Synergic use of neural networks model and remote sensing algorithms to estimate water clarity indicators in Khanpur reservoir, Pakistan

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Abstract
Freshwater reservoirs are limited and facing issues of over-exploitation, climate change effects and poor maintenance which have serious consequences for water quality. Developing countries face the challenge of collecting in situ information on ecological status and water quality of these reservoirs due to constraints of cost, time and infrastructure. In this study, a practical method of retrieval of two water clarity indicators, total suspended matter and secchi disk depth, using Sentinel-2 satellite data is adopted for preliminary assessment of water quality and trophic conditions in Khanpur reservoir, Pakistan. The study explores the synergy of utilizing two independent models, i.e., case 2 regional coast color analytical neural network model and semiempirical remote sensing algorithms to understand the spatiotemporal dynamics of water clarity patterns in the dammed reservoir, in the absence of ground measurements. The drinking water quality and trophic state of the reservoir water is determined based purely on satellite measurements. Out of the five months studied, the reservoir water has high turbidity and poor eutrophic status in three months. The results from both computational models are compared, which exhibit a high degree of statistical agreement. The study demonstrates the effective utilization of relevant analytical and semiempirical methods on satellite data to map water clarity indicators and understand their dynamics in both space and time. This solution is particularly useful for regions where routine ground sampling and observation of environmental variables are absent.

Keywords Environmental monitoring · Freshwater reservoirs · Total suspended matter · Secchi disk depth · Trophic state

Introduction
With increasing environmental pollution and water scarcity issues, the quality of water for domestic, agricultural and industrial use has been garnering serious attention from both public and administrative authorities throughout the world (Bresciani et al. 2019). For management of scarce water resources, the number of artificial reservoirs is increasing, owing to the growing energy and water needs. As these reservoirs and dams are often a primary source of water for urban and rural areas, the a priori knowledge of water quality is crucial for better understanding of environmental variables affecting it (Ouma et al. 2020). For the acquisition of data regarding lake and reservoir water quality status, numerous assessment methodologies have been extensively researched (Topp et al. 2020). A number of these studies (Bresciani et al. 2019; Ha et al. 2017; Elhag et al. 2019; Buma and Lee 2020) suggest that successful water quality monitoring is possible through applying optimal combinations of in situ data, laboratory analysis and satellite measurements. In situ and remote sensing methods are complementary in nature, and have great potential for synergic use in monitoring water quality and composing models for water quality prediction at various spatial scales (Pompeo et al. 2021). In situ analysis of water quality parameters provides detailed quantitative information to help comprehend essential reservoir and catchment characteristics; however, it is a restricted, point-based representation of freshwater ecosystems, which are generally complex and dynamic in both space and time (Sòria-Perpinyà et al. 2021). In addition, factors such as cost, access, time and pandemic restrictions...
inhibit the prospects of sustainable ground-based water quality monitoring in low-income countries.

Similar to many other developing countries, in Pakistan, in situ monitoring records of water quality of freshwater bodies and reservoirs are lacking due to several logistic constraints laid by limited monetary, infrastructural and legal provisions (Facco et al. 2021). The inland freshwater lakes in all provinces of Pakistan are being polluted rapidly, with the ecological status of many under threat. The water quality of majority of lakes lies well-below the thresholds set by world health organization (WHO), and many have lost a greater fraction of flora and fauna historically associated with these (PCRWR 2020). In order to assess the water quality of these lakes, both qualitative and quantitative indicators are needed, making it possible to determine impacts of human and natural processes in the environment. Presently, there is no lake water monitoring program conducted by the government environmental protection agencies in Pakistan due to lack of financial support to conduct traditional monitoring surveys (WWF 2007). As a consequence, no formal records of water quality parameters are present for the assessment of ecological status of freshwater lakes and reservoirs. In this context, satellite observations and geospatial processing tools have the potential to become the most practical method of retrieval of water quality parameters (Buma and Lee 2020), since satellite remote sensing provides continuous, near real-time, relatively cost-effective, speedy and non-invasive monitoring with optimum coverage (Ouma et al. 2020; Soomets et al. 2020). Moreover, in current situation (COVID-19 emergency) or future pandemics which physically restrict ground-based observation and sampling, new data, techniques and solutions around the planning and management of water resources have to be adopted in response to changes in water resources management systems. A remote sensing-based water quality monitoring framework can aid decision support systems and is crucial to prepare management authorities for extreme events that imperil water resource infrastructure operation and maintenance. Continuous monitoring through satellite observations also provides primary data for analysis of long-term trends, necessary to identify climate change effects.

