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REMOTE SENSING AND GIS MONITORING OF WIND EROSION AND DUST EMISSION IN CENTRAL ASIA

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ABSTRACT

Wind erosion and associated dust emission are major drivers of land degradation in arid and semi-arid regions of Central Asia, affecting soil condition, agricultural landscapes, ecosystems, and air quality. The aim of this review is to critically assess current remote sensing and geographic information system (GIS) approaches for monitoring wind erosion, identifying dust-source areas, and characterizing atmospheric dust emissions in Central Asia. The review synthesizes peer-reviewed studies addressing optical and radar satellite observations, unmanned aerial vehicles, GIS analysis, wind-erosion models, aerosol products, meteorological observations, and ground-based measurements. Particular attention is given to the integration of remote sensing with the Revised Wind Erosion Equation (RWEQ), the Wind Erosion Prediction System (WEPS), Google Earth Engine workflows, and atmospheric transport models. The reviewed evidence indicates that optical data are most effective for characterizing vegetation cover, exposed soil, land-cover dynamics, and surface moisture; SAR/InSAR provides complementary information on structural and temporal surface changes; and aerosol products such as AOD and AAI/UVAI describe the atmospheric phase of dust events. However, differences in spatial and temporal resolution, model parameterization, and validation procedures constrain direct comparison among studies. An integrated framework combining remote sensing, GIS, erosion modelling, meteorological observations, UAV surveys, and ground-based aerosol measurements is therefore the most promising direction for operational monitoring of wind erosion and dust emission in Central Asia.

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Keywords: *wind erosion; remote sensing; GIS; dust emission; Central Asia.*

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Introduction

Wind erosion is a major geomorphological and soil-degradation process in arid and semi-arid environments. It selectively removes fine and nutrient-rich soil fractions, alters the physical properties of the surface layer, redistributes sediment across landscapes, and can contribute to atmospheric particulate matter. Contemporary research therefore increasingly treats wind erosion and dust emission as linked stages of a continuum extending from soil-surface instability and particle detachment to atmospheric transport and deposition (Alfaro & Gomes, 2001; Jarrah et al., 2020; Borrelli et al., 2021).

Central Asia is particularly vulnerable because extensive arid landscapes coincide with strong seasonal winds, sparse vegetation, soil-surface degradation, irrigation-related land-use change, and a limited density of long-term ground observations. Regional syntheses show that soil-erosion research in Central Asian countries has expanded substantially, while methodological approaches remain heterogeneous in spatial scale, input data, and quantitative assessment procedures (Juliev et al., 2024). Evidence from other dryland regions also demonstrates that anthropogenic land-use and land-cover change can modify wind-erosion patterns (Chi et al., 2019). Climate-driven changes may further modify the spatial and temporal distribution of wind-erodible surfaces and erosion intensity (Li et al., 2020).

The desiccated Aral Sea basin provides one of the clearest examples of the regional importance of aeolian processes. The newly formed Aralkum landscape has become a major source of mineral and saline dust. Regional modelling has identified more than 27,000 km² of potential dust-source areas and estimated mean annual potential dust emission at approximately 80.5 Tg during 2010–2020, with the eastern part of the desiccated basin contributing the largest share (Banks et al., 2022; Chen et al., 2022; Xi & Sokolik, 2016). These findings demonstrate that wind erosion in Central Asia is not only a soil-degradation problem but also an atmospheric and regional environmental issue.

Conventional field methods, including sediment traps, direct measurements of particle transport, meteorological observations, and soil-surface characterization, provide essential measurements for process understanding and model validation. Their principal limitation is spatial representativeness: measurements from a limited number of sites cannot readily describe rapidly changing conditions across millions of hectares. Remote sensing and GIS consequently provide an important means of extending observations from individual sites to regional scales. Recent reviews emphasize the growing role of satellite and UAV observations in identifying erosion-prone surfaces and linking surface characteristics with erosion processes (Lackoóvá et al., 2023; Baxodirov et al., 2022).

The integration of remote sensing with wind-erosion models represents a particularly important development. The original Wind Erosion Equation (WEQ) established an empirical basis for estimating potential wind erosion (Woodruff & Siddoway, 1965), while the Revised Wind Erosion Equation (RWEQ) improved its representation of erosion-driving factors and broadened its practical applicability (Fryrear et al., 2001). More recently, Google Earth Engine has enabled large-scale implementation of RWEQ using long time series of satellite, climatic, soil, and vegetation data. For Central Asia, GEE-RWEQ has been used to generate regional maps of wind-erosion potential at 500 m resolution for 2000–2019 (Wang et al., 2020), and subsequent work has incorporated multi-source remote sensing to assess changes and their climatic and anthropogenic drivers (Yao et al., 2025).

At the atmospheric stage, satellite aerosol products, reanalysis data, ground-based measurements, and transport models provide complementary information. AOD and AAI/UVAI can identify and track aerosol plumes, whereas $PM_{2.5}$ and PM_{10} measurements quantify near-surface particulate loading. Studies of Central Asian dust events demonstrate the value of combining TROPOMI observations with CAMS, MERRA-2, ground observations, and atmospheric transport modelling (Nishonov et al., 2023). This distinction is important because an erosion-potential map describes the susceptibility or potential emission of a surface, whereas atmospheric aerosol measurements describe the resulting airborne phase.

