Rainfall Variability and Soil Erosion Mapping in Tajikistan through RUSLE-GIS Integration

Abeyou W. Worqlul et al.

[a] International Center for Agricultural Research in the Dry Areas (ICARDA), Addis Ababa, Ethiopia. a.worqlul@cgiar.org

Background

Tajikistan is a predominantly mountainous country located in Central Asia, with over 90% of its landmass classified as mountainous or semi-mountainous (Klytchnikova et al., 2024). The country is facing considerable environmental pressure due to soil erosion, which threatens both ecological stability and agricultural productivity (Qin et al., 2022; Shigaeva et al., 2013). The steep terrain, coupled with irregular rainfall patterns and intensive agricultural activity, has led to land degradation, posing a serious risk to rural communities. As in many developing countries, population growth and unsustainable land-use practices further intensify the vulnerability of landscapes to water erosion.

Addressing this challenge requires a spatially informed understanding of where and to what extent erosion occurs. Geospatial modeling offers a practical solution for identifying erosion hotspots and supporting targeted intervention strategies. In this study, we applied the Revised Universal Soil Loss Equation (RUSLE) integrated with a Geographical Information System (GIS) within the Google Earth Engine (GEE) environment to estimate the spatial distribution of water-induced soil erosion across Tajikistan. The study also evaluated rainfall variability across the country using thirty years of climate data (1994–2023) collected from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS). The rainfall analysis, coupled with soil erosion assessment, can inform national land management policies and guide local actions for soil conservation. Ultimately, this approach contributes to evidence-based decision-making aimed at preserving the productive capacity of Tajikistan's fragile landscapes in the face of growing climate uncertainty and socio-economic pressures.

Soil erosion and rainfall variability assessment of farmwork

This study utilized Google Earth Engine (GEE) to analyze both the spatial variability of rainfall and the distribution of soil erosion across Tajikistan. To estimate soil erosion, the Revised Universal Soil Loss Equation (RUSLE) model was applied, incorporating five core parameters: rainfall erosivity (R), soil erodibility (K), topographic influence (LS), land cover impact (C), and conservation practices (P). These parameters were derived using a combination of long-term rainfall records, soil properties (such as texture and organic carbon), elevation data, and a land use map. Details on the datasets and their spatial resolution are provided in Table 1. The result of the soil erosion assessment was classified into five categories of severity and reported at the district level.

To explore rainfall dynamics over time, precipitation data from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) for the period 1994-2023 were analyzed. This included computing the annual rainfall trend (slope) and the coefficient of variation (CV) for each grid cell, capturing both long-term trends and variability. The resulting spatial analysis highlights districts experiencing significant rainfall variability, offering valuable insights for water resource planning and land management strategies. The slope of annual rainfall, as well as the CV, was also reported at the district and regional level.

Table 1. Data sources and spatial resolutions of input data used as inputs for the RUSLE model and rainfall pattern assessment.

Data	Source	Spatial resolution (m)
Land-use	The Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS)	500
Digital Elevation Model (DEM)	The Shuttle Radar Topography Mission (SRTM)	30
Soil texture and organic matter (%)	FAO Harmonized World Soil Database v 1.2	250
Rainfall (mm)	Gauged data and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS)	~5500

Rainfall variability

The slope of the annual rainfall, fitted with a linear model, across the country indicated a declining rainfall trend, with an average slope of -0.79. Approximately 77% of the country experienced a decreasing rainfall trend. The district-level analysis provided insight into localized trends and variability in rainfall, which can inform climate adaptation planning and resource allocation at the sub-national level (Figure 1). Among the 60-plus districts evaluated, only 15 districts showed a positive trend, indicating an increasing rainfall trend. The district of Danghara in the Khatlon region exhibits the highest increase, with a slope of +2.50, followed by Norak in Khatlon (+2.17), Yovon in Tadzhikistan Territory (+1.53), and both Pandjakent in Sughd and Fayzobod in Khatlon (approximately +1.15).

In contrast, the majority of districts across Tajikistan show negative trends, suggesting declining rainfall. Notably, Ghonchi in Khatlon records the steepest decline at −2.60, followed by Kuhistoni Mastchoh in Leninabad (−2.15), Shurobod in Gorno-Badakhshan (−1.85), and both Roshtqala and Asht in Tadzhikistan Territory (around −1.80) (Figure 2). Overall, districts in the Khatlon region, Gorno-

Badakhshan, and parts of Leninabad appear particularly affected by drying trends, with over three-quarters of Khatlon's districts showing negative slopes. The Tadzhikistan Territory also demonstrates predominantly declining rainfall, with only a few exceptions such as Yovon and Vose.