In the literature, water clarity is a term referring to a combination of chlorophyll a (Chl-a) concentration, total suspended matter (TSM) and colored dissolved organic matter (CDOM) in water, and has been considered as a proxy for overall lake trophic status (Topp et al. 2020). TSM refers to suspended solids in water, which have organic or mineral origins and come from within the waterbodies or catchment areas. Suspended sediment concentration has proven to be most challenging water quality parameter to be retrieved using remote sensing (Garg et al. 2020). TSM strongly influences water clarity (Ouma et al. 2020), and is directly linked to other associated water clarity indicators such as turbidity and secchi disk depth. Turbidity is a measure of suspended particulate matter concentration in water bodies, and an important optical property (Sebastia-Frasquet et al. 2019). Secchi disk depth (SDD) is an approximate measure for estimating water clarity with a secchi disk; it is strongly affected by three optically significant constituents present in water bodies, i.e., Chl-a, TSM and CDOM. The association between SDD and light attenuation coefficient (Kd) is well-known; therefore, Kd has been used for deriving SDD in a number of studies (Soomets et al. 2020; Pompeo et al. 2021). Researches have shown the suitability of satellite remote sensing data for estimating water clarity determinants such as Chl-a concentration, CDOM, SDD, turbidity, and TSM, in dynamic freshwater systems (Avdan et al. 2019; Nazirova et al. 2021; Pompeo et al. 2021; Sòria-Perpinyà et al. 2021). The new earth observation satellites, launched by Copernicus European Union earth observation program, include two important missions for water monitoring, i.e., Sentinel-2 and Sentinel-3. Particularly, the ten-meter resolution open-access imagery and shorter revisit period of Sentinel-2 make it an excellent tool for conducting studies on regular monitoring of inland water bodies (Pompeo et al. 2021; Sòria-Perpinyà et al. 2021).

In the present study, a preliminary attempt of qualitative and quantitative estimation of water clarity indicators has been made purely using satellite data for Khanpur reservoir, which is a major water conservation site in Khanpur watershed, Pakistan. Khanpur reservoir has provided beneficial water supply for nearly forty years with many positive aspects for the neighboring areas, such as progress in agriculture and tourism. Unfortunately, the watershed is facing challenges of rapid urbanization and deforestation. As a result, the removal of tree cover from precipitous slopes has led to accelerated rates of surface erosion due to which the probability of landslides and surface runoff increases drastically (Zaheer et al. 2016). In this context, increased sediment load in the river discharge can negatively affect the water clarity, creating favorable conditions for lake eutrophication (Watanabe et al. 2015), which renders the reservoir water quality unfavorable for safe drinking and consumption. To date, no study has been conducted on the geospatial assessment of water clarity parameters in Khanpur reservoir, to the best of author’s knowledge. Therefore, in the absence of any ground measurements or in situ water clarity data of Khanpur reservoir, the main objectives of this study are: to retrieve quantitative and qualitative estimates of water clarity indicators, TSM and SDD, through exclusive use of remotely sensed data; to study seasonal variation of water clarity patterns in the dammed reservoir; to determine the drinking quality and trophic state of reservoir water using satellite-based TSM and SDD measurements; and to evaluate the level of conformity between results from analytical and semiempirical models used in the study.
Data and methods