Radar observations provide another complementary information source. Sentinel-1 SAR and multi-temporal InSAR approaches can characterize structural and temporal changes of the land surface under conditions where optical observations are affected by cloud cover or illumination. Recent SBAS-InSAR research in the southern Aral Sea basin identified areas of rapid and slow erosion, stable surfaces, and zones of accumulation, while also demonstrating relationships with soil moisture and wind conditions (Chen et al., 2025).

Despite these advances, an integrated regional monitoring framework that links surface condition, erosion potential, dust emission, atmospheric transport, and impact zones remains insufficiently

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standardized. Differences in sensor characteristics, temporal coverage, model parameterization, validation methods, and definitions of erosion and dust indicators limit comparability among studies. The objective of this review is therefore to critically synthesize current remote sensing and GIS-based methods for monitoring wind erosion and dust emission in Central Asia, compare their strengths and limitations, and identify priorities for an integrated spatial-temporal monitoring system.

2. Method

This review was designed as a critical synthesis of peer-reviewed literature on remote sensing, GIS, wind-erosion modelling, dust-source identification, and atmospheric aerosol monitoring relevant to Central Asia. The literature base was assembled primarily from Scopus and Web of Science using combinations of the terms “wind erosion”, “dust emission”, “dust storm”, “remote sensing”, “GIS”, “RWEQ”, “WEPS”, “SAR”, “InSAR”, “UAV”, “Central Asia”, “Aral Sea”, and “Aralkum”.

Studies were considered relevant when they addressed at least one of the following: (i) spatial or temporal assessment of wind erosion; (ii) identification or characterization of dust-source areas; (iii) estimation or observation of dust emission; (iv) application of optical, radar, UAV, or aerosol remote sensing; or (v) integration of remote sensing, meteorological, soil, and ground observations with erosion or atmospheric transport models. The selected literature was grouped by data type, analytical method, spatial scale, principal indicators, and methodological limitations.

The synthesis followed three analytical levels. First, surface-oriented approaches were examined, including optical satellite observations, SAR/InSAR, UAV surveys, and GIS-based integration. Second, wind-erosion models were compared with respect to their conceptual basis, data requirements, outputs, and suitability for Central Asian conditions. Third, atmospheric monitoring approaches were evaluated by considering aerosol products, PM measurements, reanalysis datasets, and transport modelling. The final synthesis focused on how these components can be combined into a coherent monitoring chain from soil-surface susceptibility to atmospheric dust and potential impact zones.

Because the study is a review, no primary field or laboratory experiment was conducted. The conclusions are therefore based on the evidence and methodological characteristics reported in the reviewed literature. Particular attention was paid to limitations and validation requirements so that modelled erosion potential would not be interpreted as a direct measurement of sediment flux.

3. Results or Findings

3.1. Wind erosion and dust emission in Central Asia

The reviewed literature indicates pronounced spatial and temporal heterogeneity of wind erosion across Central Asia. Erosion intensity is controlled by interacting meteorological, soil, vegetation, and land-use factors, with the highest susceptibility generally occurring on exposed desert surfaces, degraded lands, and the desiccated Aral Sea bed. Large-scale assessments using RWEQ and remote sensing show that wind speed, vegetation cover, soil moisture, surface condition, and land use are among the dominant controls of spatial variability (Li et al., 2020; Wang et al., 2020). Soil erodibility itself is a critical parameter and requires careful regional characterization because it controls the susceptibility of the surface to detachment and transport (Gao et al., 2022; Webb et al., 2006, 2009).

The Aral Sea basin is a particularly important regional source. Dust-source mapping and emission modelling indicate extensive areas of potentially active surface deflation and substantial annual emissions (Banks et al., 2022; Chen et al., 2022). Earlier analyses using satellite observations also identified the desiccated basin as an active dust source, while later work has emphasized the role of land-use change and desiccation in enhancing anthropogenic and natural dust emissions (Indoitu et al., 2015; Xi & Sokolik, 2016). The magnitude and seasonality of emissions demonstrate why surface erosion monitoring should be connected with atmospheric observations.

Regional studies further indicate that the distribution of erosion-prone areas can shift seasonally and interannually. Changes in wind regime, snowmelt, vegetation dynamics, soil moisture, and land use

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may alter the spatial pattern of erosion potential (Wang et al., 2020; Yao et al., 2025). Consequently, a static erosion-risk map cannot fully represent the temporal dynamics of Central Asian dust-source activity.

3.2. Remote sensing and quantitative assessment of wind erosion

Optical satellite observations provide the most widely used regional information on vegetation cover, exposed soil, land-cover change, surface reflectance, and moisture-related characteristics. Landsat, Sentinel-2, and MODIS time series can support the identification of erosion-prone surfaces and provide variables required for model parameterization. Their principal limitation is that spectral observations generally describe surface condition rather than directly measuring particle detachment or sediment flux (Lackoóvá et al., 2023).

