



Application Of Remote Sensing For Estimating Suspended Sediment Concentration And Identifying Critical Erosion-Prone Sub-Basins In The Gamasyab Watershed

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ABSTRACT

Aims: Large amounts of fertile soil are lost annually due to erosion, and significant losses are caused by sedimentation. In this context, remote sensing is an efficient tool for monitoring erosion and sedimentation because it offers wide coverage at low cost. This study evaluated the applicability of Sentinel-2-based empirical suspended sediment concentration (SSC) estimation in the data-limited Gamasyab watershed. It used the derived spatial SSC patterns to prioritize sediment-prone sub-watersheds relatively.

Materials & Methods: Sentinel-2 images from 2016–2020 were quality-checked, and cloud- or error-affected scenes were excluded. We extracted spectral reflectance at the Pole Chehr station, accounting for river width and band resolution, and compared it with field suspended sediment concentration (SSC) data to develop linear, exponential, and polynomial models. We used the best-performing model, an exponential model based on Band 5, to estimate SSC for six dates and rank the sub-watersheds.

Findings: The Band 5 exponential model showed the best calibration performance ($R^2 = 0.83$, RMSE = 23.19, MAD = 16.92). Estimated SSC indicated that sub-watershed 1 had the highest concentrations among the five sub-watersheds, ranging from 31.20 to 640 mg.L⁻¹, likely due to highly erodible geological formations. Sub-watershed 2 showed intermediate SSC values, whereas sub-watersheds 3–5 were classified as medium- to low-erodibility areas.

Conclusion: The results indicate that Sentinel-2, particularly band 5, effectively estimates SSC and identifies erosion-prone areas in the Gamasyab watershed, with sub-watershed 1 identified as the highest-priority sediment-prone area based on satellite-derived SSC patterns.

Keywords: Sediment Hotspots; Sentinel-2 MSI; Spectral Band Analysis; Suspended Sediment Concentration; Watershed Prioritization..

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Introduction

Studies that estimate erosion and sedimentation rates are crucial for understanding water-driven soil degradation processes. These studies help protect soil and water resources while reducing environmental and economic damage. Soil erosion is a major environmental challenge that threatens ecosystem stability, agricultural productivity, and human livelihoods ^[1]. Water erosion removes nutrient-rich topsoil and reduces soil fertility, ultimately lowering agricultural productivity. Furthermore, erosion-generated sediments are transported through river systems and accumulate in waterways, irrigation canals, and reservoirs, reducing storage capacity and operational efficiency. Global annual soil loss from erosion is estimated at 75 billion tons ^[2]. Previous studies have estimated that annual global reservoir storage losses due to sedimentation range from approximately 0.5% to 1% of initial storage capacity ^[3]. In Iran, soil erosion and land degradation are major environmental challenges, affecting extensive areas of the country and threatening soil and water resources ^[4]. Consequently, assessing sediment production within watersheds, identifying areas with high sediment yield, and prioritizing vulnerable regions are essential steps for improving watershed management and implementing effective soil conservation measures.

In this study, “higher-priority sediment-prone sub-watersheds” refers to sub-watersheds with relatively high observed or satellite-estimated suspended sediment concentrations in the river system. These areas do not necessarily represent the original sites of soil erosion or confirmed sediment sources, because observed sediment may have originated upstream

and been transported through the drainage network. Therefore, higher-priority sediment-prone sub-watersheds are interpreted as areas exhibiting relatively high SSC conditions that may reflect the combined influence of upstream erosion processes, sediment transport pathways, hydrological connectivity, and watershed characteristics.

Satellite imagery has become an effective tool for monitoring river water quality, particularly suspended sediment concentration (SSC), identifying pollution sources, and tracking sediment transport processes ^[5]. Satellite data provide simultaneous coverage of large areas and capture the spectral reflectance characteristics of surface features. Numerous studies have shown a strong relationship between satellite-recorded spectral reflectance and suspended sediment concentration in water bodies. In particular, red and near-infrared wavelengths strongly correlate with suspended sediment load and can therefore be used to estimate SSC ^[6]. Suspended sediment particles influence solar radiation reflection in the visible and near-infrared regions of the electromagnetic spectrum, and higher sediment concentrations generally increase surface water reflectance ^[7]. However, satellite imagery for river monitoring may be constrained by factors such as river width and sensor spatial resolution. To avoid spectral mixing between water and land pixels, the river channel should be wider than the satellite pixel spatial resolution ^[8]. High-resolution satellite missions such as Sentinel-2 have significantly improved remote sensing’s ability to monitor sediment dynamics in river systems ^[9, 10].

Numerous studies have applied remote sensing techniques to estimate suspended

sediment concentration and analyze sediment dynamics in river watersheds. For example, Zhang et al. (2014) demonstrated that Landsat sensors can effectively quantify suspended sediment concentration in the Yellow River estuary after applying appropriate atmospheric correction procedures ^[11]. Paulista et al. (2023) estimated suspended sediment concentration in the Teles Pires River, Brazil, using remote sensing and found that the red band reflectance best predicted SSC ^[12]. Parvizi et al. (2024) examined the relationship between suspended sediment concentration and vegetation cover using Sentinel-2 imagery and reported strong correlations between SSC and NDVI values ^[13]. Recent studies have also used advanced techniques such as machine learning and high-resolution multispectral imagery to improve sediment monitoring. For instance, Song et al. (2025) applied machine learning algorithms combined with Sentinel-2 imagery to estimate SSC in the Yellow River valley ^[14], while Silabi et al. (2025) proposed an erosion elasticity index for prioritizing erosion-prone sub-watersheds ^[15]. In addition, Cao et al. (2026) developed a remote sensing-based model to monitor longitudinal variations in suspended-sediment concentration in the Pearl River watershed ^[16]. More recent research has further highlighted the increasing role of satellite imagery in monitoring sediment dynamics within river watersheds ^[16- 18]. Within watersheds, certain areas contribute disproportionately to sediment production because of specific geological, geomorphological, and land-use conditions. These areas are commonly referred to as sediment hotspots or critical sediment-prone areas, where erosion intensity and

sediment delivery to the river network are particularly high. Identifying these zones is crucial for watershed management because targeted conservation measures can significantly reduce watershed-scale sediment yield ^[19-22].

Most previous studies have focused on estimating suspended sediment concentration at hydrometric stations, and few have integrated satellite-derived SSC estimates with spatial watershed analysis to identify critical sediment-producing areas across entire watersheds.

The Gamasyab watershed, located in the northeastern part of the Karkheh Watershed in western Iran, is characterized by steep slopes, erodible geological formations, and diverse land-use activities that contribute to significant sediment production and transport. Intense rainfall events and rapid runoff drive large temporal fluctuations in suspended sediment concentrations in this watershed.

Unlike our previous study, which focused primarily on Sentinel-2-based SSC estimation at hydrometric stations, this study extends the analysis to the watershed scale. Rather than developing a fundamentally new SSC estimation approach, this study evaluates the applicability of established Sentinel-2-based approaches under the specific environmental and data-limited conditions of the Gamasyab watershed. More importantly, this study integrates satellite-derived SSC estimates with spatial watershed analysis to examine spatial sediment patterns and provide a relative prioritization of sediment-prone sub-watersheds. This application-oriented framework is intended to support watershed management in regions where field sediment observations are spatially limited.