Study area

Khanpur reservoir, built to conserve water from the Haro river, is an important dam constructed in 1983 for supplying water to the megalopolises of Islamabad and Rawalpindi, and the industrial complexes at Taxila. Haro river, originating from the Moshpuri hills, flows through steep gorges and is eventually dammed at Khanpur, north of the capital city of Islamabad. Primary sources of water for the river are springs and streams which are majorly fed by rainwater, and supply water for domestic needs throughout the year. However, this discharge becomes scanty during dry periods and the perennial flow is retained through seepage from numerous springs (Nauman et al. 2019). The highest discharge in the river occurs during the months of February, March and August. The study area is characterized by a subhumid-to-humid subtropical climate with average maximum temperature of 17.6–40.1 °C, and average minimum temperatures of 2.1–21.6 °C. Rainfall in this region is highly unpredictable and mostly occurs from July to September, in the local monsoon season (Zaheer et al. 2016). The dammed reservoir, shown in Fig. 1, is situated at a height of 550 m above mean sea level and has an area of about 7,137,852.36 m².

Data preparation

For the present study, the source of remotely sensed data was multispectral instrument (MSI) sensor on board Sentinel-2 satellites (A and B). Both these Sentinel-2 missions are placed in the same sun-synchronous polar orbit, with 180° phase between them. These earth observation satellites capture the changes in surface conditions using 13 spectral bands. Wide swaths and high temporal resolution of these satellites provide monitoring support for earth surface features (ESA 2021). Five cloud-free level 1C images acquired during 2020 pertaining to different seasons have been used in this study. After the acquisition of satellite data from Copernicus open access hub, resampling of bands to 10 m spatial resolution was performed in the open-source ESA Sentinel Toolbox SNAP for all the images, and spatial subsets were prepared encompassing the study area. The details of images are given in Table 1. Before extracting any information related to water quality parameters from satellite imagery, atmospheric correction is essential due to low reflectance property of water. Therefore, among the different methods cited in literature, the case 2 regional coast color (C2RCC) processing technique for atmospheric correction was adopted for Sentinel-2 data, which has been developed for optically complex waters, i.e., case 2 waters (Pompeo et al. 2021). This atmospheric correction technique, available in the open-source ESA Sentinel toolbox SNAP (https://step.esa.int/main/toolboxes/snap/), was used to atmospherically correct all the spectral bands in Sentinel-2 images. After the atmospheric correction processes, the SNAP native products conc_tsm (in g/m³) and kd_z90max (in m) were obtained which provided quantitative estimates of TSM and SDD, respectively.

The boundary of Khanpur reservoir was delineated using high-resolution Quick Bird imagery.

Estimation of indicators

Quantitative estimation of TSM and SDD

For the purpose of quantitative estimation of water clarity indicators, total suspended matter (TSM) and secchi disk depth (SDD), C2RCC analytical model has been used. Analytical models are physics-based techniques which involve modeling of inherent optical properties (IOPs) of a given waterbody in conjunction with apparent optical properties to derive theoretical absorption and backscattering values. An inverse equation is then utilized to make estimates of optically active constituents of the given waterbody (Ouma et al. 2020). The ‘inversion’ problem is solved by means of mathematical optimization or nonlinear regression methods, such as artificial neural networks (ANNs), for creating analytical algorithms (Mathews 2011). However, these models are occasionally sensitive to model the behavior of optically non-homogeneous waterbodies (Topp et al. 2020). C2RCC is based on ANNs trained with a large repository of reflectance and radiation spectra, employing simulations from radiative transfer models. This analytical model initially derives IOPs, and then computes quantitative estimations of concentrations of optically active substances (Toming et al. 2017). There is a room for users to change certain input parameter values in the algorithm that require regional correction, such as atmosphere transmittance, temperature, elevation, cloud risk coefficients and air pressure (Nazirova et al. 2021). Among the various C2RCC outputs, the ones of interest for this study were the absolute concentration of TSM (conc_tsm, in g/m³) and the product kd_z90max (in m). The product conc_tsm is computed by the C2RCC neural network processor using the following equation:

\[
\text{conc}_\text{tsm} = (\text{iop}_\text{bpart} \ast 0.986) + (\text{iop}_\text{bwit} \ast 1.72),
\]  