The combination of satellite observations with GIS and RWEQ substantially expands the spatial and temporal scope of wind-erosion assessment. Wang et al. (2020) demonstrated that GEE-RWEQ can produce monthly maps of wind-erosion potential across Central Asia at 500 m spatial resolution for 2000–2019. Such workflows reduce the computational burden of processing multi-year, multi-source datasets and make regional comparisons more feasible. More recent work in the Aral Sea region has further linked RWEQ outputs with multi-source remote sensing and factor attribution (Yao et al., 2025).

The results of the reviewed studies also support the use of independent indicators such as dust-storm indices, AOD, and AAI/UVAI for evaluating the spatial and temporal consistency of modelled erosion potential. However, agreement between a modelled erosion index and an aerosol indicator should be interpreted as complementary evidence rather than direct validation of sediment flux. Independent field measurements remain necessary to quantify actual particle transport and to constrain model uncertainty (Borrelli et al., 2021).

Table 1

Comparative characteristics of remote sensing and GIS methods for wind erosion and dust emission monitoring

Method / data source	Key parameters / indicators	Main application	Advantages and limitations
Optical satellite data (Landsat, Sentinel-2, MODIS)	NDVI; surface reflectance; bare-soil indicators; land-cover change; moisture-related indices	Vegetation and exposed-soil assessment; identification and temporal monitoring of erosion-prone areas	Large-area coverage and long archives; repeated observations. Cloud effects and mainly indirect characterization of erosion.
Satellite aerosol products (TROPOMI, MODIS)	AOD; AAI/UVAI; aerosol-plume characteristics	Detection and tracking of dust events and atmospheric aerosol transport	Regional-to-continental coverage. Limited ability to directly quantify individual ground sources; retrieval uncertainty.
SAR / InSAR (Sentinel-1)	Radar backscatter; temporal coherence; surface deformation/displacement	Detection of surface changes associated with erosion, sediment removal, and accumulation	Independent of daylight and comparatively resistant to cloud cover. Interpretation is complex and requires ancillary data.
UAV remote sensing (RGB, multispectral, photogrammetry)	High-resolution imagery; vegetation indices; DSM/DTM; surface morphology	Detailed mapping of erosion features, exposed soil, vegetation gaps, and local dust-source areas; field validation	Very high spatial resolution and flexible acquisition. Limited coverage, weather dependence, and additional processing.
GIS-based spatial analysis	Soil properties; land cover; terrain; wind; moisture; erosion-risk factors	Integration and spatial analysis of remote sensing, soil, meteorological, and field data; erosion-risk mapping	Integrates heterogeneous datasets and supports decision-making. Does not independently measure erosion and depends on input-data quality.
Integrated RS–GIS modelling (RWEQ, GEE-RWEQ)	Wind speed; soil erodibility; vegetation; roughness; climate; satellite-derived variables	Quantitative spatial-temporal assessment of erosion potential and high-risk areas	Suitable for regional assessment and long-term monitoring. Model uncertainty, parameter sensitivity, and need for field validation.

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Table 1 shows that the methods are complementary rather than interchangeable. Optical observations primarily characterize surface and vegetation conditions, aerosol products describe the atmospheric phase, SAR/InSAR adds information on structural and temporal surface change, and UAV surveys provide localized high-resolution observations. GIS acts as the integration environment, while RWEQ-based approaches translate heterogeneous observations into spatially explicit estimates of erosion potential. The most robust regional strategy is therefore a multi-source workflow supported by independent field validation (Lackoóvá et al., 2023; Baxodirov et al., 2022).

3.3. Comparison of wind-erosion models

Wind-erosion models differ in conceptual structure, data requirements, temporal representation, and intended application scale. The original WEQ was developed as an empirical equation for estimating potential wind erosion using factors such as soil erodibility, surface roughness, climatic conditions, field length, and vegetation cover (Woodruff & Siddoway, 1965). RWEQ retained a comparatively accessible structure while improving the representation of erosion-driving conditions and has become suitable for GIS-based regional assessments (Fryrear et al., 2001; Seo et al., 2020).

WEPS represents a more process-oriented modelling framework with continuous daily simulation of weather, soil, vegetation, hydrology, management, and erosion processes. Its detailed process representation is advantageous for field-scale management and event analysis, but the model requires a comparatively large and well-parameterized input dataset (Hagen, 1991, 2004; Wagner, 2013). Reviews of wind-erosion models emphasize that model selection should reflect the target scale, available data, and required process detail rather than a simple assumption that a more complex model is always preferable (Jarrah et al., 2020).

For Central Asia, GEE-RWEQ is particularly promising because it combines a relatively tractable erosion model with large-scale satellite and climate datasets. Nevertheless, its output should be interpreted as modelled erosion potential rather than direct sediment flux. Soil erodibility, vegetation dynamics, wind forcing, and satellite-derived parameters must be regionally evaluated and, where possible, calibrated against field observations (Wang et al., 2020; Yao et al., 2025).