Accordingly, the objectives of this study were

to: (1) evaluate the performance of Sentinel-2 spectral variables for estimating SSC using the available in-situ observations at the Pole Chehr station; (2) examine the spatial variability of satellite-derived SSC within the Gamasyab watershed; and (3) use these spatial patterns to prioritize sediment-prone sub-watersheds for watershed management. In this study, sediment hotspots refer to sub-watersheds that contribute relatively higher suspended-sediment concentrations to the river network and therefore represent priority zones for sediment management. These zones closely relate to erosion-prone areas, since areas with higher erosion potential tend to generate larger sediment loads that the drainage network transports and downstream monitoring detects as elevated SSC values. Therefore, by integrating satellite-derived SSC estimates with spatial watershed analysis, this study offers a practical approach to identify sediment hotspots and prioritize sediment-prone sub-watersheds within the Gamasyab watershed. We used Sentinel-2 imagery from 2016 to 2020 to estimate suspended sediment concentration using empirical regression models derived from field measurements at the Pole Chehr hydrometric station. We then generated spatial distribution maps of SSC and used them to analyze sediment patterns across the watershed and prioritize sub-watersheds based on relative SSC conditions. This approach provides a practical framework for identifying sediment hotspots and supporting sediment management and erosion control strategies within the Gamasyab watershed.

Materials & Methods

Study Area

The study area is situated within the Gamasyab River watershed, which is located

in the northeastern part of the Karkheh watershed. Covering approximately 11,040 km², the Gamasyab watershed lies between 47°07' and 49°10' E longitude and 33°48' and 34°54' N latitude. The river is 80 meters wide, and the watershed elevation ranges from 1,275 to 3,680 meters above sea level. The watershed perimeter is 636 km, and its compaction coefficient (Gravelius method) is 1.7. The watershed shape is approximately elongated. The watershed has a mean slope of 7.96%. Geologically, this area lies within the Zagros folded structures and is dominated by limestone, dolomite, marl, and shale, primarily from Mesozoic and Cenozoic carbonate formations. The marly and shale layers are highly sensitive to water erosion, and the arrangement of folds and faults influences river flow direction. Geomorphologically, the area features mountainous to hilly topography with steep slopes and deep upstream V-shaped valleys, while alluvial plains and fans develop downstream. The drainage network is relatively dense at higher altitudes. Key processes include surface and groove erosion on steep slopes; mass movements, such as landslides, in marly units; alluvial deposition in downstream plains; sediment transport during seasonal floods; and lateral erosion in certain river sections. Soils in the region are primarily shallow mountainous (lithic and classical), while deeper and more fertile alluvial soils are found in the plains. However, marly soils that support poor vegetation are highly erodible. The dominant vegetation includes Zagros oak forests, semi-dense pastures, and both rainfed and irrigated agricultural lands in the plains. The Pole Chehr Hydrometry Station measures water level and suspended sediment concentration (SSC) daily. The

shows the general location of the Gamasyab watershed, Table 1 lists the geological units of the Karkheh Watershed, and Figure 2 presents its geological map [22].

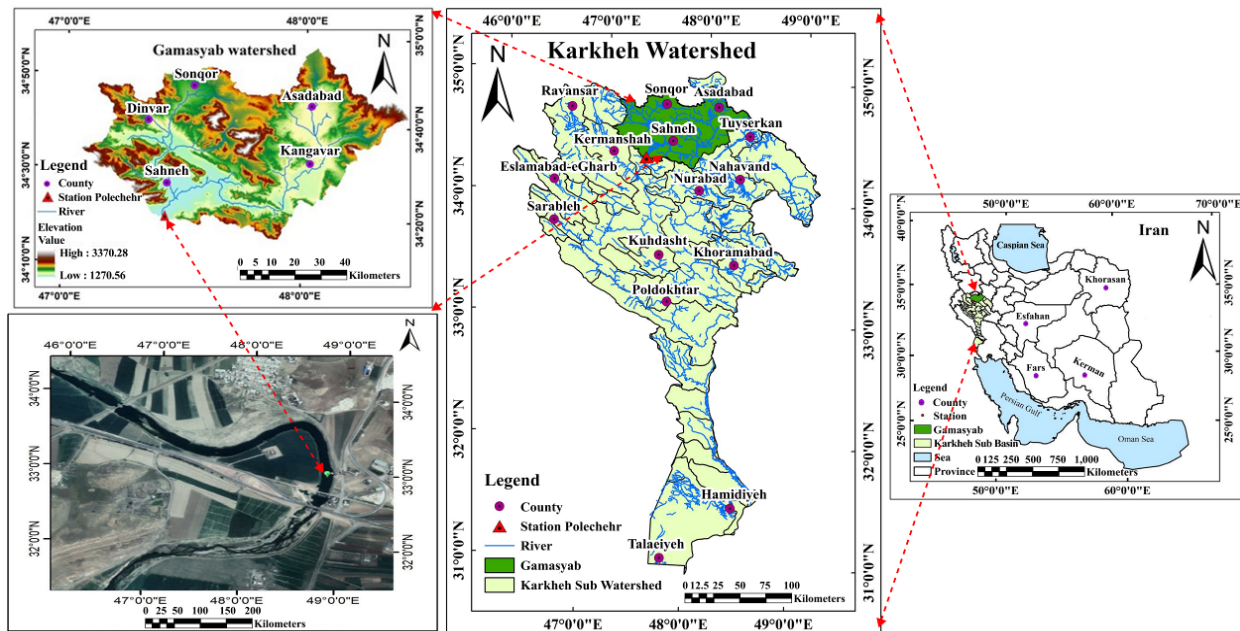


Figure 1) Geographical location of the study area in the Karkheh and Gamasyab watersheds, Iran.

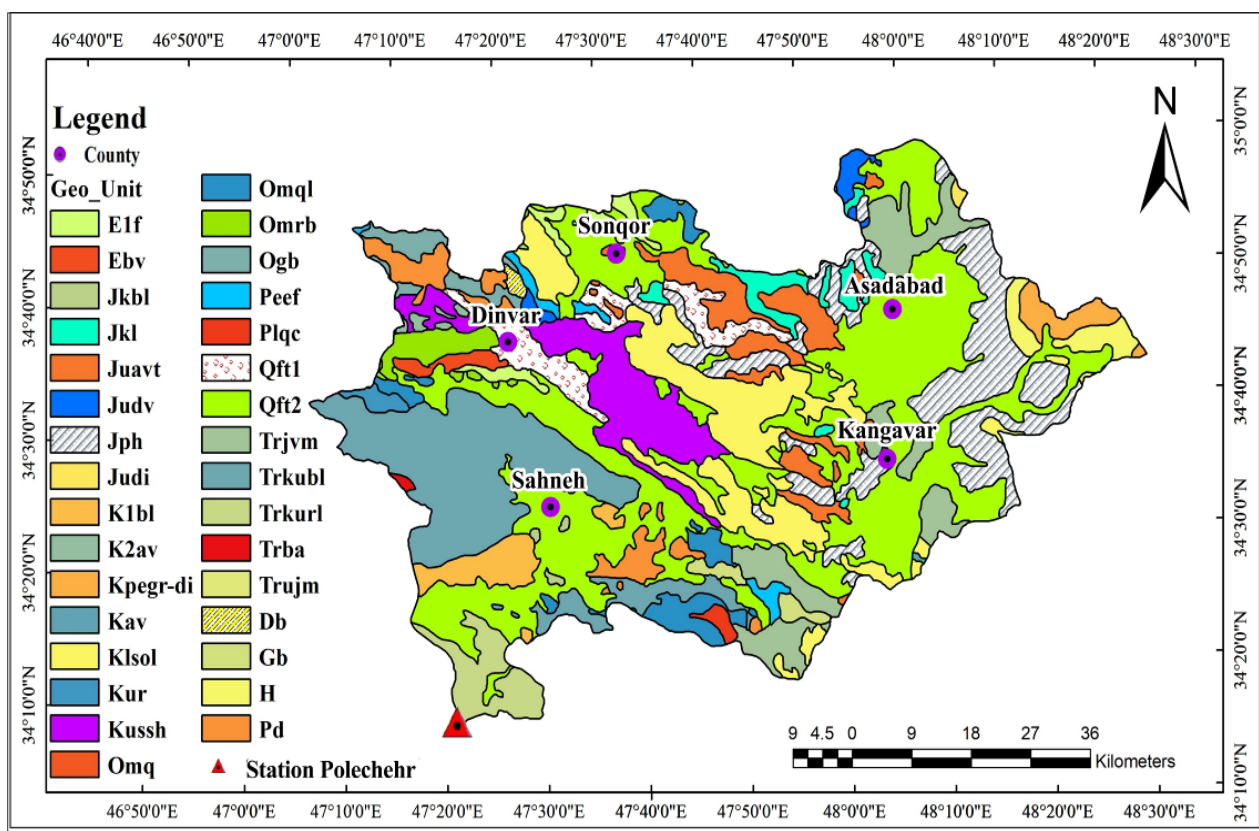


Figure 2) Geological map of the Gamasyab watershed.