(1)

where iop_bpart is scattering coefficient of marine particles at 443 nm, and iop_bwit is scattering coefficient of white particles at 443 nm.
The SNAP native product $kd_{z90max}$ represents the depth below water surface at which 90% extinction of incident light occurs. The conversion of this product to SDD was carried out using the following equation suggested by Pompeo et al. (2021):

$$SDD = 0.7 \times kd_{z90max}.$$  \hspace{1cm} (2)

![Khanpur reservoir](image)

**Fig. 1** Khanpur reservoir

**Table 1** Sentinel-2 images with acquisition dates

| Serial no | Date of acquisition  |
|-----------|----------------------|
| 1         | January 16, 2020     |
| 2         | April 10, 2020       |
| 3         | July 14, 2020        |
| 4         | September 22, 2020   |
| 5         | December 31, 2020    |
Qualitative estimation of TSM and SDD

Semiempirical models comprising of multi-band indices were used to qualitatively estimate the water clarity indicators. These semiempirical indices or band ratios highlight the spectral characteristics of constituents of interest, while suppressing the spectral response of extraneous optical parameters (Topp et al. 2020). These models are generally characterized with the advantages of computational and implementation simplicity. However, these make inherent assumptions regarding the uniformity of atmospheric and water conditions across a scene, which may produce erroneous results (Mathews 2011). Qualitative remote sensing retrievals of suspended particulate matter include the red and near infrared wavelengths of electromagnetic spectrum. Increased reflectance at these wavelengths due to high TSM concentration is linked with decreased SDD and hence low water clarity (Sòria-Perpinyà et al. 2021). Several studies have demonstrated the suitability of these spectral bands for monitoring of suspended matter concentration and SDD in optically complex regions, such as inland water bodies (Garg et al. 2020; Soomets et al. 2020; Premkumar et al. 2021).

Initially, the water pixels in each image were identified using the normalized difference water index (NDWI), and subsequently, only the reservoir area delineated using appropriate NDWI threshold was retained for the calculation of semiempirical algorithms. Since suspended matter in water causes turbid conditions, the qualitative estimation of TSM was done using normalized difference turbidity index (NDTI), the effectiveness of which has been reported by Garg et al. (2020) and Facco et al. (2021) for mapping turbidity in reservoirs. On the other hand, SDD has been qualitatively estimated using band ratio \(\frac{R_{\text{560(nm)}}}{R_{\text{709(nm)}}}\), as recommended by Sòria-Perpinyà et al. (2021). Remote sensing top of atmosphere (TOA) reflectance in individual spectral bands was used to calculate the aforementioned algorithms in Arc GIS 10.5. The formulae of both indices, adopted for Sentinel-2 spectral bands, are given as:

\[
\text{NDTI} = \frac{(B4 - B5)}{(B4 + B5)}, \quad (3)
\]

\[
\text{Band Ratio(SDD)} = \frac{B3}{B5}. \quad (4)
\]

Conformity of quantitative and qualitative estimations

The correlation between quantitative and qualitative estimates of TSM and SDD was checked to evaluate the degree of conformity between results of the two approaches used. Hundred randomly selected points in the reservoir have been used to calculate the degree of relationship between the two sets of corresponding estimates, i.e., TSM and NDTI, SDD and band ratio (SDD), separately for each date of acquisition of Sentinel-2 imagery. Statistical measures of Pearson’s correlation coefficient \(r\) and coefficient of determination \(R^2\) have been utilized to summarize the level of conformity between the quantitative and qualitative estimations of TSM and SDD.