Table 2

Comparison of wind-erosion models and their applicability to Central Asian conditions

Model / approach	Concept and main inputs	Main outputs / scale	Applicability to Central Asia
WEQ	Empirical equation using soil erodibility, roughness, climate, field length, and vegetation	Potential annual erosion; mainly field-scale assessment	Simple and historically important; limited representation of temporal dynamics and heterogeneous regional surfaces.
RWEQ	Empirical/semi-mechanistic approach incorporating wind, soil erodibility, vegetation, crust, and surface condition	Potential soil loss; field-to-regional assessment	Well suited to GIS-based regional mapping; requires local parameterization and validation.
WEPS	Process-based continuous simulation of weather, soil, vegetation, hydrology, management, and erosion	Soil loss/deposition; saltation, creep, suspension, PM_{10}; field scale	Detailed process representation; high data requirements and need for locally appropriate inputs.
SWEEP	Single-event implementation of the WEPS erosion submodel	Soil loss and transport for individual wind events	Useful for strong-event and experimental analysis; less suited to regional long-term monitoring.
GEE-RWEQ / RS–GIS integration	RWEQ integrated with Google Earth Engine, satellite, climate, soil, vegetation, and wind datasets	Multi-temporal regional maps of erosion potential and risk zones	Strongest regional option among reviewed approaches; represents potential rather than direct sediment flux and requires independent validation.

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The comparison indicates that model applicability depends on the spatial-temporal scale of the question and on data availability. WEQ is historically important, RWEQ is comparatively practical for regional GIS applications, WEPS provides detailed process simulation, and SWEEP is useful for individual events. For Central Asia, the most scalable pathway is the integration of RWEQ with remote sensing and GIS, complemented by field measurements and atmospheric observations (Seo et al., 2020; Jarrah et al., 2020).

3.4. SAR/InSAR and high-resolution surface monitoring

SAR observations complement optical data because radar acquisition is independent of daylight and less affected by cloud cover. Sentinel-1 time series and InSAR methods can provide information on structural and temporal changes of exposed surfaces. In the southern Aral Sea basin, SBAS-InSAR has been used to distinguish areas of rapid and slow erosion, stable surfaces, and accumulation, with soil moisture identified as an important controlling factor and wind speed linked to material transport (Chen et al., 2025).

InSAR should not be interpreted as a universal direct measure of wind-erosion intensity. Radar-derived changes may reflect several interacting processes, including moisture variation, surface roughness, sediment redistribution, and other deformation mechanisms. Its strongest value is therefore achieved when SAR/InSAR is integrated with optical data, soil-moisture information, digital terrain data, meteorological observations, and erosion models.

3.5. Dust storms and atmospheric aerosol monitoring

Atmospheric monitoring represents a different analytical level from surface erosion assessment. TROPOMI/UVAI, AOD, $PM_{2.5}$, PM_{10}, CAMS, and MERRA-2 can characterize aerosol loading, plume extent, and atmospheric conditions associated with dust events. Satellite aerosol products are especially valuable for regional-scale event detection, while ground-based PM measurements provide local quantitative information required for validation.

A study of strong dust storms in Central Asia using TROPOMI, CAMS, and MERRA-2 demonstrated that combined satellite and reanalysis information can reproduce the spatial and temporal structure of dust events, while also revealing differences among reanalysis products in $PM_{2.5}$ estimation (Nishonov et al., 2023). Analysis of the November 2021 extreme dust event in Uzbekistan further showed the value of combining satellite observations, ground aerosol measurements, and Lagrangian transport modelling for event reconstruction (Nishonov et al., 2023).

At the source-to-atmosphere level, dust emission modelling and atmospheric transport should be linked. Studies of the Aral Sea region demonstrate that combining surface erosion modelling with transport modelling can connect potential source areas, estimated emissions, and downwind pathways (Chen et al., 2022; Banks et al., 2022). Global aerosol research further confirms the usefulness of AOD for characterizing the atmospheric dust burden, although satellite retrievals require careful interpretation under heterogeneous surface and atmospheric conditions (Voss & Evan, 2020).

3.6. Integrated monitoring framework

The synthesis supports a multi-level monitoring chain: soil and vegetation condition → surface susceptibility → wind erosion → particle transport → dust emission → atmospheric aerosol → dust storm → spatial extent and impact. Each stage is best represented by different observations and models, while GIS provides the spatial environment for their integration. This conceptual framework is consistent with the broader methodological transition from isolated monitoring products toward integrated geospatial assessment (Baxodirov et al., 2022).

Figure 1 summarizes the proposed integration of optical satellite observations, SAR/InSAR, aerosol products, UAV data, meteorological and soil information, GIS processing, erosion models, and field validation. The principal analytical advantage is that it preserves the distinction between surface erosion

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potential and atmospheric dust while allowing the two stages to be linked through source identification and transport analysis.