Table 1) Geological units of the Gamasyab watershed.

Number	Geology Unit	Layer Material	Number	Geological Unit	Layer Material
1	Qft2	Alluvial deposits	17	Ebv	Basaltic volcanic rocks
2	E1f	Limestone and conglomerate	18	gb	Layered and isotropic gabbro
3	Klsol	Thick layering of limestone	19	K1bl	Thick layering of Orbitolina limestone
4	Kpegr-di	Cretaceous intrusive rocks	20	Ogb	Gabbro
5	db	Diabase	21	h	Metamorphic carbonate rocks
6	Jkl	Limestone and crystallized lime	22	Judi	Upper Jurassic diorite
7	Trjvm	Phyllites, slate	23	Kur	Radiolarian chert and shale
8	Trkurl	Thinly layered radiolarite chert	24	Trkubl	Limestone
9	Jph	Phyllite, slate and meta-sandstone	25	Jkbl	Ovolite limestone
10	Juavt	Andesite volcanic tuff	26	Judv	Rhyolite to Rhyodacite Volcanoes
11	Kussh	Dark gray shale	27	Kav	Red sandstone and shale with calcareous sandstone bed
12	Omql	Coral limestone	28	Omq	Limestone, marl, gypsum marl, sand and sandstone
13	Omrbl	Sandstone, marl, gypsum marl	29	Pd	Red sandstone and shale with calcareous sandstone bed
14	Peef	Turbidite flysch, sandstone and limestone mudstone	30	Plqc	Piedmont conglomerate
15	Qft1	Pedimentary deposits	31	Trba	Red to light green conglomerate and microconglomerate with sandstone and shale
16	Trujm	Transition zone consisting of phyllite with intercalation of crystallized limestone and acidic volcanic zones.	32	K2av	Andesite volcano

Methodology

In this study, Sentinel-2 satellite imagery and in-situ suspended sediment concentration (SSC) measurements were integrated to investigate sediment dynamics in the Gamasyab watershed. The primary methodological objective was to evaluate empirical relationships between Sentinel-2 spectral reflectance and field-measured SSC in the Gamasyab watershed and then apply the best-performing relationship to assess SSC patterns spatially. The methodological workflow consisted of four main steps:

1. Satellite image selection and pre-processing.
 2. Synchronization of satellite observations with field measurements.
 3. Development and evaluation of empirical regression models between spectral reflectance and SSC.
 4. Spatial analysis of SSC distribution across watershed sub-watersheds.
- This integrated approach combines satellite observations with field measurements to investigate sediment transport patterns in river systems [6, 9, 10, 12]. The overall workflow of the study is illustrated in Figure 3.

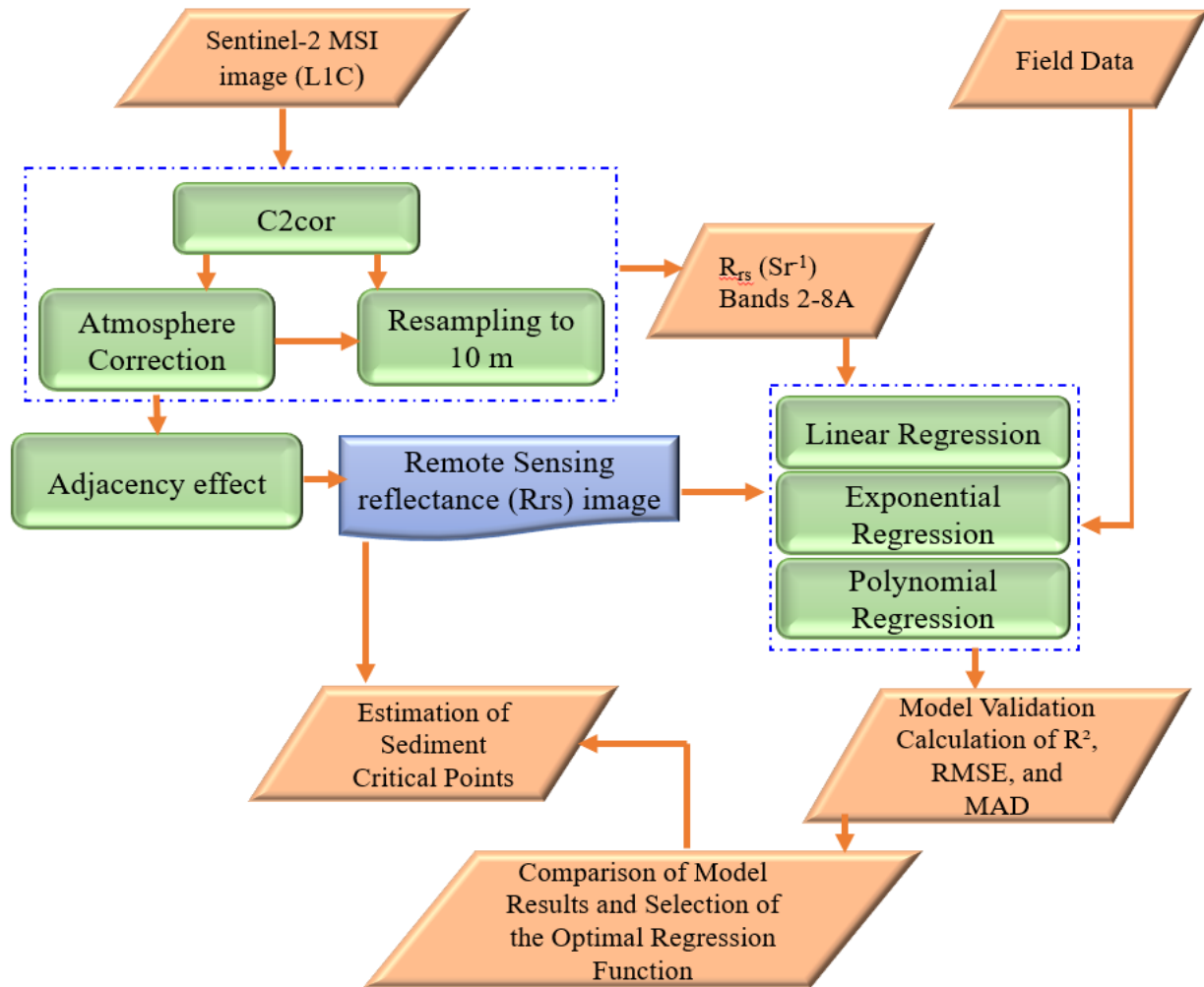


Figure 3) Study flowchart.