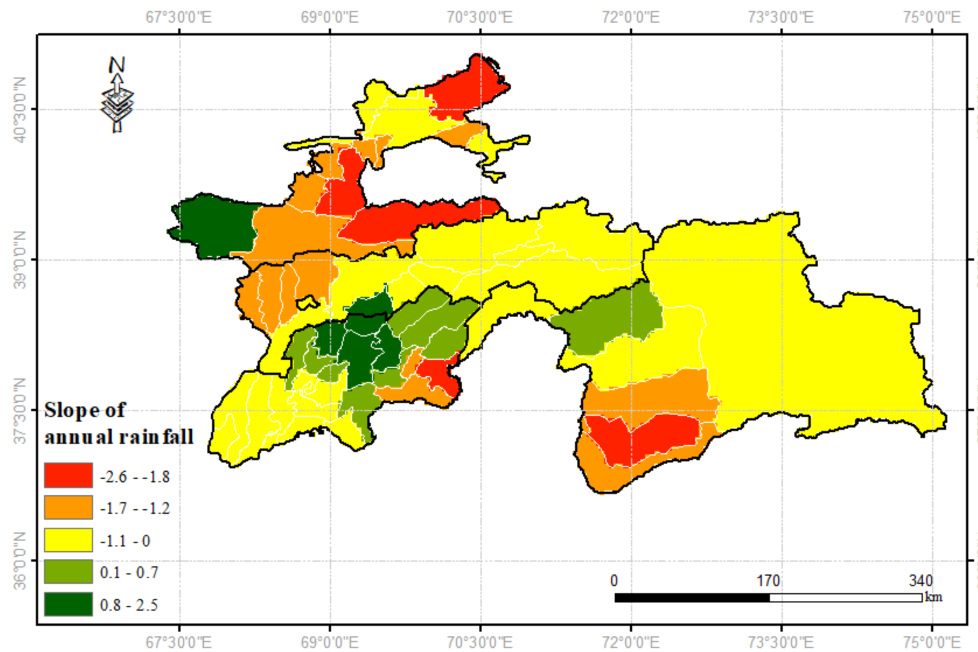

Figure 1. The slope of the annual rainfall trend, reported at the district level (1994 – 2023)

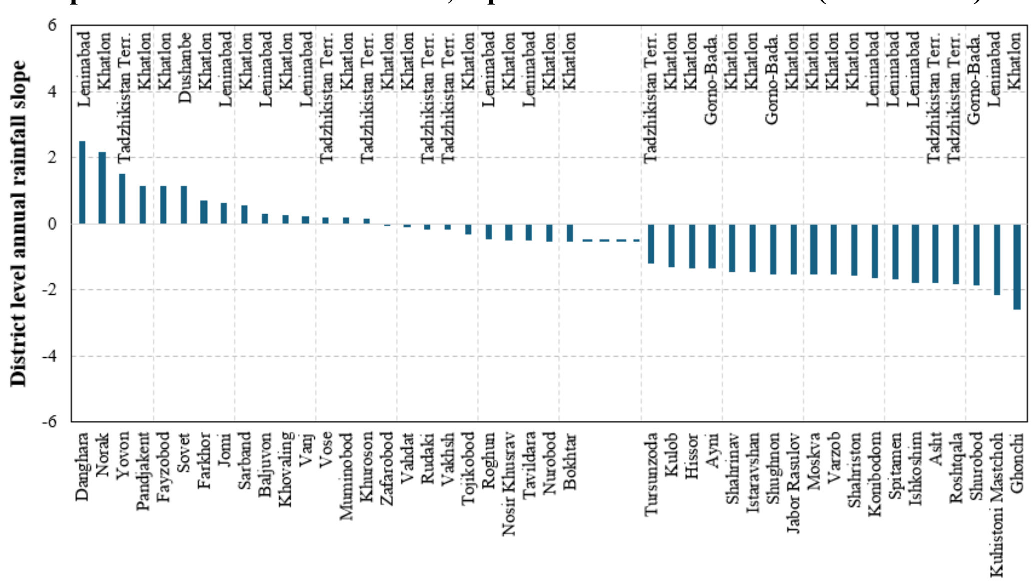

Figure 2. Partial district-level slope annual rainfall (1994–2023).