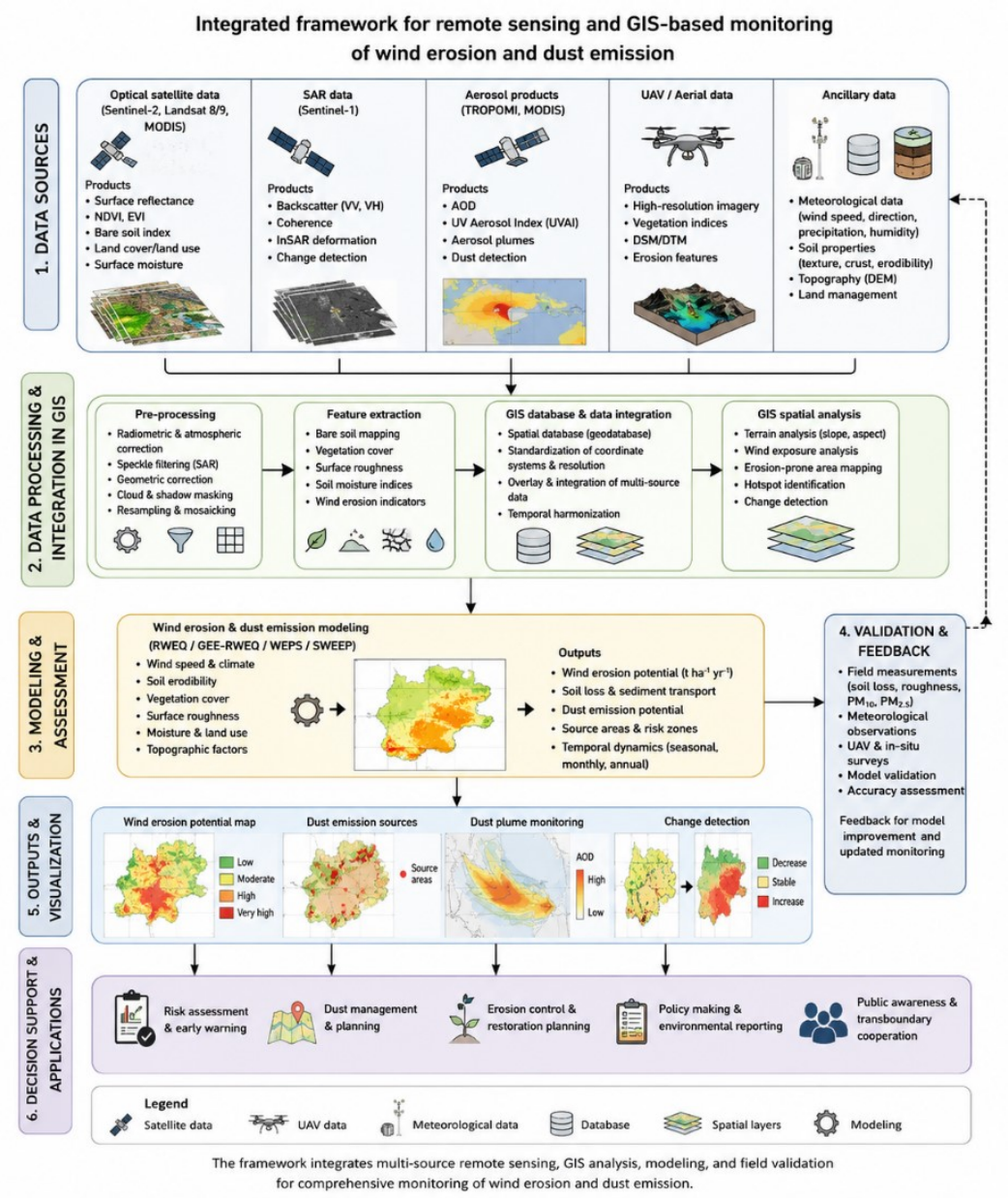


Figure 1. Integrated framework for remote sensing and GIS-based monitoring of wind erosion and dust emission

4. Discussion

4.1. Comparative performance of current monitoring methods

The evidence reviewed indicates that the principal difference among monitoring approaches lies in the type of information they provide. Field measurements are closest to the physical process and are indispensable for validation, but their spatial coverage is limited. Optical remote sensing provides repeated regional observations of surface condition, whereas SAR/InSAR supplies complementary information on structural and temporal surface change. UAVs bridge the scale gap by enabling detailed surveys of selected sites. GIS provides the analytical framework for combining these datasets.

The most important methodological limitation is the tendency to interpret a surface indicator as a direct measure of erosion. Vegetation indices, bare-soil indices, moisture indicators, and radar backscatter describe environmental conditions associated with erosion susceptibility, but they do not by themselves quantify the amount of soil removed. This distinction is particularly important in heterogeneous Central Asian landscapes, where the same spectral or radar response may arise from different combinations of soil texture, roughness, moisture, crusting, and vegetation.

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Model-based approaches improve quantitative interpretation but introduce parameter and structural uncertainty. GEE-RWEQ is highly suitable for regional screening because it can process long satellite and climate records, while WEPS offers greater process detail at smaller scales. A rational regional strategy is therefore hierarchical: use remote sensing and GEE-RWEQ to identify and monitor broad risk patterns; use UAV and field measurements to validate selected hotspots; and use detailed process-based or event-scale models where management or event reconstruction requires greater physical detail.

4.2. Source-to-atmosphere integration

A critical implication of the literature is that wind erosion and atmospheric dust should be monitored as connected but analytically distinct stages. Surface-oriented models and remote sensing can identify where erosion is likely to occur, whereas aerosol products and PM observations indicate whether and where airborne dust is present. Atmospheric transport models then provide the link between source regions and downwind exposure.