Satellite Image Selection and Pre-processing

Sentinel-2 is equipped with a multispectral imager that provides spatial resolutions ranging from 10 to 60 m, a swath width of 290 km, and a revisit time of about five days at the equator. In this study, Sentinel-2 Level-1C images covering the Gamasyab watershed were obtained from the Copernicus Open Access Hub for the period 2016–2020. The high spatial resolution and short revisit time make Sentinel-2 imagery well-suited for monitoring water quality and suspended-sediment dynamics in inland waters. To ensure reliable reflectance measurements, only images with cloud cover lower than 5% were selected. Scenes affected by clouds,

cloud shadows, or abnormal reflectance values were excluded during the initial screening process.

Atmospheric correction was performed using the Sen2Cor processor implemented in the Sentinel Application Platform (SNAP) developed by the European Space Agency. Sen2Cor converts Top-Of-Atmosphere (TOA) reflectance values to surface reflectivity and applies atmospheric, terrain, and cirrus corrections. These corrections minimize atmospheric scattering and improve the accuracy of surface reflectance values used in water quality applications [23, 24]. Initially, 50 Sentinel-2 scenes were collected for the study area. After applying quality-control

criteria, we selected and retained 18 scenes with available sediment measurements at the Pole Chehr hydrometric station for further analysis.

Spectral Band Selection

Sentinel-2 multispectral imagery provides several spectral bands sensitive to variations in water-quality parameters, including suspended sediment concentration.

Previous studies show that wavelengths in the red and red-edge regions respond strongly to suspended sediment concentration in inland waters [6, 7, 9, 10, 12, 14]. Suspended sediment particles increase scattering of solar radiation in the visible and near-infrared regions, increasing reflectance as sediment concentration rises.

Based on these findings, several spectral variables were evaluated in this study, including the red band (B4, 665 nm), the red-edge band (B5, 705 nm), and band products derived from B4 and B5. We selected these spectral variables because they are sensitive to changes in water turbidity and suspended-sediment concentration. In addition, band products were tested because they can reduce illumination effects and improve the detection of spectral signals associated with suspended sediments.

Synchronization of Satellite and Field Data

Suspended sediment concentration (SSC) data were obtained from the Pole Chehr hydrometric station. According to the available monitoring records, suspended sediment samples were generally collected twice per month, while discharge data were recorded routinely at the station.

To minimize temporal mismatch between satellite observations and field measurements, only sediment observations corresponding to the same date as the

satellite overpass were used. Sentinel-2 satellites typically pass over the study area in the late morning; therefore, sediment measurements recorded on the same day are considered representative of conditions during the satellite acquisition period. Although exact temporal synchronization between field sampling and satellite overpass is not always possible, this approach is commonly used in remote sensing studies of suspended-sediment monitoring [25, 26].

Pixel Extraction and Mixed-Pixel Considerations

Sentinel-2 imagery has a spatial resolution of 10-20 m. In comparison, the mean width of the Gamasyab River near the Pole Chehr station is approximately 80 m, allowing selection of several water-dominated pixels within the river channel.

To minimize mixed-pixel effects and contamination from adjacent land surfaces, we extracted spectral values only from pixels in the central portion of the river channel. In contrast, pixels near the riverbanks were excluded. For each satellite image, we extracted reflectance values from eight central water pixels and examined pixel-to-pixel variability. Some scenes showed variation among individual pixels, likely reflecting local spatial heterogeneity and surface conditions within the river channel. The mean reflectance of the selected pixels was therefore calculated to obtain a representative spectral signal for the hydrometric station. Averaging multiple water pixels reduces local spatial variability and random sensor noise, improving the stability of the reflectance values used in the regression analysis. Previous remote sensing studies of suspended sediment concentration have used similar pixel-averaging approaches [18].

Reflectance–SSC Relationship and Model Development

Surface reflectance values extracted from Sentinel-2 imagery were paired with corresponding in-situ suspended sediment concentration (SSC) measurements recorded at the Pole Chehr hydrometric station. These paired observations were used to establish an empirical relationship between spectral reflectance and suspended sediment concentration.

Suspended sediments are typically distributed throughout the water column and can influence the surface reflectance detected by satellite sensors. Although water depth may affect light attenuation and path radiance, in optically deep and relatively turbid waters, suspended particles, rather than bottom reflectance, primarily control the reflectance signal. Therefore, water depth generally has limited influence on the reflectance–SSC relationship in turbid river environments ^[27].

In turbulent river systems such as the Gamasyab River, suspended sediments are usually well mixed within the water column, particularly during high-flow conditions. To quantify the relationship between satellite-derived reflectance and SSC values, we tested several regression models, including linear regression, exponential regression, polynomial regression, and band-product models.

Dataset Preparation and Model Validation

The final dataset consisted of 18 paired observations of satellite reflectance and field-measured suspended sediment concentration.

After quality control and filtering, the dataset was divided into two subsets before model fitting:

- 12 observations for model calibration

- 6 observations for independent model validation

Before regression analysis, the dataset was visually inspected using scatter plots to identify potential outliers or abnormal values. No significant outliers were detected. The 12 calibration observations were used exclusively to fit the candidate regression models and estimate their coefficients. Model selection was performed solely using the calibration subset, and the six validation observations were not used during either model fitting or model selection.

After selecting the best-performing model, we applied the calibration-derived equation directly to the six independent validation observations without re-estimating the model coefficients. Predicted SSC values were compared with the corresponding field-measured SSC values. Hold-out validation performance was evaluated using RMSE and MAD as measures of out-of-sample prediction error.

Because the validation subset consisted of only six observations, we interpreted the validation results cautiously as a preliminary assessment of model performance under the conditions represented by the available observations. Calibration and validation statistics were therefore reported separately. The relatively small sample size resulted from the strict requirement for cloud-free satellite observations and same-day correspondence with field SSC measurements. Although these criteria improved temporal consistency between satellite and field observations, the limited number of paired samples increased statistical uncertainty, particularly for the validation subset.

Quantitative Evaluation of Model Performance

For model calibration and selection, we

evaluated candidate regression models using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute deviation (MAD), as presented in Equations 1–3 [28]. R^2 quantified each candidate model's goodness of fit to the calibration data, whereas RMSE and MAD quantified the magnitude of differences between observed and model-estimated SSC values. MAD represents the mean absolute difference between observed and estimated SSC values and provides an additional measure of model error. We selected the regression model with the highest calibration R^2 , along with comparatively low RMSE and MAD, as the optimal empirical model for SSC estimation. Independent hold-out validation was subsequently performed using the six observations that were not involved in model fitting or model selection.

$$R^2 = \frac{\sum_{t=1}^n (A_t - F_t)^2}{\sum_{t=1}^n (A_t - \bar{A}_t)^2} \quad \text{Eq. (1)}$$

$$R^2 = \frac{\sum_{t=1}^n (A_t - F_t)^2}{\sum_{t=1}^n (A_t - \bar{A}_t)^2} \quad \text{Eq. (2)}$$

$$\text{MAD} = \frac{\sum_{t=1}^n |A_t - F_t|}{n} \quad \text{Eq. (3)}$$

where A_t is the measured SSC, F_t is the calculated SSC, and N refers to the sample size.

Low RMSE values indicate higher overall accuracy and smaller errors in the model's predictive capability.

Spatial Analysis of Sediment Distribution

After identifying the optimal regression model (the exponential model derived from Band 5), we applied the selected equation to Sentinel-2 imagery to estimate

suspended sediment concentration across the Gamasyab watershed.

Spatial distribution maps of SSC were generated for selected dates representing different hydrological conditions. These maps were used to investigate the spatial variability of suspended sediment concentration within the watershed.

The watershed was then divided into five sub-watersheds using drainage network and elevation data in a GIS environment. We extracted satellite-derived SSC values for each sub-watershed to compare relative spatial variation in sediment concentration across the watershed. The primary objective of this spatial application was to characterize relative spatial variation in SSC among the delineated sub-watersheds rather than to treat the model-derived values as direct field measurements at each upstream location. The model's empirical spectral domain was defined by the B5 reflectance range in the calibration dataset (0.0001–0.164), and estimates corresponding to B5 values outside this range were treated as extrapolated predictions and interpreted with greater caution.

