

Satellite-Derived Turbidity Seasonality and Long-Term Trend in Manchar Lake, Pakistan (2016-2024): A Sentinel-3 Analysis

Hamza Khaliq [1*], Muhammad Ghawas kareem [2], Abdul Rauf [3], Muhammad Aziz Abid [4]
[1] College of Environment, Hohai University, Nanjing, 210098, China
[2] College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098, China
[3] Cartography and GIS, Hohai University, Nanjing, 210098, China
[4] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China

* Corresponding Author: **Hamza Khaliq**

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Abstract
Manchar Lake is a shallow, seasonally variable freshwater lake in Sindh, Pakistan, subject to agricultural drainage, saline inflow, and domestic and industrial pressures. This study characterizes seasonal variability and evaluates evidence for a monotonic change in satellite-derived turbidity using the Copernicus Land Monitoring Service Lake Water Quality product from Sentinel-3 OLCI. The supplied time series comprised 305 nominal 10-day composites from 11 May 2016 to 21 October 2024. Trend was evaluated using the Mann-Kendall test and Sen's slope estimator at three temporal resolutions: the raw 10-daily series, monthly observations analyzed with a seasonal Mann-Kendall framework, and annual means for complete years 2017-2023. The analysis found a positive but statistically non-significant tendency in all three formulations. For annual means, the reported Sen's slope was +0.26 NTU per year (Kendall's tau = 0.43, $p = 0.23$), equivalent to approximately +3.0% of the study-period mean per year. The 2017 and 2023 annual means differed by 18.3%. July-September turbidity averaged 11.12 NTU compared with 7.97 NTU in October-June (39.6% higher; Mann-Whitney U test, $p < 0.001$). These results support a strong recurring seasonal association, but they do not by themselves establish monsoon causation or a confirmed long-term increase. Independent field validation, explicit quality-control reporting, and a longer record are needed to determine whether the indicative upward tendency represents a persistent change in lake turbidity.

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Keywords: Manchar Lake; turbidity trend; Mann-Kendall test; Sen's slope; Sentinel-3; seasonal variability; remote sensing

1. Introduction

Turbidity is a widely used indicator of freshwater condition because it reflects suspended sediment, algal material, and colloidal matter that affect light penetration, aquatic habitat, and water-treatment requirements. Determining whether turbidity is increasing, decreasing, or stable requires more than visual inspection of a time series. Seasonal cycles, irregular observation intervals, compositing, missing observations, and serial dependence can all affect the apparent direction and statistical significance of a trend. Non-parametric methods, including the Mann-Kendall test and Sen's slope estimator, are useful because they do not require a particular distribution and are comparatively robust to outliers. However, serial correlation and strong seasonality must be considered when interpreting their variance and p-values [1-3, 12].

Manchar Lake, in Sindh Province, Pakistan, is a shallow and highly seasonal lake that has experienced substantial water-quality stress associated with agricultural return flows, saline intrusion, and domestic and industrial effluent [4-6]. Previous studies have described the lake's water quality, salinity, and ecological condition using field observations and remote-sensing data [4, 6].

Remote sensing can extend the temporal and spatial coverage of such assessments, but satellite-derived water-quality products remain subject to atmospheric-correction error, shoreline mixing, cloud contamination, retrieval uncertainty, and the absence of local in situ validation [7, 10, 11].

The long-term direction of lake turbidity is therefore important but should be distinguished from the recurring seasonal cycle. A seasonal increase may reflect hydrological and optical conditions that repeat each year, whereas a long-term trend requires evidence of systematic change across years after the seasonal structure has been addressed. The present study has two objectives: (i) to quantify the direction, magnitude, and statistical evidence for a monotonic change in satellite-derived turbidity over the 2016-2024 Sentinel-3 record; and (ii) to quantify the difference between July-September and October-June observations. The results are interpreted as patterns in a satellite-derived product. Attribution to monsoon rainfall or other physical drivers requires independent hydrometeorological observations and is not inferred from the turbidity series by itself.