This distinction is particularly important for the Aral Sea region. Potential source mapping alone does not quantify atmospheric exposure, while an aerosol plume alone does not uniquely identify its surface origin. The strongest evidence is obtained when source susceptibility, meteorological forcing, emission estimates, aerosol observations, and transport trajectories converge. Such integration can improve source attribution and help distinguish local dust generation from transported regional aerosol.

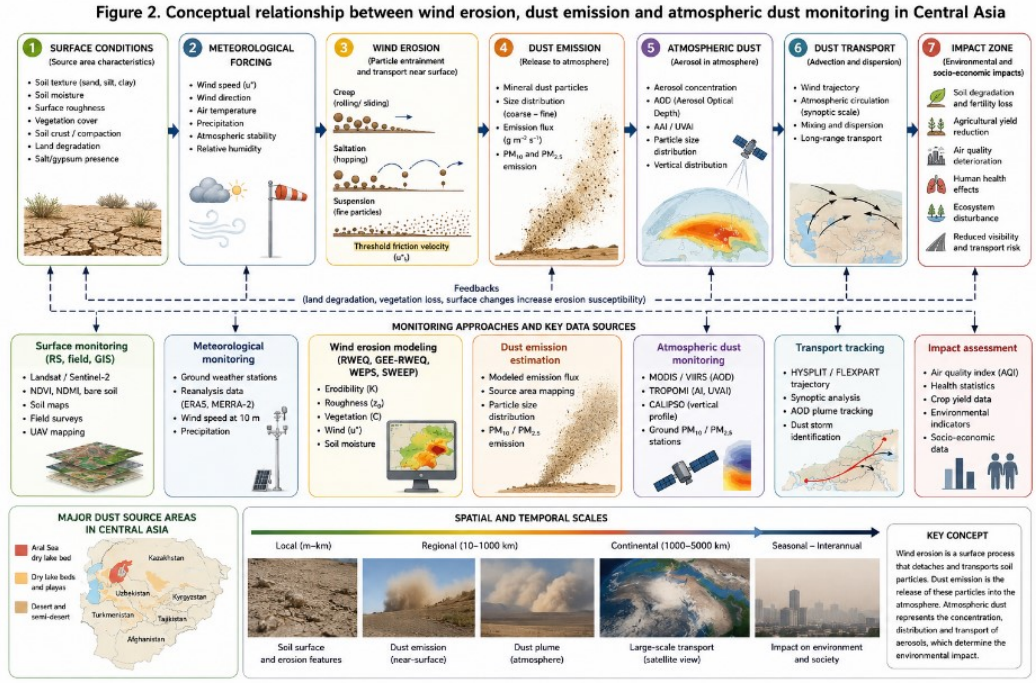


Figure 2. Conceptual relationship between wind erosion, dust emission and atmospheric dust monitoring in Central Asia

Figure 2 conceptualizes the physical sequence from soil-surface destabilization to atmospheric dust. Wind speed and direction interact with soil moisture, texture, roughness, and vegetation cover to control particle detachment and transport by creep, saltation, and suspension. The finest fraction contributes to atmospheric particulate matter and may be transported over long distances. Accordingly, $PM_{2.5}/PM_{10}$, AOD, and AAI/UVAI characterize the atmospheric stage, while surface remote sensing and erosion models are primarily used to characterize source susceptibility and potential emission. The framework highlights the need to combine both stages rather than treating either one as a complete representation of the dust cycle (Alfaro & Gomes, 2001; Voss & Evan, 2020).

4.3. Methodological gaps and priorities for Central Asia

Four methodological gaps are particularly important. First, results from different studies are difficult to compare because spatial and temporal resolutions, model formulations, threshold definitions, and validation criteria vary. Second, field validation remains insufficient relative to the spatial extent of

arid landscapes. Third, many studies address only one stage of the process—surface condition, erosion potential, or atmospheric aerosol—without integrating the complete chain. Fourth, the uncertainty associated with soil erodibility, moisture, roughness, and meteorological forcing is not always quantified explicitly.

Future regional monitoring should therefore prioritize standardized protocols for field validation, harmonized multi-source datasets, and uncertainty assessment. Optical and radar satellite time series should be linked with meteorological forcing and soil information; UAV surveys should be used strategically for high-resolution validation; and PM observations should be co-located with representative source areas where possible. Machine-learning methods may improve nonlinear relationships between remotely sensed variables and measured erosion or dust indicators, but such approaches should remain physically interpretable and independently validated.

A practical Central Asian monitoring architecture should operate at several spatial scales. Regional satellite and GIS products can identify candidate source areas; field and UAV observations can characterize surface properties and validate model outputs; event-scale observations can capture strong wind episodes; and aerosol and transport products can track downwind dispersion. Such a hierarchy is more realistic than attempting to use a single universal sensor or model for all stages of the process.

4.4. Implications for soil protection and environmental monitoring

From a soil-science perspective, integrated monitoring can support early identification of surfaces with increasing susceptibility to deflation, enabling targeted measures for vegetation restoration, surface stabilization, and erosion control. From an environmental perspective, linking source maps with atmospheric observations can improve assessment of dust exposure and regional air-quality risks. The combination is particularly relevant to degraded agricultural and desert landscapes of Uzbekistan and neighboring Central Asian countries.