It should be noted that this analysis indicates relative spatial patterns of suspended sediment concentration, which may reflect differences in geomorphological conditions, lithology, and sediment transport processes within the watershed.

Findings

Before evaluating relationships between Sentinel-2 spectral variables and SSC, this study calculated descriptive statistics for the 18 measured SSC observations. The SSC values ranged from 0.44 to 118.86 mg.L^{-1} , with a mean of 27.80 mg.L^{-1} and a median of 16.37 mg.L^{-1} . The standard deviation

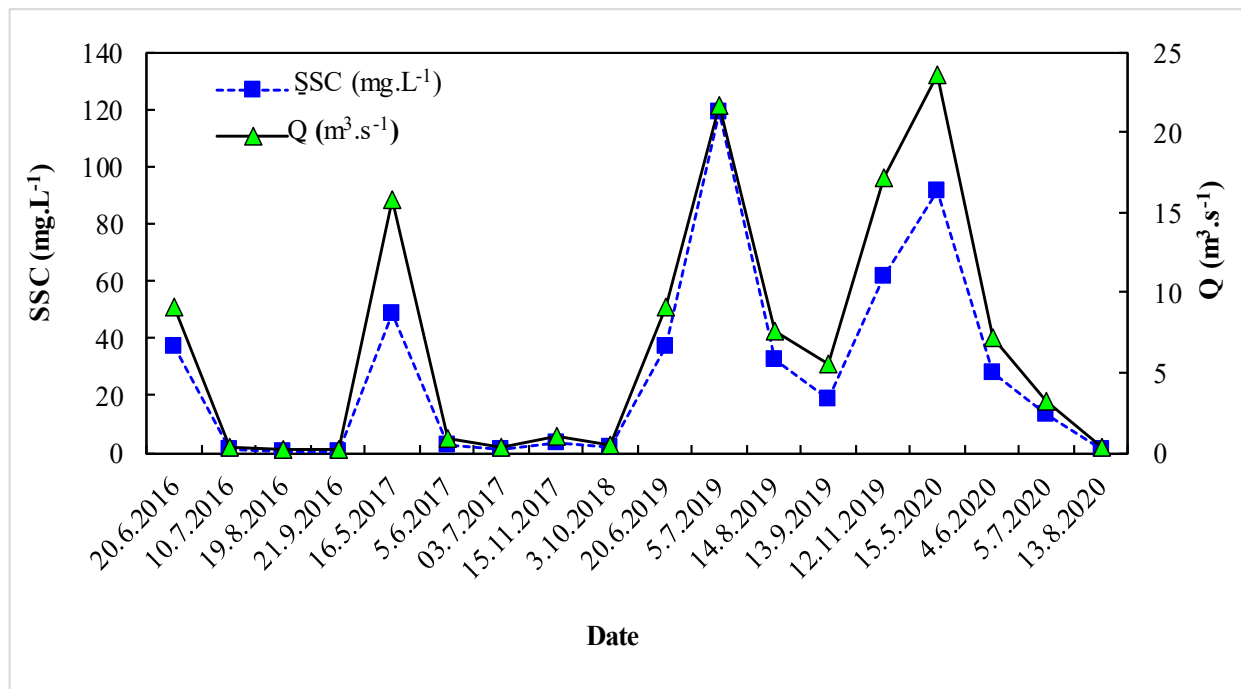


Figure 4) Comparison of flow discharge and sediment at the Pole Chehr hydrometric station for 2016-2020.

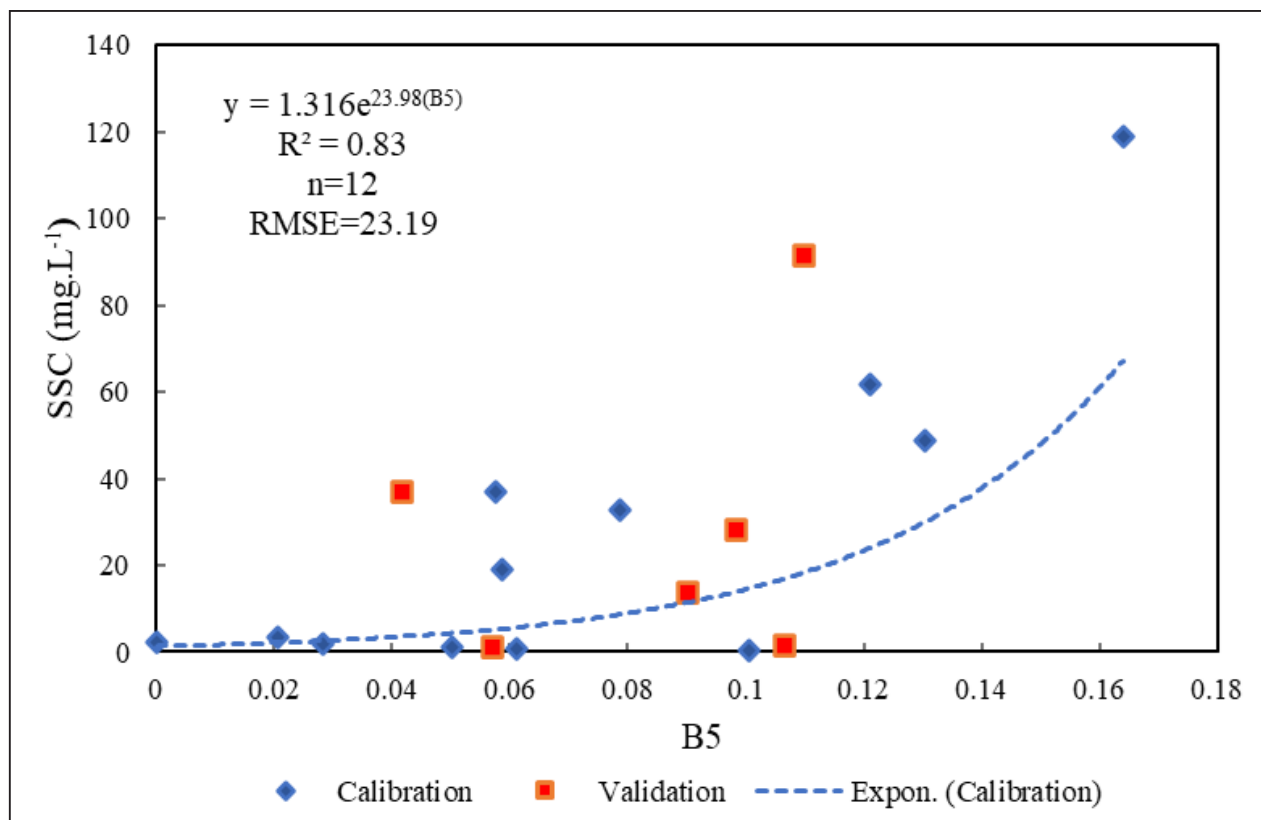


Figure 5) The best regression model (exponential model based on Band 5) based on Sentinel-2 images for estimating suspended sediment concentration in the Gamasyab River during the calibration and validation stages at the Pole Chehr station.

was 34.26 mg.L^{-1} , while the first and third quartiles were 1.62 and 36.93 mg.L^{-1} , respectively. The coefficient of variation was 123.23% , indicating substantial variability in SSC among the sampling dates.

In this study, eight bands of Sentinel-2 satellite imagery were utilized to estimate suspended sediment concentration using both individual bands and band products. Table 2 shows that SSC values recorded at the Pole Chehr hydrometric station ranged from 0.44 to 118.86 mg.L^{-1} . The highest correlation was observed for band 5 (B5), consistent with previous studies ^[26].

