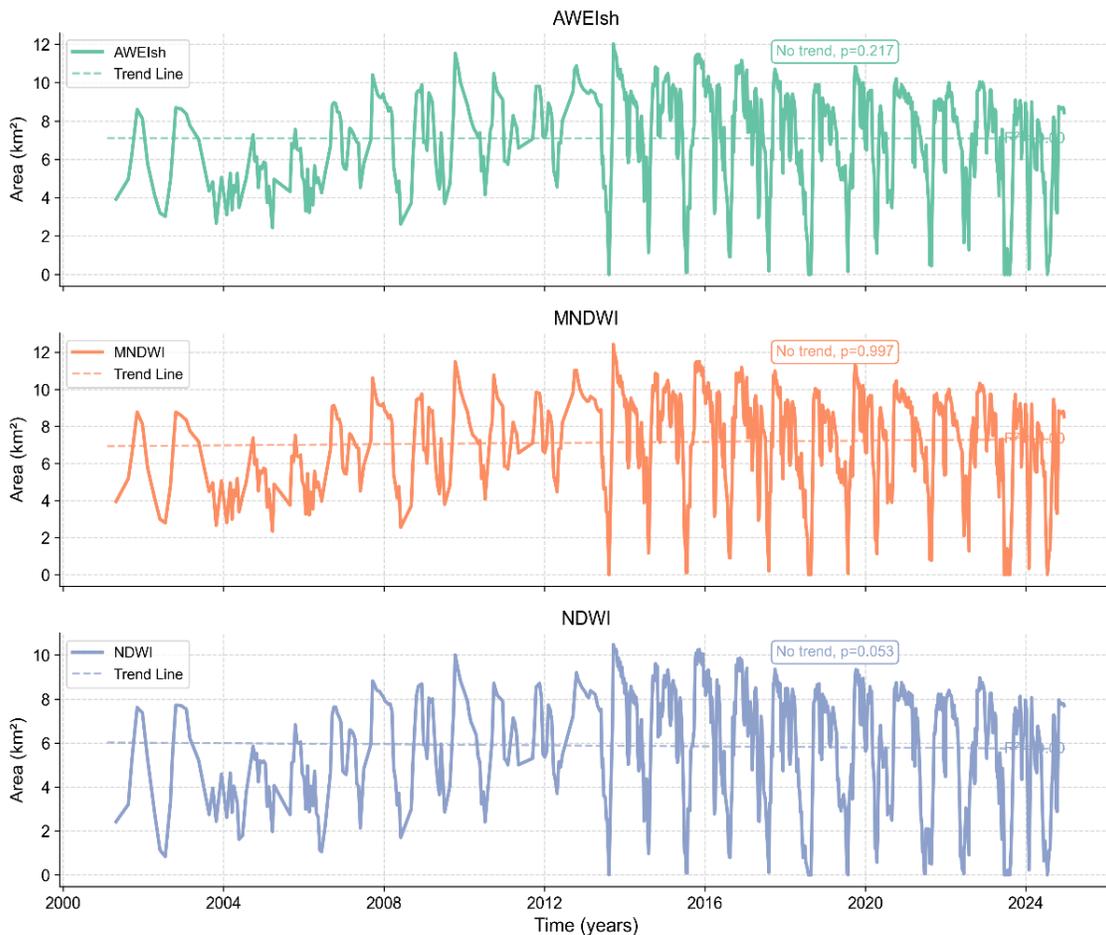

Figure 4. Temporal variation of Handero Lake water extent (2001–2024) as measured by NDWI, MNDWI, and AWEIsh.