The practical value of the proposed framework lies not in replacing field measurements but in using them more strategically. Remote sensing can identify where measurements are most needed, models can estimate where risk is likely to increase, and atmospheric observations can determine whether source activity translates into measurable aerosol loading. This feedback can support adaptive monitoring and more efficient allocation of field resources.

5. Conclusion and Implications

The critical review demonstrates that remote sensing and GIS have become central components of modern monitoring of wind erosion and dust emission in Central Asia. Optical satellite data are particularly effective for characterizing vegetation cover, exposed soil, land-cover dynamics, and moisture-related surface properties; SAR/InSAR adds complementary information on structural and temporal surface changes; UAVs provide high-resolution local observations; and aerosol products and ground-based PM measurements characterize the atmospheric stage of the dust process.

Among the reviewed erosion models, RWEQ and its GEE-integrated implementations offer a practical basis for regional screening and long-term spatial-temporal assessment, whereas WEPS provides greater process detail for field-scale applications and SWEEP is useful for individual events. None of these approaches should be interpreted as a complete substitute for field measurements. Their reliability depends on input-data quality, parameterization, spatial-temporal scale, and independent validation.

The main methodological conclusion is that wind erosion and atmospheric dust should be treated as linked but distinct stages. A robust monitoring system should connect soil and vegetation condition, meteorological forcing, erosion potential, source identification, dust emission, atmospheric aerosol observations, and transport analysis within a GIS-based framework. This integrated approach is especially relevant to the Aral Sea basin and other degraded arid landscapes of Central Asia, where large dust sources and limited ground-observation networks create a strong need for spatially extensive monitoring.

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Future work should focus on standardized field-validation protocols, improved regional parameterization of erosion models, integration of optical and SAR observations, systematic UAV validation, machine-learning-assisted risk mapping, and operational linkage of source models with aerosol and atmospheric transport products. Such developments can provide a methodological basis for early identification of high-risk areas, more effective soil-protection measures, and improved assessment of the environmental consequences of dust storms in Central Asia.

REFERENCES

1. Alfaro, S. C., & Gomes, L. (2001). Modeling mineral aerosol production by wind erosion: Emission intensities and aerosol size distributions in source areas. Journal of Geophysical Research: Atmospheres, 106(D16), 18075–18084. https://doi.org/10.1029/2000JD900339
2. Banks, J. R., Heinold, B., & Schepanski, K. (2022). Impacts of the desiccation of the Aral Sea on the Central Asian dust life-cycle. Journal of Geophysical Research: Atmospheres, 127, e2022JD036618. https://doi.org/10.1029/2022JD036618
3. Borrelli, P., Alewell, C., Alvarez, P., Ayach Anache, J. A., Baartman, J., Ballabio, C., et al. (2021). Soil erosion modelling: A global review and statistical analysis. Science of the Total Environment, 780, 146494. https://doi.org/10.1016/j.scitotenv.2021.146494
4. Chen, Z., Gao, X., & Lei, J. (2022). Dust emission and transport in the Aral Sea region. Geoderma, 428, 116177. https://doi.org/10.1016/j.geoderma.2022.116177
5. Chen, Z., Gao, X., & Lei, J. (2025). Monitoring of wind erosion in the southern Aral Sea using SBAS-InSAR technology. International Soil and Water Conservation Research, 13(3), 551–563. https://doi.org/10.1016/j.iswcr.2025.05.005
6. Chi, W., Zhao, Y., Kuang, W., & He, H. (2019). Impacts of anthropogenic land use/cover changes on soil wind erosion in China. Science of the Total Environment, 668, 204–215. https://doi.org/10.1016/j.scitotenv.2019.03.015
7. Fryrear, D. W., Chen, W., & Lester, C. (2001). Revised Wind Erosion Equation. Annals of Arid Zone, 40(3). https://doi.org/10.56093/aaz.v40i3.65816
8. Gao, G., Yin, X., Ding, G., Zhao, Y., Sun, G., & Wang, L. (2022). Soil erodibility for wind erosion: A critical review. Science of Soil and Water Conservation, 20(1), 143–150. https://doi.org/10.16843/j.sswc.2022.01.019
9. Hagen, L. J. (1991). A wind erosion prediction system to meet user needs. Journal of Soil and Water Conservation, 46(2), 106–111. https://doi.org/10.1080/00224561.1991.12456588
10. Hagen, L. J. (2004). Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. Environmental Modelling & Software, 19(2), 171–176. https://doi.org/10.1016/S1364-8152(03)00119-1
11. Indoitu, R., Kozhoridze, G., Batyrbaeva, M., Vitkovskaya, I., Orlovsky, N., Blumberg, D., & Orlovsky, L. (2015). Dust emission and environmental changes in the dried bottom of the Aral Sea. Aeolian Research, 17, 101–115. https://doi.org/10.1016/j.aeolia.2015.02.004
12. Jarrah, M., Mayel, S., Tatarko, J., Funk, R., & Kuka, K. (2020). A review of wind erosion models: Data requirements, processes, and validity. CATENA, 187, 104388. https://doi.org/10.1016/j.catena.2019.104388
13. Juliev, M., Kholmurodova, M., Abdikairov, B., & Abuduwaili, J. (2024). A comprehensive review of soil erosion research in Central Asian countries (1993–2022) based on the Scopus database. Soil and Water Research, 19(4), 244–256. https://doi.org/10.17221/82/2024-SWR
14. Lackoóvá, L., Lieskovský, J., Nikseresht, F., Halabuk, A., Hilbert, H., Halászová, K., & Bahreini, F. (2023). Unlocking the potential of remote sensing in wind erosion studies: A review and outlook for future directions. Remote Sensing, 15(13), 3316. https://doi.org/10.3390/rs15133316