2. Materials and Methods

2.1. Study area and data source

Manchar Lake is located in Sindh Province, Pakistan, approximately 18 km west of Sehwan. The lake lies within approximately 26°23' to 26°28' N and 67°34' to 67°43' E, and is bordered by the Indus River to the east, the Kirthar Mountains to the west, and the Laki Hills to the south [6]. Its surface area is strongly seasonal; approximately 220 km² in April 2019 and 256 km² in November 2019 were reported in a recent assessment [6]. Turbidity observations were obtained from the Copernicus Land Monitoring Service Lake Water Quality 2016-2024 product (300 m, global, 10-daily, version 1) derived from Sentinel-3 OLCI observations [8]. The product is distributed as nominal 10-day periods beginning on days 1, 11, and 21 of each month. Its documented fields include mean turbidity, within-period turbidity standard deviation, and the number of observations used to estimate turbidity [9]. The supplied trend file contained 305 lake-level observations spanning 11 May 2016 to 21 October 2024. The source manuscript labels the lake-level statistic as a median. Because the public product is raster-based, the manuscript must state explicitly whether this value was calculated as a median across valid lake pixels, taken from a pre-aggregated lake-level record, or produced by another operation.

The complete date-value table, original NetCDF files or download identifiers, pixel mask, quality flags, valid-pixel counts, and aggregation code should accompany the submission. Quality-control reporting should also state the minimum valid-pixel threshold, treatment of quality-risk flags, use of a shoreline buffer, and whether a fixed or date-varying water mask was used. These details are important because the lake changes in area and the product documentation identifies shoreline and retrieval limitations for lake averages [9].