3.2 Performance of Water Indices

The performance of three widely used water indices (NDWI, MNDWI, AWEI) was evaluated by visually inspecting satellite imagery from key periods and locations. Optimal threshold values were identified for each index to distinguish water from non-water pixels, specifically (NDWI, 0.111), (MNDWI, 0.16), and (AWEI, 9.984). These thresholds were determined through iterative assessment to ensure the most accurate delineation of lake water features. Among the indices, MNDWI consistently showed superior performance, especially in areas with sparse vegetation and flat terrain. It provided more precise boundaries and more accurate detection of both small and large bodies of water. In contrast, NDWI exhibited lower sensitivity, often failing to identify some actual water pixels, particularly in riverine and shallow water environments. Although NDWI highlighted broader water areas, it struggled in complex landscapes with mixed land cover. AWEI demonstrated high specificity for larger water bodies, effectively reducing false positives in shaded or urban regions (Figure 5). However, it occasionally misclassified certain non-water surfaces, such as darker soil or shadowed areas, as water. It was less effective in detecting smaller or narrower water features, such as rivers and isolated ponds. Notably, both AWEI and NDWI had limitations in accurately mapping small-scale water features, especially in highly heterogeneous environments. In summary, MNDWI outperformed the other indices in terms of spatial accuracy and reliability for detecting surface water across various land cover types. While AWEI was particularly good at detecting large open water bodies under shadowed conditions, its performance was limited for minor or narrow water features. Although widely used, NDWI showed lower classification accuracy compared to the other two indices.
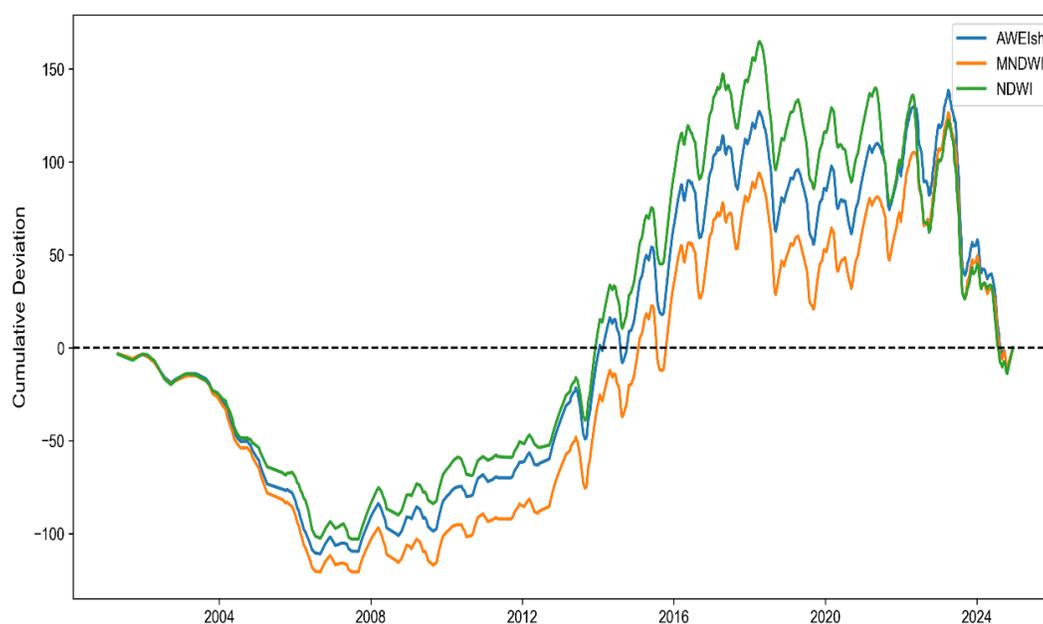

Figure 5. Comparative performance of NDWI, MNDWI, and AWEIsh indices based on cumulative deviation and threshold calibration.

4. Discussion

Over the 24-year analysis period, the central water body of Handero Lake remained relatively stable despite noticeable year-to-year variability along its edges. This stability likely results from consistent hydrological inputs from monsoonal rains and irrigation systems supplied by the Indus River basin, as supported by findings from Khan et al. (2020), who highlighted the importance of canal-fed lakes in maintaining perennial water presence in the Lower Indus Basin. However, the peripheral water bodies exhibited signs of shrinkage in certain years, possibly due to evapotranspiration losses, decreased inflows from upstream water regulation, or land-use encroachment, all concerns raised by Ashraf and Routray (2020) regarding unregulated hydrological management and agricultural growth in the basin.