ISSN: 2181-3337 | SCIENTISTS.UZ

15. Li, J., Ma, X., & Zhang, C. (2020). Predicting the spatiotemporal variation in soil wind erosion across Central Asia in response to climate change in the 21st century. Science of the Total Environment, 709, 136060. https://doi.org/10.1016/j.scitotenv.2019.136060
16. Baxodirov, Z. A., Mamatkulov, A. R., & Nurmatov, R. Sh. (2022). Noveyshie metody monitoringa vetrovoy erozii pochv [Latest methods for monitoring soil wind erosion]. Science and Innovation, 6, 38–46. https://doi.org/10.5281/zenodo.7086755; https://doi.org/10.5281/zenodo.13908141
17. Nishonov, B. E., Kholmatjanov, B. M., Labzovskii, L. D., Rakhmatova, N., Shardakova, L., Abdulakhatov, E. I., Yarashev, D. U., Toderich, K. N., Khujanazarov, T., & Belikov, D. A. (2023). Study of the strongest dust storm occurred in Uzbekistan in November 2021. Scientific Reports, 13, 20042. https://doi.org/10.1038/s41598-023-42256-1
18. Seo, I. W., Lim, C. S., Yang, J. E., Lee, S. P., Lee, D. S., Jung, H. G., Lee, K. S., & Chung, D. Y. (2020). An overview of applicability of WEQ, RWEQ, and WEPS models for prediction of wind erosion in lands. Korean Journal of Agricultural Science, 47(2), 381–394. https://doi.org/10.7744/kjoas.20200028
19. Tatarko, J., Sporcic, M. A., & Skidmore, E. L. (2013). A history of wind erosion prediction models in the United States Department of Agriculture prior to the Wind Erosion Prediction System. Aeolian Research, 10, 3–8. https://doi.org/10.1016/j.aeolia.2012.08.004
20. Van Pelt, R. S., Zobeck, T. M., Potter, K. N., Stout, J. E., & Popham, T. W. (2004). Validation of the wind erosion stochastic simulator (WESS) and the revised wind erosion equation (RWEQ) for single events. Environmental Modelling & Software, 19(2), 191–198. https://doi.org/10.1016/S1364-8152(03)00122-1
21. Voss, K. K., & Evan, A. T. (2020). A new satellite-based global climatology of dust aerosol optical depth. Journal of Applied Meteorology and Climatology, 59(1), 83–102. https://doi.org/10.1175/JAMC-D-19-0194.1
22. Wagner, L. E. (2013). A history of wind erosion prediction models in the United States Department of Agriculture: The Wind Erosion Prediction System (WEPS). Aeolian Research, 10, 9–24. https://doi.org/10.1016/j.aeolia.2012.10.001
23. Wang, W., Samat, A., Ge, Y., Ma, L., Tuheti, A., Zou, S., & Abuduwaili, J. (2020). Quantitative soil wind erosion potential mapping for Central Asia using the Google Earth Engine platform. Remote Sensing, 12(20), 3430. https://doi.org/10.3390/rs12203430
24. Webb, N. P., McGowan, H. A., Phinn, S. R., & McTainsh, G. H. (2006). AUSLEM (AUStralian Land Erodibility Model): A tool for identifying wind erosion hazard in Australia. Geomorphology, 78(3–4), 179–200. https://doi.org/10.1016/j.geomorph.2006.01.012
25. Webb, N. P., McGowan, H. A., Phinn, S. R., McTainsh, G. H., & Leys, J. F. (2009). Simulation of the spatiotemporal aspects of land erodibility in the northeast Lake Eyre Basin, Australia, 1980–2006. Journal of Geophysical Research: Earth Surface, 114, F01013. https://doi.org/10.1029/2008JF001097
26. Woodruff, N. P., & Siddoway, F. H. (1965). A wind erosion equation. Soil Science Society of America Journal, 29(5), 602–608. https://doi.org/10.2136/sssaj1965.03615995002900050035x
27. Xi, X., & Sokolik, I. N. (2016). Quantifying the anthropogenic dust emission from agricultural land use and desiccation of the Aral Sea in Central Asia. Journal of Geophysical Research: Atmospheres, 121, 12270–12281. https://doi.org/10.1002/2016JD025556
28. Yao, F., Ding, J., Bao, A., & Li, J. (2025). Attribution and risk assessment of wind erosion in the Aral Sea regions using multi-source remote sensing and RWEQ on GEE. Remote Sensing, 17(16), 2788. https://doi.org/10.3390/rs17162788

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