Results

Spatiotemporal patterns of TSM and SDD

The maps of total suspended matter (TSM) and secchi disk depth (SDD) derived from case 2 regional coast color (C2RCC) processor showing spatial variability of quantitative water clarity indicators across different sections of Khanpur reservoir during the study period are shown in Figs. 2 and 3, respectively. The mean quantitative estimations of concentrations of TSM and SDD from the C2RCC processor and corresponding mean qualitative values derived from semiempirical algorithms are given in Table 2, for all individual multi-temporal images.

The results of TSM and SDD from semiempirical model (C2RCC), as well as from semiempirical algorithms normalized difference turbidity index (NDTI) and band ratio (SDD), show identical temporal pattern for the dammed reservoir. The highest mean TSM concentration is obtained for the month of September, concurrent with the highest mean value of NDTI, whereas the lowest mean TSM concentration occurs in April along with the lowest mean NDTI value for the same month. SDD, which naturally decreases when TSM concentration is high, has also exhibited a good negative relationship with TSM, as depicted by both qualitative and quantitative estimates. Mean value of SDD is the highest in the month of April when mean TSM is the lowest, while the reverse holds true in the month of September.

Water quality and trophic status of Khanpur reservoir

For a preliminary assessment of water quality status of Khanpur reservoir, the mean TSM concentrations from C2RCC processor outputs for each month of image acquisition were converted from g/m³ to their equivalent nephelometric turbidity unit (NTU) using linear conversion equation described by Muduli et al. (2021) in Eq. (5). The mean TSM concentrations in equivalent NTU are given in Table 3:

\[
\text{Turbidity(NTU)} = \frac{\text{TSM}}{3.4216}. \quad (5)
\]

In a similar vein, quantitative SDD estimates from C2RCC processor were utilized to make assumptions about
Fig. 2 Spatiotemporal patterns of TSM

Fig. 3 Spatiotemporal patterns of SDD

Table 2 Mean values of quantitative and qualitative estimates

| Month     | Mean TSM (g/m³) | Mean SDD (m) | Mean NDTI | Mean band ratio (SDD) |
|-----------|-----------------|--------------|-----------|-----------------------|
| January   | 25.521          | 0.201        | -0.1989   | 1.792                 |
| April     | 2.796           | 4.647        | -0.3446   | 3.860                 |
| July      | 24.403          | 0.199        | -0.1533   | 1.827                 |
| September | 26.821          | 0.200        | -0.1377   | 1.453                 |
| December  | 6.955           | 1.600        | -0.2157   | 1.971                 |
the trophic state of Khanpur reservoir. The SDD values were converted to trophic state classes using classification scheme similar to Watanabe et al. (2015) and Pompeo et al. (2021), as given in Table 4.

### Conformity of quantitative and qualitative estimations

In order to assess the degree of relationship and statistical agreement between the qualitative and quantitative estimations from the two independent methods, i.e., C2RCC analytical neural network model and semiempirical remote sensing algorithms, values from 100 randomly generated, spatially distributed points within the reservoir body were studied. The pairs of qualitative and quantitative estimations at these 100 sites were subject to correlation and regression analysis. The quantitative estimates of TSM and SDD have been referred to as C2RCC-TSM and C2RCC-SDD in this analysis, while the qualitative estimates of the same are referred to as NDTI-TSM and band ratio (SDD),

| Month    | Mean TSM (g/m³) | Equivalent in NTU |
|----------|-----------------|-------------------|
| January  | 25.521          | 7.460             |
| April    | 2.796           | 0.810             |
| July     | 24.403          | 7.133             |
| September| 26.821          | 7.838             |
| December | 6.955           | 2.033             |

| SDD (m)                 | Equivalent trophic state     |
|-------------------------|-------------------------------|
| 0–0.6                   | Hypereutrophic                |
| 0.6–0.8                 | Supereutrophic                |
| 0.8–1.1                 | Eutrophic                     |
| 1.1–1.7                 | Mesotrophic                   |
| 1.7–2.4                 | Oligotrophic                  |
| > 2.4                   | Ultraoligotrophic             |

**Table 3** Mean TSM and equivalent NTU

**Table 4** SDD and corresponding trophic states

![Fig. 4](image_url) Conformity of secchi disk depth estimates in: A January, B July, C September, D December
respectively. The scatter plots between the qualitative and quantitative estimates are shown in Figs. 4 and 5, while the metrics for measuring relationship are given in Table 5.