The correlation between single-band values, band product, and the reflectance of spectral bands was evaluated using three regression models: linear, exponential, and polynomial. The coefficients of determination (R^2) for these models are presented in Table 3. Bands 4 and 5 in single-band mode, as well as the $B5 \times B4$ product, showed stronger correlations, with band 5 having the highest R^2 values (0.66 - 0.83).

A comparison of discharge and sediment at the Pole Chehr hydrometric station in 2016–2020 showed that sediment concentration increased with discharge (Figure 4). The

Table 2) Suspended matter recorded at the Pole Chehr hydrometric station and the mean reflectance of the corresponding spectral bands.

Date	Codes of the Tiles	Suspended Sediment (mg.L^{-1})	B2	B3	B4	B5	B6	B7	B8	B8A
20.6.2016	T38SQD	36.93	0.034	0.073	0.049	0.041	0.032	0.037	0.040	0.037
10.7.2016	T38SQD	1.04	0.063	0.114	0.078	0.057	0.023	0.029	0.032	0.032
19.8.2016	T38SQD	0.44	0.082	0.127	0.102	0.100	0.067	0.071	0.081	0.074
21.9.2016	T38SQD	0.67	0.042	0.082	0.066	0.061	0.044	0.046	0.053	0.051
16.5.2017	T38SQD	48.947	0.098	0.146	0.129	0.130	0.111	0.122	0.119	0.122
5.6.2017	T38SQD	2.341	0.007	0.048	0.020	0.0001	0.0001	0.0001	0.0001	0.0001
03.7.2017	T38SQD	0.95	0.027	0.055	0.048	0.050	0.046	0.048	0.049	0.045
15.11.2017	T38SQD	3.25	0.024	0.038	0.026	0.020	0.017	0.020	0.018	0.016
3.10.2018	T38SQD	1.85	0.032	0.051	0.039	0.028	0.024	0.027	0.031	0.025
20.6.2019	T38SQD	36.93	0.069	0.121	0.063	0.057	0.082	0.004	0.0001	0.0001
5.7.2019	T38SQD	118.857	0.079	0.115	0.213	0.164	0.178	0.261	0.311	0.421
14.8.2019	T38SQD	32.638	0.069	0.101	0.080	0.078	0.040	0.049	0.039	0.034
13.9.2019	T38SQD	18.991	0.067	0.109	0.066	0.058	0.023	0.025	0.024	0.020
12.11.2019	T38SQD	61.726	0.070	0.099	0.059	0.121	0.021	0.022	0.022	0.022
15.5.2020	T38SQD	91.52	0.098	0.139	0.108	0.111	0.044	0.037	0.032	0.030
4.6.2020	T38SQD	28.013	0.070	0.107	0.077	0.098	0.067	0.060	0.045	0.065
5.7.2020	T38SQD	13.746	0.077	0.107	0.090	0.090	0.073	0.075	0.088	0.077
13.8.2020	T38SQD	1.54	0.051	0.085	0.049	0.106	0.101	0.104	0.032	0.097

Table 3) Coefficient of determination between suspended-solids values recorded at the hydrometric station and reflectance in single-band mode and band products.

Regression Model	B2	B3	B4	B5	B6	B7	B8	B8A	B5.B4
Linear	0.36	0.28	0.65	0.66	0.41	0.23	0.19	0.25	0.58
Exponential	0.25	0.16	0.69	0.83	0.58	0.27	0.23	0.31	0.61
Polynomial	0.36	0.29	0.7	0.8	0.59	0.31	0.32	0.4	0.66

Table 4) Sediment values extracted from Sentinel-2 images for sediment ranking and critical-point determination.

Number	Date	Sub-Watersheds 1 (mg.L ⁻¹)	Sub-Watersheds 2 (mg.L ⁻¹)	Sub-Watersheds 3 (mg.L ⁻¹)	Sub-Watersheds 4 (mg.L ⁻¹)	Sub-Watersheds 5 (mg.L ⁻¹)
1	20.06.2016	640	406.82	5.60	14.35	4.62
2	21.09.2016	107.33	80.36	40.23	8.20	6.4
3	03.07.2017	201.15	46.3	32.91	25.52	4.8
4	15.11.2017	73	27	25.06	16.05	3
5	05.07.2020	31.20	25.35	17.29	13.09	10
6	13.08.2020	52.56	32.55	18.87	15	4.5

results indicate that the highest sediment concentrations were observed on 5 July 2019 and 15 May 2020. Overall, the suspended sediment concentration measured (recorded) at the Pole Chehr hydrometric station ranged from 0.44 to 118.86 mg.L⁻¹. After evaluating the candidate spectral bands and regression models using the calibration dataset (Table 3), the exponential model based on Band 5 reflectance was identified as the best-performing model (Equation 4), with a calibration R² of 0.83, RMSE of 23.19 mg.L⁻¹, and MAD of 16.92 mg.L⁻¹. Model performance was subsequently assessed using an independent hold-out validation subset consisting of six observations that had not been used for

model fitting or model selection. We applied the calibration-derived equation directly to these observations without re-estimating the model coefficients. Comparing field-measured SSC values with SSC values predicted by the calibration-derived model yielded validation RMSE and MAD of 33.96 and 23.74 mg.L⁻¹, respectively. Given the small independent validation subset (n = 6), these results are interpreted cautiously as a preliminary out-of-sample assessment of model performance rather than evidence of broad model generalizability. The results of fitting empirical models based on Sentinel-2 images for estimating suspended sediment concentration in the Gamasyab River (Pole Chehr Station) are presented in Equation 4.

$$y = 1.316e^{23.98(B5)} \quad \text{Eq. (4)}$$

Figure 5 illustrates the Band 5 exponential model and the distribution of the calibration and independent validation observations at the Pole Chehr station. We developed the model using 12 observations, while excluding the remaining six from model fitting and using them solely for independent validation.

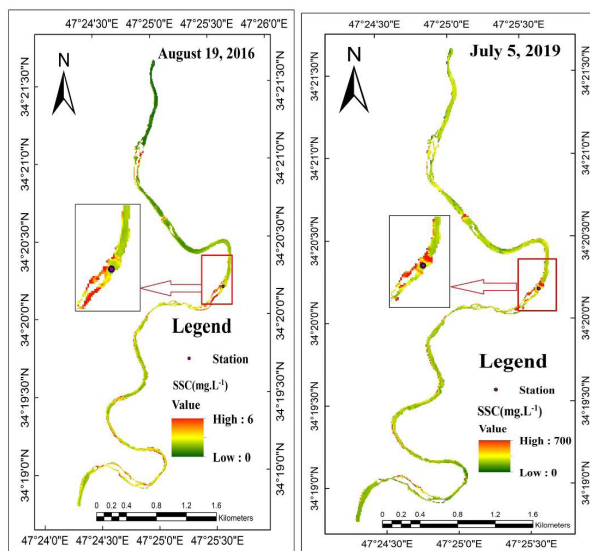


Figure 6) Spatial distribution of estimated suspended sediment concentration (SSC) for the rainy months (July) and dry month (August) - Pole Chehr hydrometric station.

Figure 6 shows the spatial distribution of estimated suspended sediment concentration (SSC) for the rainy months (July) and dry months (August) at the Pole Chehr hydrometric station. As shown in the figure, sediment values are higher in the rainy months than in the dry months.