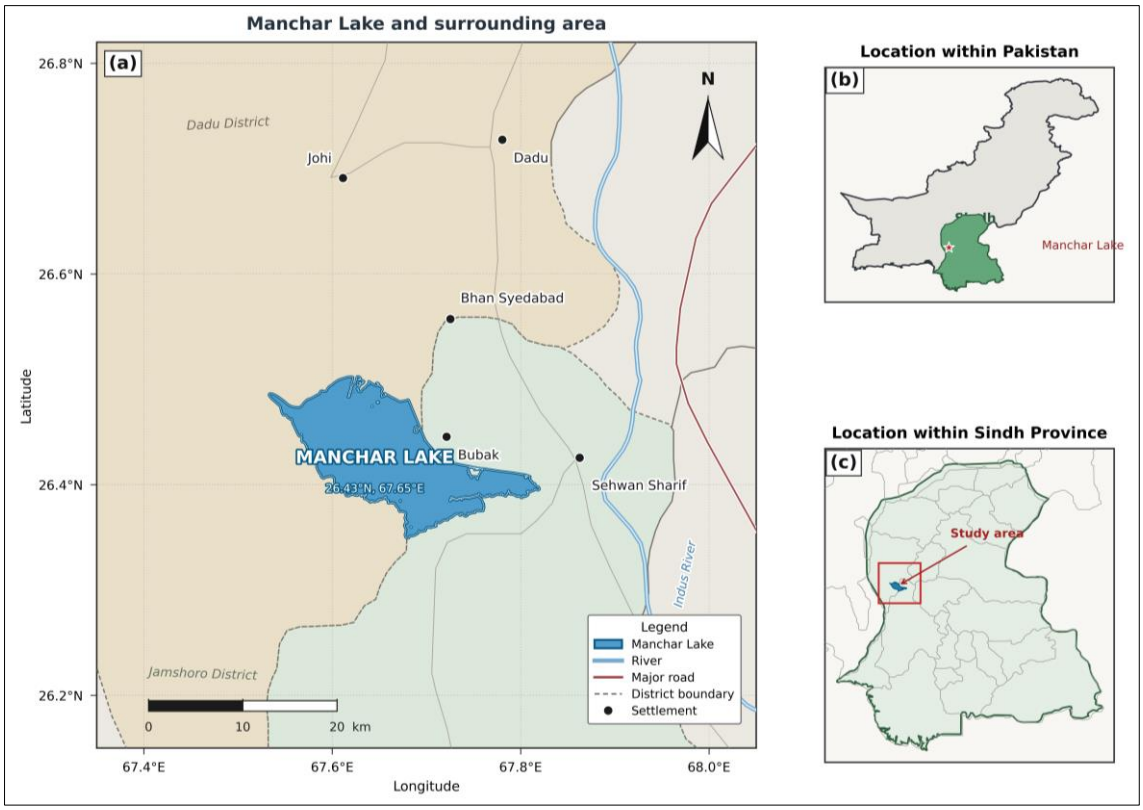


Fig 1: Location of Manchar Lake in Sindh Province, Pakistan. Panel (a) shows the lake and surrounding settlements, major roads, the Indus River, and district boundaries; panels (b) and (c) locate the study area within Pakistan and Sindh Province, respectively. The mapped shoreline is a cartographic reference and does not represent a single-date hydrological extent. Coordinate system: WGS 84 (EPSG:4326). Administrative boundaries and base vectors: Natural Earth v5.1.1 and geoBoundaries Pakistan ADM2; lake geometry and settlement locations: © OpenStreetMap contributors.

2.2. Trend detection

Three temporal representations were evaluated. First, the raw 305-observation 10-daily series was tested directly. Second, monthly means were analyzed with a seasonal Mann-Kendall framework that compares observations within the same calendar month across years. This is distinct from creating a

deseasonalized anomaly series; the manuscript uses the term seasonal Mann-Kendall analysis unless an explicit anomaly calculation is documented. Third, annual means were calculated for the seven complete calendar years 2017-2023. Partial years 2016 and 2024 were excluded from the annual trend test but retained in descriptive figures.

For observations x1, x2, ..., xn ordered by time, the Mann-Kendall statistic is:

$$S=k=1n-1j=k+1nsgnxj-xk \quad (1)$$

where sgn(θ) equals +1 if θ is positive, 0 if θ is zero, and −1 if θ is negative. Under the null hypothesis of no trend, S is approximately normally distributed with mean zero and a variance that depends on the sample size n and on any tied values in the series [1, 3]; the resulting standardized statistic Z is compared against the standard normal distribution to obtain a two-sided p-value, with the null hypothesis of no trend rejected at the conventional $\alpha = 0.05$ level when $p < 0.05$. Kendall's tau, reported alongside S, is a rank-correlation measure of the strength and direction of the trend, with positive values indicating an increasing tendency and negative values a decreasing one.

The rate of change was estimated using the Sen's slope estimator [2], the median of the pairwise slopes between every pair of observations:

$$Q=medianxj-xkj-k \text{ for all } k < j \quad (2)$$

Sen's slope Q is expressed in the original units of the series per unit time (NTU per 10-day step, per month, or per year, depending on the series tested) and is reported here in NTU per year and as a percentage of the overall study-period mean turbidity to give an interpretable annual rate of change.

2.3. Seasonal comparison

Composites were classified as July-September or October-June. The two groups were compared using a two-sided Mann-Whitney U test. The result is interpreted as a difference in the distributions of satellite-derived turbidity, not as a direct test of a difference in means. The difference in reported group means was expressed relative to the October-June mean. The magnitude of the rank-biserial effect size was reported as 0.47; its sign depends on the order used to define the U statistic. Because observations within years are temporally related, a year-block or block-bootstrap sensitivity analysis should accompany the individual-composite comparison.

3. Results

3.1. Temporal pattern of observed turbidity

The supplied series had a mean turbidity of 8.80 NTU, a median of 7.71 NTU, a standard deviation of 4.25 NTU, and a range of 2.15-23.56 NTU. Figure 2 shows the complete record together with the annual-complete-year Sen's slope line. The series displays recurring within-year variability, with higher values generally occurring from late spring through summer and lower values during autumn and winter. The unusually low values near the end of 2024 must be interpreted cautiously because the record ends on 21 October 2024, before a complete post-monsoon cycle is available.