### Discussion

**Spatiotemporal patterns of TSM and SDD**

The surface water clarity parameters in Khanpur reservoir vary with environmental and meteorological conditions. In January of 2020, high TSM concentration has been recorded by both case 2 regional coast color (C2RCC) output and normalized difference turbidity index (NDTI) values, since low temperature is generally associated with denser and turbid waters. Moreover, the rainfall record of the nearest meteorological station showed a high mean monthly precipitation of 273.1 mm in January which explains the high total suspended matter (TSM) concentration and low secchi disk depth (SDD) in Khanpur reservoir, as high precipitation events tend to increase suspended matter and turbidity in reservoir waters (Zhou et al. 2015). Meanwhile, as the
spring season commences, stream runoff increases in the months of February and March supplying huge quantities of freshwater to Haro river, and the highest discharge rate is recorded in these months. This influx of freshwater in huge quantity causes liquidation of high suspended sediment concentration in the reservoir, and resultantly low mean TSM and high mean SDD values occur in April, as estimated from the quantitative and qualitative techniques. In July, the local Monsoon season starts and continues till the end of September, in which weather is characterized with violent stormy conditions. As cited in the literature, the amount of suspended matter in water has a statistically significant negative correlation with air pressure and positive correlation with wind speed (Pompei et al. 2020); therefore, high wind speed prevalent in this season and storm water runoff containing heavy suspended sediment load from the deforested catchment areas contribute toward higher mean TSM concentration and lower mean SDD values in the dammed reservoir. Eventually, in December, mean TSM concentration and mean NDTI values again decrease since the atmospheric pressure is high and amount of precipitation recorded is the lowest in this month, i.e., 96.2 mm for the nearest meteorological station. Supplementing these observations, the quantitative and qualitative estimates of SDD again show an increase due to low TSM concentrations. The spatial variations in TSM and SDD maps within each climatological window are also consistent. In general, the lake center turbidity is lower than nearshore turbidity. This is due to the fact that narrow upstream reservoir area has higher TSM concentration and low SDD due to frequent resuspension and dynamic behavior of sediments, whereas, deeper regions of reservoir have relatively clear water due to density stratification and settling down of suspended sediments.

**Water quality and trophic status of reservoir**

A comparison of multi-temporal TSM results of reservoir water with thresholds prescribed by WHO for drinking water quality revealed that out of the five months assessed in this study, three months exceeded turbidity threshold of 5 NTU, which is advised for safe water consumption. In only April and December, the NTU equivalents fell below the prescribed threshold. On the other hand, as SDD values varied both spatially and temporally (Fig. 3), the trophic state analysis encompasses both dimensions to investigate the ecological status of the reservoir. It is obvious from the spatiotemporal SDD observations that the trophic state of the reservoir water alters seasonally and spatially, reflecting the change in nutrient concentrations and availability. The reservoir favored hypereutrophic conditions in the month of January, with SDD values between 0.201 and 0.202 m, coupled with high TSM concentration. In April, the situation reversed as TSM concentration fell considerably and SDD values for the reservoir mostly lied in the range of 2.4-10 m, exhibiting ultraoligotrophic conditions. Only near the northeastern portions of reservoir where the mouth of Haro river lies, eutrophic to hypereutrophic conditions existed, but in very small patches. From July to September, the conditions remained hypereutrophic with SDD values mostly lying between 0.1 and 0.2 m. Eventually in December, due to low TSM concentration, SDD values in reservoir mostly ranged between 1.1 and 2.4 m characterizing oligotrophic to ultraoligotrophic conditions. Only northeastern stretch of the reservoir where the mouth of Haro river exists and in other sparse portions, low SDD values classified in hypereutrophic range existed.