The annual rainfall CV estimated across the country indicated a variability ranging from 15 to 30.4%, with a national average of 21.9% (Figure 3). Districts such as Shahriston (30.4%), Varzob (28.9%), and Norak (27.78%) show the highest variability, primarily concentrated in the Khatlon region. These areas experience substantial year-to-year fluctuations in rainfall, presenting serious challenges for agriculture, water resource planning, and climate resilience. Moderate variability is observed in districts like Jomi, Sarband, and Rudaki, where CV values range between 24% and 25%, offering slightly more stable conditions for rainfed farming and irrigation. In contrast, eastern and northern regions, particularly within Leninabad and Gorno-Badakhshan, display lower rainfall variability—evident in districts such as Tavildara (15.61%), Jirgatol (15.38%), and Vanj (18.08%)—suggesting more predictable climatic conditions possibly influenced by mountainous geography and orographic effects (Figure 4). High-CV areas should be prioritized for investments in climate-smart agriculture, drought preparedness, and water harvesting systems, while low-CV districts may serve as relatively secure zones for rainfed farming and long-term agricultural planning.

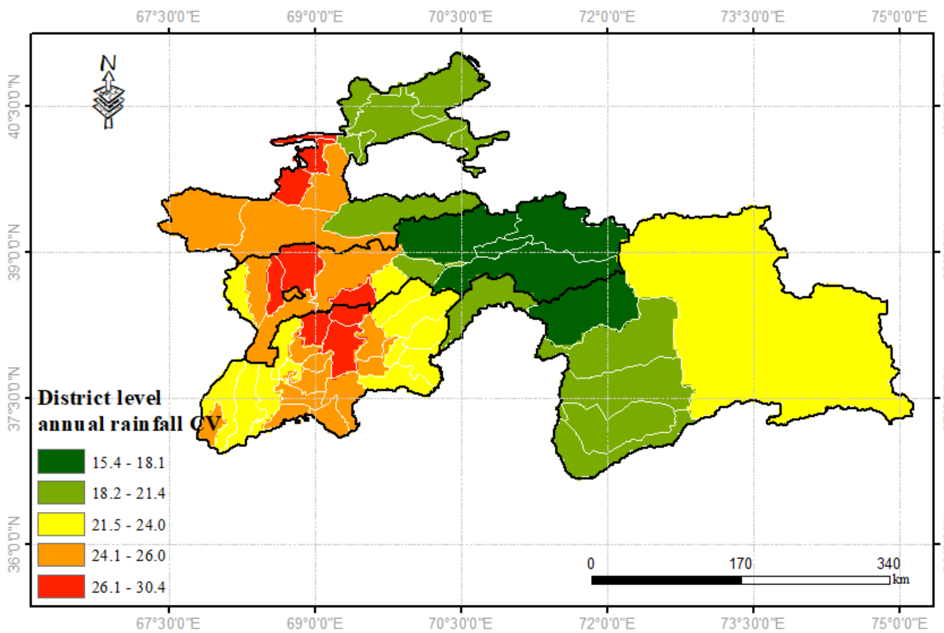

Figure 3. The annual rainfall coefficient of variability reported at the district level (1994 – 2023)

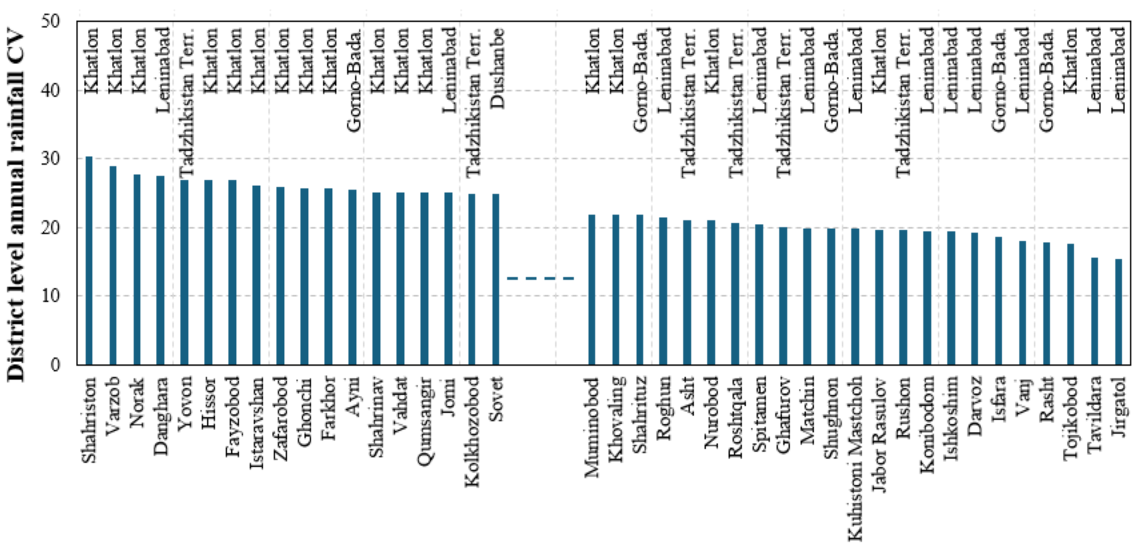

Figure 4. Partial districts level rainfall variability measured with CV (1994 – 2023)