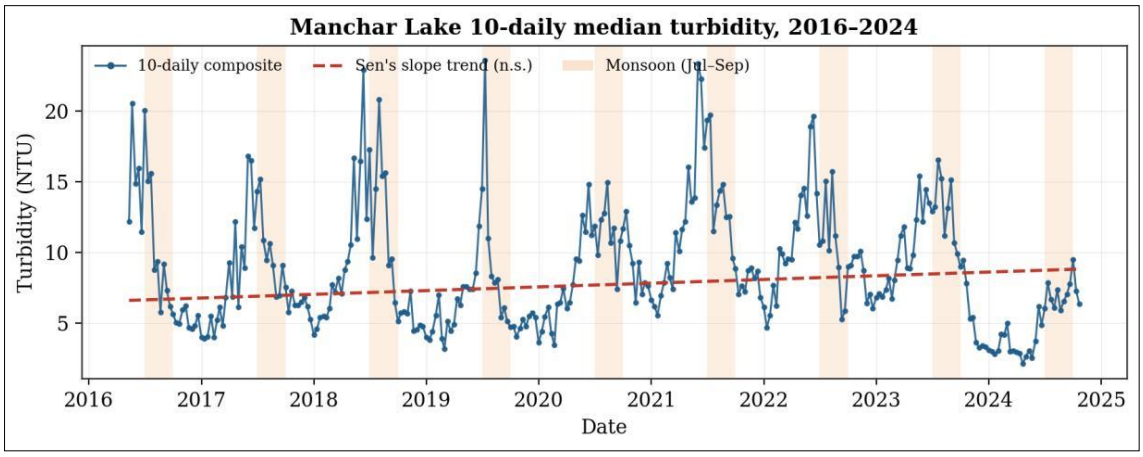


Fig 2: Lake-level turbidity for Manchar Lake, 2016-2024 (blue), with the Sen's slope line from the complete-year annual analysis (red dashed; +0.26 NTU per year; not statistically significant). Shaded bands indicate July-September periods.

3.2. Long-term trend

All three reported trend estimates were positive, but none reached the conventional 0.05 significance threshold. The annual complete-year analysis is the most readily interpretable summary because it avoids comparing partial years. Its reported Sen's slope was +0.26 NTU per year, with Kendall's tau = 0.43 and p = 0.23. The annual mean increased from 8.16 NTU in 2017 to 9.65 NTU in 2023, an endpoint difference of 18.3% over six years. This endpoint comparison is descriptive and should not be treated as a substitute for a trend test.

Table 1: Reported Mann-Kendall trend statistics at three temporal resolutions.

Series tested	N	Kendall's τ	S	p-value	Sen's slope	Rate (%/yr)
Raw 10-daily composites, 2016-2024	305	0.006	262	0.883	+0.02 NTU/yr	+0.2%
Deseasonalized monthly means, 2016-2024	102	0.057	22	0.494	+1.49 NTU/yr	+16.9%
Annual means, complete years, 2017-2023	7	0.429	9	0.230	+0.26 NTU/yr	+3.0%

Note: The numerical values in this table are retained from the supplied analysis. Before submission, recompute the test using the archived date-value series, the documented spatial aggregation, actual observation dates, and an autocorrelation-robust sensitivity analysis.