After ranking the sub-watersheds by sediment, Table 4 shows that Sub-watershed 1 had the highest model-derived SSC values, which may be associated with alluvial materials and the Quaternary Qt2 formation, characterized by relatively high erodibility. Sub-watershed 2, despite alluvial barriers and thick-layered limestone and volcanic rhyolite (low erodibility), shows lower

sediment values than Sub-watershed 1. Sub-watershed 3 shows lower erosion and sediment production because of dark gray schist, shale, and thick-layered limestone, along with fewer alluvial barriers. Sub-watershed 4, characterized by andesitic tuff and thick-layered limestone (low erodibility) and limited alluvial barriers, also shows reduced sediment production. Sub-watershed 5 has moderate erodibility and lower sediment production because of radiolarian chert, andesite (external volcanic, resistant to erosion), and limestone. Furthermore, coarse-grained sediment deposition upstream has transferred fine-grained sediments downstream. These results show that remote sensing and satellite imagery can effectively support sediment ranking to improve watershed management. Figure 7 illustrates the sediment ranking of sub-watersheds. Rank 1 indicates high sediment values. In addition, Table 4 presents the sediment values obtained on the six studied dates.

As shown in Table 4, SSC varied considerably across the five sub-watersheds, both spatially and temporally, over the six investigated dates. Sub-watershed 1 consistently showed the highest satellite-estimated SSC values, ranging from 31.20 to 640 mg.L^{-1} , followed by sub-watershed 2, with values ranging from 25.35 to 406.82 mg.L^{-1} . In contrast, sub-watersheds 3–5 exhibited substantially lower SSC values. The greatest spatial contrast was observed on 20 June 2016, when SSC reached 640 mg.L^{-1} in sub-watershed 1 compared with only 4.62 mg.L^{-1} in sub-watershed 5. Assessment of the 30 reported SSC estimates showed that 24 estimates (80%) corresponded to equation-implied B5 values within the calibration range of 0.0001–0.164, whereas six estimates (20%) corresponded to values above the upper calibration limit.

These extrapolated cases occurred mainly in Sub-watershed 1 and, to a lesser extent, Sub-watershed 2. The highest estimate (640 mg.L^{-1}) corresponded to an equation-implied B5 value of approximately 0.258 and therefore represented substantial extrapolation beyond the calibration domain.

The relatively high SSC values observed in sub-watershed 1 may reflect highly erodible Quaternary deposits and alluvial materials. In contrast, the lower concentrations in other sub-watersheds are consistent with more resistant lithological units, including limestone, chert, and volcanic rocks.

This geological consistency supports the relative spatial pattern observed among the sub-watersheds; however, it should not be interpreted as validation of the absolute magnitude of SSC estimates generated outside the calibration domain.

The highest SSC values in sub-watersheds 1 and 2 were recorded on 20 June 2016. These elevated values may reflect the combined influence of rainfall conditions, erosion-prone formations, vegetation cover, hydrological connectivity, and other watershed controls; however, these factors were not quantitatively evaluated in the present study. On subsequent dates, SSC generally decreased, which may reflect temporal variability in rainfall, vegetation conditions, and hydrological processes.

It should be emphasized that elevated SSC within a sub-watershed does not necessarily indicate that the sediment was generated locally, because sediment may have originated upstream and been transported through the drainage network. Therefore, these results should be interpreted as a relative spatial assessment of sediment-prone conditions rather than as direct evidence of sediment-source contributions

or sediment yield. Overall, the findings indicate considerable spatial and temporal heterogeneity in SSC within the Gamasyab watershed.

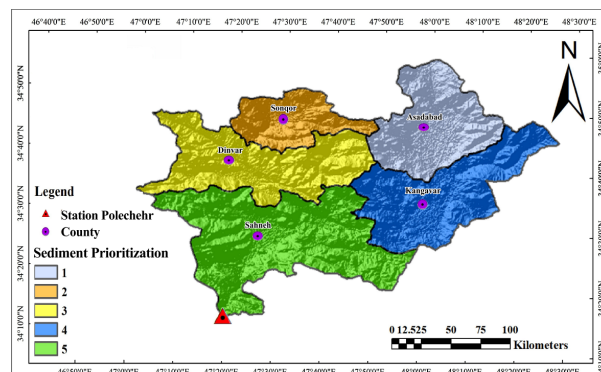


Figure 7) Prioritization of sub-watersheds in the Gamasyab watershed based on suspended sediment concentration (SSC).

Figure 7 shows the relative prioritization of the five sub-watersheds based on satellite-derived SSC patterns. Sub-watershed 1 was the highest-priority sediment-prone area, followed by sub-watershed 2, while sub-watersheds 3–5 had comparatively lower priority. This ranking reflects a relative spatial assessment of suspended-sediment conditions and should not be interpreted as a direct identification of sediment-source areas or sediment yield.

Discussion

Remote sensing offers a useful approach for investigating suspended sediment dynamics in river systems, especially where field measurements are limited. Consistent with previous studies [9, 10, 12], these results support using Sentinel-2 spectral information for empirical SSC estimation. Therefore, this study's main significance lies not in introducing a new spectral or regression-based method, but in evaluating an established approach under the specific environmental and data-limited conditions

of the Gamasyab watershed and extending the resulting SSC estimates to prioritize sediment-prone sub-watersheds.

The results indicate that Sentinel-2 multispectral imagery can estimate suspended sediment concentration (SSC) and examine its spatial distribution within the Gamasyab watershed. We observed a relationship between SSC measurements and spectral reflectance, particularly in the red-to-red-edge region. Among the evaluated bands, Band 5 showed the strongest empirical performance in the available dataset. This finding generally aligns with previous studies showing the sensitivity of visible, red, and near-infrared wavelengths to suspended sediment concentration ^[9, 10]. However, Paulista et al. ^[12] reported that the red spectral band provided the most accurate predictor of SSC in the Teles Pires River.

In contrast, Band 5 in the red-edge region performed best in the present study. These differences may reflect variations in sediment characteristics, water optical properties, hydrological conditions, and watershed-specific environmental characteristics. Previous research has also demonstrated the usefulness of these spectral regions for monitoring suspended matter in aquatic environments ^[29]. Meanwhile, Long and Pavelsky ^[25] highlighted the applicability of red and near-infrared spectral information for SSC estimation.

Temporal variations in SSC were observed among the investigated dates, with higher concentrations generally coinciding with higher-discharge conditions. This pattern suggests a possible association between hydrological variability and sediment mobilization; however, rainfall intensity, hydrograph position, and vegetation

conditions were not quantitatively evaluated in the present study. Therefore, the elevated SSC values observed during some dates, including July 2019, should be interpreted cautiously as potentially associated with rainfall-runoff and discharge conditions rather than as evidence of a demonstrated causal relationship. The nonlinear relationships identified by the exponential and polynomial models further indicate that the reflectance–SSC relationship may be influenced by several factors, including particle size, mineral composition, sediment concentration, and water optical conditions. Spatial analysis revealed considerable variability in satellite-derived SSC among the sub-watersheds. Sub-watershed 1 consistently exhibited higher SSC values, whereas sub-watersheds dominated by comparatively resistant lithological units such as chert, andesite, and compact limestone showed lower concentrations. These spatial patterns may reflect differences in lithology, geomorphology, hydrological connectivity, and sediment transport processes. However, elevated SSC within a sub-watershed does not necessarily indicate that the sediment was generated locally. Sediment may originate upstream and be transported through the drainage network before it is detected within a given sub-watershed.

The higher SSC pattern observed in Sub-watershed 1 is physically consistent with its comparatively erosion-prone geological setting, including Quaternary deposits and alluvial materials. However, because the selected B5–SSC relationship is exponential, estimates generated beyond the upper B5 calibration limit are particularly sensitive to extrapolation. Therefore, the geological setting supports the relative spatial pattern,

but does not validate the absolute magnitude of the highest extrapolated SSC estimates. Therefore, the prioritization of the five sub-watersheds should be interpreted as a relative spatial assessment based on satellite-derived SSC patterns rather than as direct identification of sediment-source areas or quantification of sediment yield. Independent sediment-budget, sediment-connectivity, or source-tracing analyses would be required to determine each sub-watershed's actual contribution to downstream sediment loads.