The results depict that the months of January, July, and September were characterized with high turbidity and poor trophic state of the reservoir water as per preliminary estimations from C2RCC analytical neural network model. These initial results of water quality and trophic status of Khanpur reservoir derived through satellite observations should be validated through ground observations, and call for a greater attention of authorities toward reservoir management and subsequent water treatment strategies for safe consumption.

**Conformity of quantitative and qualitative estimations**

To evaluate the conformity of results of both estimation techniques, the month of April, in which the estimates of TSM and SDD depicted low correlation and hence low confidence on reliability of observations, was excluded from the analysis. The statistical analysis for rest of the months shows a high degree of positive relationship between the quantitative and qualitative estimates of TSM and SDD derived from analytical C2RCC model and semiempirical RS algorithms, respectively. In these months, Pearson’s $r$ ranges from 0.71–0.98 and 0.72–0.94 for TSM and SDD, respectively, while $R^2$ is greater than 0.5 for all observations of SDD and TSM. Moreover, it is also pertinent to note from Figs. 4 and 5 that highest correlation between qualitative and quantitative estimates of SDD and TSM occurs in the month of January (4A and 5A), while the second highest correlation of estimates of SDD and TSM occurs in the month of September (4C and 5C). Similarly, the third and fourth highest correlation between qualitative and quantitative estimates of SDD and TSM occurs in concurrence, in the month of December (4D and 5D) and July (4B and 5B), respectively. In this manner, the level of conformity between the outputs from both used techniques shows a characteristic seasonal hierarchy. Also, the high degree of agreement between the estimations of water clarity indicators from two entirely different approaches shows the relevance of these satellite data-based techniques in providing proxy observations to compensate for the absence of in situ data.
Conclusions

The knowledge of water clarity indicators of freshwater reservoirs is important in determining not only the quality of water, but also their ecological status. Monitoring of spatiotemporal dynamics of these indicators is critical to implement sustainable environmental management programs. In this study, a preliminary investigation of two water clarity parameters, i.e., TSM and SDD has been done for Khanpur reservoir, Pakistan, purely using Sentinel-2 satellite data. C2RCC analytical neural network model and semiempirical remote sensing algorithms have been used to independently retrieve quantitative and qualitative estimates, respectively, of TSM and SDD from multi-temporal satellite images. The results of the study indicate that out of five months studied in 2020, in three months, the reservoir water turbidity exceeds the WHO threshold for safe drinking water due to high suspended sediment concentration. Moreover, certain portions of the reservoir rank high in the trophic state classification during high TSM concentration and low SDD events, exhibiting conditions favorable for lake eutrophication. The statistical agreement between the qualitative and quantitative estimations was also computed, depicting a high degree of correlation between the results of both techniques used in this study. These validated image processing techniques enable observations of the spatial and temporal variations in estimated water clarity indicators as a response to different seasonal conditions, when there is no in situ data to help assess the quality and trophic state of reservoir water. The satellite-derived water clarity products, with automatic calculations and visual outputs, can speed up the monitoring of freshwater reservoirs since the need to generate and validate new models previously is overcome. This benefit can be effectively exploited for initial investigation and management of water quality and ecological status of inland freshwater reservoirs in developing world, where monetary and infrastructural constraints inhibit water quality monitoring regimes.

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Availability of data and material The satellite data used in this study can be accessed online from Copernicus Open Access Hub and is also available with authors. Additionally, all the processed stages data is available with authors.

Code availability Not Applicable.

Declarations

Conflict of interest There is no conflict of interest.

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