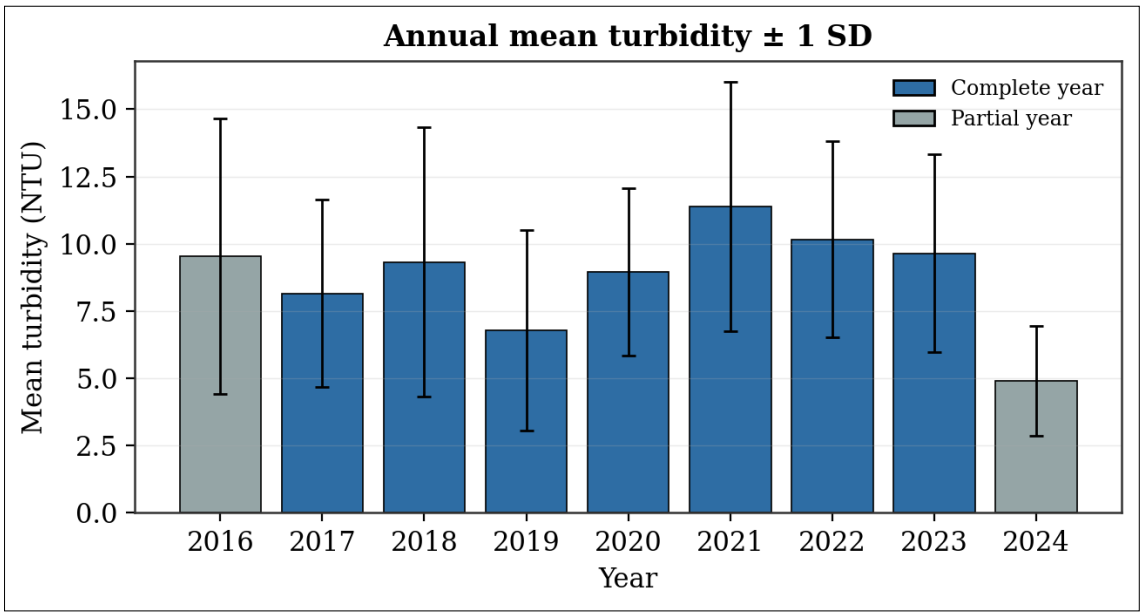


Fig 3: Annual mean turbidity ± 1 standard deviation, 2016-2024. Grey bars indicate partial years (2016 and 2024), which were excluded from the annual trend test; blue bars indicate complete years.

3.3. Seasonal pattern and July-September contrast

The seasonal cycle was large relative to the reported long-term tendency. Monthly means increased from a January mean of 4.84 NTU to 10.80 NTU in May and 13.88 NTU in June, remained high in July and August (13.54 and 11.33 NTU), and declined thereafter. July-September composites (n = 81) averaged 11.12 NTU, compared with 7.97 NTU for October-June composites (n = 224), corresponding to a 39.6% higher reported mean. The Mann-Whitney U statistic was 13, 337 with $p < 0.001$, and the absolute rank-biserial effect size was 0.47. The June maximum and the absence of independent rainfall or inflow data mean that this result should be described as a July-September seasonal association rather than proof of a monsoon-driven causal effect. The monthly distributions are shown in Figure 4.