The comparison of water indices illustrated the strengths and suitability of each method in different contexts. NDWI, while useful for broad water mapping, tended to overestimate water extent, especially in areas with moist soil, wetlands, or vegetation, due to its reliance on green and NIR reflectance (McFeeters, 2013). This over classification issue is well-known and was evident in Handero Lake's outer zones, where NDWI showed false water pixels in vegetated or developed areas. Conversely, MNDWI, which replaces the NIR band with SWIR1, provided greater accuracy in differentiating water from surrounding land cover, reducing confusion in urban or mixed spectral regions; this performance trend has been confirmed by Xu (2006) and in similar arid-region studies (Feyisa et al., 2014; Mallick et al., 2022). AWEIsh, specifically designed to avoid shadow-related classification errors, was highly effective in identifying water in complex lighting and land cover conditions, providing conservative yet accurate water estimates, especially during periods with high solar angles or thick atmospheres. While its conservative approach reduced false positives, AWEIsh was less effective in detecting narrow or fragmented water features, an issue noted by Liu et al. (2022), who observed that the index might overlook shallow or vegetated water bodies. This trade-off between specificity and sensitivity highlights the importance of using multiple indices in conjunction to produce a balanced and comprehensive view of lake water, as emphasized by Pekel et al. (2016) and Wang et al. (2018). Despite the overall stability of Handero Lake's main water body, the observed changes in surface extent along its edges raise significant ecological and management concerns. Handero Lake provides habitat for migratory birds, fisheries, and biodiversity in the Indus Delta, making its hydrological stability critical for maintaining ecosystem services. Peripheral shrinkage threatens breeding grounds and fisheries that sustain nearby communities in Thatta District, while seasonal expansions increase vulnerability to agricultural runoffs and pollution. Since local livelihoods in Sindh depend heavily on fisheries, irrigation water, and small-scale farming, changes in the lake's margins could directly influence food security and income. Small reductions during drought-prone times and expansions during heavy monsoon years highlight the lake's vulnerability to both climate variability and human activities. This sensitivity reflects broader global trends showing increasing pressure on freshwater ecosystems, with nearly a quarter of freshwater species at risk of extinction due to changes in water flow and land use (Dudgeon & Strayer, 2025; Collen et al., 2014). In addition, sediment coming from upstream activities, along with unmanaged aquaculture and agricultural runoff, may further harm the lake's ecological

health, supporting Aslam et al. (2024)'s call for integrated wetland vulnerability assessments using machine learning and remote sensing.

From a policy perspective, study findings highlight the need for integrated wetland management strategies in Sindh Province. Improved monitoring of lake margins using multi-index remote sensing could serve as an early warning system for local water managers, informing interventions by the Sindh Irrigation Department and provincial environmental authorities. Linking remote sensing with adaptive policy tools could enhance climate resilience, guide Ramsar site protection, and ensure that biodiversity and livelihoods remain safeguarded. While this study provides valuable long-term insights, the absence of in-situ field validation constrains the quantitative accuracy of the results. Thresholds were derived iteratively from Landsat imagery, which ensures internal consistency but does not substitute for ground truth data. Future research should incorporate field-based water measurements and high-resolution imagery to validate spectral classifications. Integrating socio-hydrological data would further improve the relevance of findings for adaptive water governance.

5. Conclusion

The study presents a detailed spatiotemporal analysis of the water changes in Handero Lake from 2001 to 2024, utilizing multi-sensor Landsat data and three key spectral water indices. By employing a multi-index approach combined with cloud-free composites, threshold calibration, and index-specific sensitivity analysis, the research successfully uncovers both the stability and fluctuations of lake surface dynamics in response to climate and human activities. The study reveals that while the lake's main water body has remained relatively stable, primarily supported by monsoon inflows and irrigation, its marginal zones have undergone intermittent changes, likely due to upstream water regulation, seasonal shifts, and local land-use modifications. Beyond methodological advances, the findings have clear applied implications for Sindh Province. The observed stability of the lake core suggests resilience under current irrigation and climatic conditions; however, edge variability indicates ecological vulnerability and socio-economic risk. Multi-index monitoring offers provincial water managers and conservationists a replicable, low-cost framework for identifying critical buffer zones and prioritizing adaptive interventions. Such approaches can inform wetland conservation policies, guide biodiversity protection, and strengthen Sindh's climate resilience planning.

Among the indices tested, MNDWI proved to be the most accurate and suitable for mapping lake water in flat, semi-arid areas. Similarly, AWEIsh was highly effective in complex terrains and shaded regions. NDWI, although popular, tends to overclassify in heterogeneous landscapes. This integrated method not only advances research on wetland monitoring in South Asia but also offers a replicable framework for long-term freshwater ecosystem assessment in regions with limited data and ecological sensitivity. The central core of Handero Lake remained hydrologically stable over the 24 years, indicating resilience to short-term environmental changes. NDWI overestimated water coverage in mixed land cover areas due to spectral confusion, especially in zones near vegetation and urban areas. MNDWI showed higher accuracy

in identifying water bodies, especially in flat and semi-arid areas with little urban disturbance. AWEIsh performed well in shadowy and complex lighting conditions, but it was less responsive to narrow or fragmented water features. The findings highlight the need for targeted wetland conservation strategies, especially in buffer zones along the lake margins where hydrological changes are more significant.

Acknowledgments

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