Although suspended sediment data were obtained from the Pole Chehr hydrometric station, which is located in the downstream part of the watershed, the use of satellite-derived SSC information enabled a broader spatial interpretation of suspended sediment conditions. Nevertheless, because the empirical SSC–reflectance relationship was calibrated using data from a single downstream monitoring station, its transferability to upstream sub-watersheds with different sediment characteristics, channel morphology, water depth, and optical properties remains uncertain. The generated SSC maps should therefore be interpreted as spatial estimates and relative patterns of suspended sediment concentration rather than as direct measurements of sediment yield or definitive identification of sediment-source areas. Accordingly, the identified high-SSC areas should be considered relatively higher-priority sediment-prone areas rather than confirmed sediment-source locations. Human activities, including agricultural expansion, construction, and localized mining, may also influence sediment mobilization in parts of the watershed, particularly near river channels. However, the present study did not quantitatively

analyze these factors and therefore treats them as plausible contributors rather than demonstrated drivers of the observed SSC patterns.

Overall, integrating Sentinel-2 imagery with regression-based modeling offers a potentially useful approach for watershed-scale SSC assessment under data-limited conditions. However, the limited number of paired satellite–field observations, reliance on a single hydrometric station, and uncertainties in temporal matching and sediment transport pathways limit the results' generalizability. Future studies should incorporate additional hydrometric stations, more field observations across a wider range of hydrological conditions, and complementary analyses such as sediment connectivity, sediment budgeting, or source tracing to distinguish better observed SSC patterns from actual sediment-source contributions.

Study Limitations

Although the results of this study demonstrate the potential of Sentinel-2 imagery for estimating suspended sediment concentration and identifying sediment-prone areas in the Gamasyab watershed, several limitations should be considered. A major limitation of this study is the small number of paired satellite–field observations available for model development and independent evaluation. Only 18 observations met the strict cloud-free and temporal-matching criteria; 12 were used for calibration and 6 for validation. Although these quality-control procedures reduced temporal and atmospheric inconsistencies, the small sample size—particularly the six-observation validation subset—results in substantial statistical uncertainty. Therefore, validation statistics should not

be interpreted as evidence of broad model generalizability. Instead, they provide a preliminary assessment of model behavior under the environmental conditions represented by the available observations. Additional field observations covering a wider range of hydrological and sediment conditions are required before the model can be considered transferable to other periods or watersheds.

Another limitation is extrapolation beyond the calibrated model's empirical spectral domain. Although most reported sub-watershed estimates (80%) fell within the calibration range, six estimates (20%) exceeded the upper calibration limit. These high values should therefore be regarded as extrapolated, high-uncertainty model outputs rather than quantitatively validated SSC concentrations. Accordingly, the model is better suited for evaluating relative spatial variation and sub-watershed prioritization than for precise absolute SSC estimation outside the calibration domain.

This limited sample size mainly reflects strict image selection criteria, including cloud-free conditions and temporal correspondence between satellite acquisition dates and available sediment records. Although these criteria reduced the number of usable observations, they ensured reliable conditions for establishing relationships between spectral reflectance and suspended sediment concentration [27].

Second, suspended sediment data were obtained from a single hydrometric station (Pole Chehr) located in the downstream part of the watershed. Although this station provides long-term monitoring data, relying on one station may not fully represent the spatial variability of sediment generation processes within upstream sub-watersheds.

Therefore, the identified high-SSC or sediment-prone areas should be interpreted as a preliminary relative spatial assessment rather than as direct identification or exact quantification of sediment-source contributions from individual sub-watersheds [16].

Another limitation concerns the field-sampling metadata. The authors did not collect the SSC data directly; they were obtained from archived monitoring records of the Iranian Ministry of Energy. Although the available information indicated that suspended sediment samples were collected using a standard depth-integrated sampling procedure, detailed metadata on the exact sampler model and possible modifications of the sampling procedure during flood or high-flow conditions were not available. The archived records provided to the authors did not include detailed information on the laboratory analytical procedure used for SSC determination; therefore, this aspect could not be independently verified and is acknowledged as a limitation. Therefore, these missing sampling and analytical details could not be independently evaluated in the present study.

Another limitation relates to the temporal mismatch between satellite imagery and hydrometric station observations. Although sediment measurements recorded on the same calendar day as the Sentinel-2 overpass were used, the observations were not always exactly time-matched. Therefore, short-term fluctuations from rainfall events, rapidly changing flow conditions, or movement along rising and falling hydrographs may add uncertainty to the reflectance–SSC relationship and regression models [25]. In addition, flood events may generate rapid increases in sediment concentration that

cannot always be fully captured by satellite observations ^[17]. Lithological differences and sediment connectivity conditions within the watershed may also influence sediment production and transport pathways. Variations in geological formations, vegetation cover, or geomorphological barriers may interrupt sediment transfer from hillslopes to the main channel, which could affect the interpretation of potential sediment-prone areas.

Furthermore, the mixed-pixel effect may influence satellite-based water quality retrieval, especially in narrow river channels where land and water signals overlap within a single pixel. In this study, we reduced this effect by extracting reflectance from central river pixels and averaging multiple pixels across the channel ^[18]. Despite these limitations, integrating satellite imagery and hydrometric observations provides useful insights into the spatial distribution of suspended sediment in the Gamasyab watershed.

Using same-day rather than exactly time-matched field and satellite observations may introduce additional uncertainty under rapidly changing hydrological conditions.

Conclusion

This study evaluated the applicability of an established Sentinel-2-based empirical approach for SSC estimation under the environmental and data-limited conditions of the Gamasyab watershed. It examined its utility for relative spatial prioritization of sediment-prone sub-watersheds. Among the evaluated spectral relationships, the Band 5 exponential model showed the strongest calibration performance ($R^2 = 0.83$, $MAD = 16.92$, and $RMSE = 23.19$), while independent validation produced $RMSE$ and MAD values

of 33.96 and 23.74 mg.L^{-1} , respectively. However, because the model was developed from only 18 paired observations and independently evaluated using six observations from a single monitoring station, its predictive performance should be considered preliminary and site-specific. The results therefore indicate promising potential under the environmental and hydrological conditions represented by the available observations at the Pole Chehr station, rather than broad generalizability across other watersheds or hydrological regimes.

The nonlinear behavior observed in the sediment-reflectance relationship further indicates that empirical SSC estimation may be sensitive to local sediment and hydrological conditions.

Spatial analysis revealed substantial heterogeneity in SSC among the sub-watersheds. Sub-watersheds 1 and 2 were identified as relatively higher-priority sediment-prone areas, whereas sub-watersheds dominated by more resistant lithological units exhibited comparatively lower SSC values. These spatial differences may reflect variations in lithology, geomorphology, hydrological connectivity, and local land-use conditions.

However, elevated SSC should not be interpreted as direct evidence of local sediment-source contribution or sediment yield.

This study's main contribution is applying Sentinel-2-based SSC estimation in a data-limited watershed and integrating it with spatial analysis to support relative sub-watershed prioritization. The resulting SSC maps provide useful spatial information for preliminary watershed-scale sediment assessment and management planning.

However, the independent validation dataset included only six observations; therefore, the validation results should be interpreted as a limited hold-out assessment rather than strong evidence of temporal model transferability. Additional field observations across a wider range of hydrological conditions, along with data from additional hydrometric stations, are needed before the developed relationship can be generalized to other watersheds or hydrological regimes. Future studies should also consider longer temporal datasets, multi-sensor observations, sediment-connectivity analysis, and additional independent field validation to improve model robustness and transferability.

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