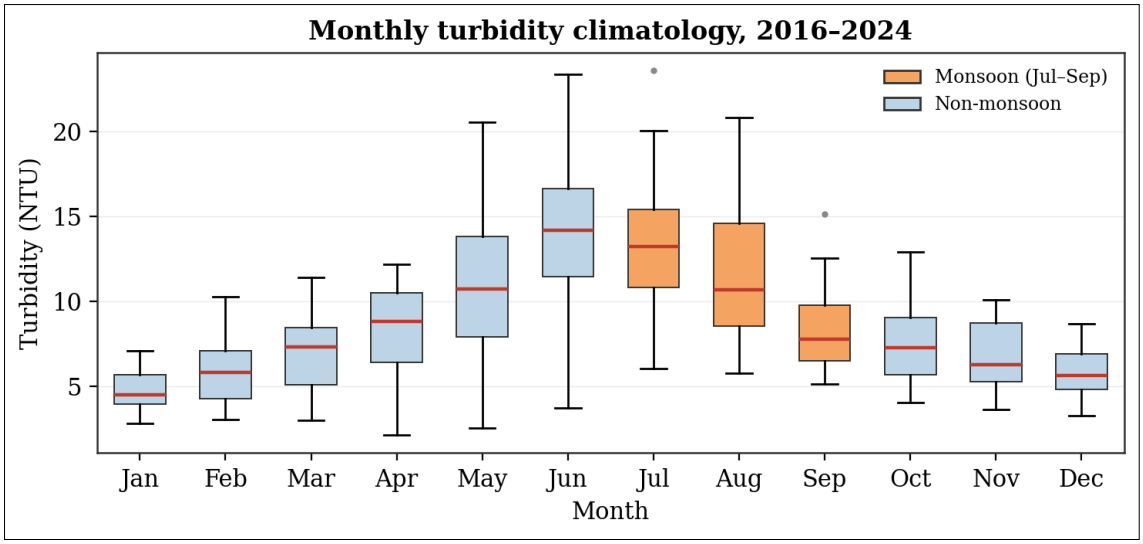


Fig 4: Monthly lake-level turbidity distributions, 2016-2024. Boxes show the interquartile range and median; whiskers show the 1.5 × IQR range. July-September observations are shaded orange.

4. Discussion

The main finding is an asymmetry between seasonal variability and the evidence for long-term change. The July-September contrast is large and recurring, whereas the reported year-over-year tendency is small relative to natural variability and statistically inconclusive. The correct interpretation is therefore not that turbidity has already been shown to increase, but that the available record provides a positive estimate that is not yet distinguishable from variability at the chosen significance level. The apparent seasonal pattern is consistent with processes that can affect turbidity in shallow lakes, including runoff, sediment resuspension, changing water extent, and inflow. Nevertheless, the satellite series alone cannot identify which process is responsible. The use of July-September as a monsoon period should be supported by local rainfall or inflow observations, and the strongest monthly value in June should be discussed rather than hidden within the non-monsoon group. A useful follow-up would compare turbidity with rainfall, inflow, water level, surface area, and salinity using lagged correlations or a hierarchical seasonal model.

Several limitations affect the strength of the trend inference.

First, 305 10-day composites are not equivalent to 305 independent field measurements; adjacent observations can be serially correlated. Second, the annual analysis contains only seven complete years and consequently has limited power. Third, a changing lake footprint and shoreline mixing can alter the set of pixels contributing to a lake-level statistic. Fourth, atmospheric correction, cloud and haze screening, retrieval limits, and possible platform or processing changes can introduce non-environmental variation. The CLMS documentation describes the product fields, quality-risk information, and limitations relevant to these issues [8, 9]. The study would be substantially strengthened by a reproducible pixel-level extraction, a fixed-core-water-mask sensitivity test, explicit quality thresholds, a check for sensor or processing discontinuities, and independent comparison with in situ turbidity observations. Results should be reported with confidence intervals and, where appropriate, block-bootstrap or autocorrelation-robust p-values. These additions would turn a useful descriptive analysis into a stronger environmental-monitoring contribution.

5. Conclusions

A continuous 10-daily turbidity record for Manchar Lake (2016–2024, N = 305) was reconstructed from the Copernicus Sentinel-3 Lake Water Quality product and tested for trend using the Mann-Kendall test and Sen's slope estimator at three temporal resolutions. All three tests agreed on the direction of change a weak upward tendency but none reached statistical significance ($p > 0.05$ throughout). The most standard estimate, from annual means over the seven complete calendar years 2017-2023, placed this tendency at approximately +3% per year (Sen's slope +0.26 NTU/year, tau = 0.43, $p = 0.23$), consistent with an 18.3% increase between the 2017 and 2023 annual means. By contrast, the monsoon-season seasonal cycle was large and highly significant: turbidity during July-September averaged 39.6% higher than during the rest of the year ($p < 0.001$). Manchar Lake's turbidity is therefore currently characterized by a strong, reliable seasonal monsoon signal and a long-term trend that remains statistically inconclusive; continued monitoring with a longer record is needed to confirm or rule out the indicative upward tendency identified here.

Data availability

The Copernicus Land Monitoring Service Lake Water Quality product is publicly available through the dataset DOI listed in Reference [8].

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