Spatial distribution of soil erosion

Soil erosion rates across Tajikistan's districts vary significantly, from negligible rates in Bokhtar (0.03 t/ha) to catastrophic losses in Ishkoshim (127 t/ha), which is 12 times higher than the FAO's tolerable threshold of 10 t/ha/yr (Montanarella et al., 2015). This was influenced by topography, vegetation cover, land use, and rainfall patterns (Figure 5). The annual average soil erosion across the country is ~ 43.4 t/ha with a coefficient of variation of 400%. The highest soil losses are observed in mountainous districts, especially in Gorno-Badakhshan. Districts like Rushon (114 t/ha), Ishkoshim (127 t/ha), and Darvoz (54.20 t/ha) experience severe erosion with extremely high maximum values, reaching over 140 t/ha in some areas. Similarly, in the Leninabad region, Ayni (89 t/ha) and Kuhistoni Mastchoh (97 t/ha) also exhibit high soil loss rates, consistent with their mountainous terrain and steep slopes. Moderate soil erosion is observed in districts like Norak (26 t/ha) and Shurobod (22 t/ha) in Khatlon, and Varzob (34 t/ha) and Vahdat (32 t/ha) in Tajikistan. On the other hand, districts in lowland areas such as Bokhtar (0.03 t/ha), Qumsangir (1 t/ha), Vakhsh (1.30 t/ha), and Kolkhozobod (1.53 t/ha) report very low erosion, highlighting the role of flat topography and possibly better vegetation cover or land management. The classification of soil erosion risk levels indicates that approximately 33% of the country falls under the "very low" risk category (0 to 5 t/ha). In comparison, 17% of the country is susceptible to "low" risk (5 to 15 t/ha). About 16% of the land experiences "moderate" erosion (15 to 30t/ha), 12% falls under the severe erosion category, and the remaining 22% of the country is susceptible to excessive soil erosion (>50 t/ha). Figure 6 shows the top 21 districts with the highest soil erosion rate, along with their respective regions.

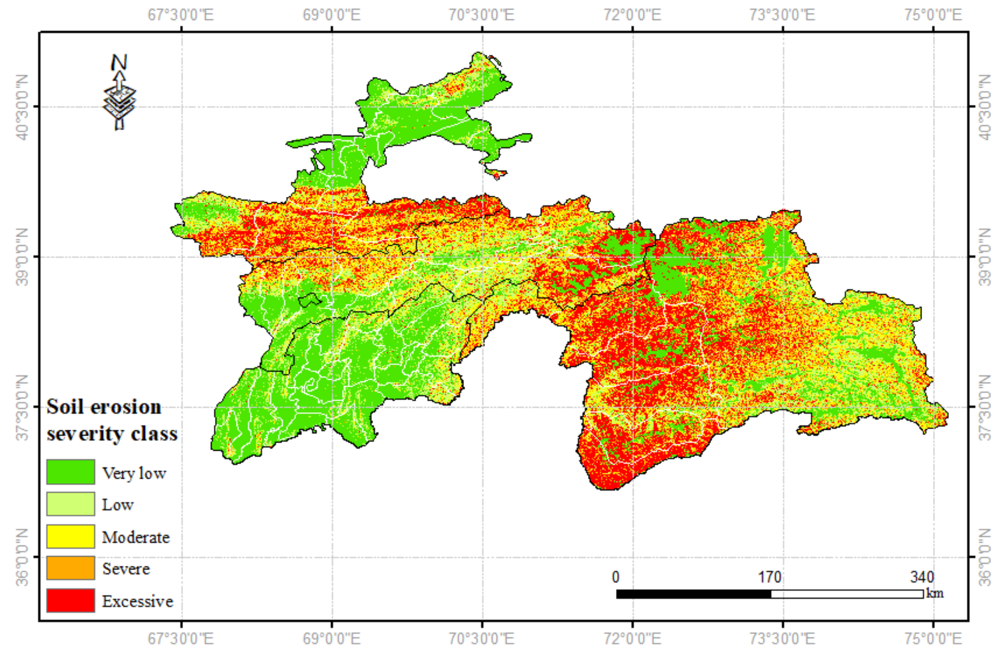

Figure 5. Spatial Distribution of Estimated Annual Soil Erosion Rates in Uzbekistan

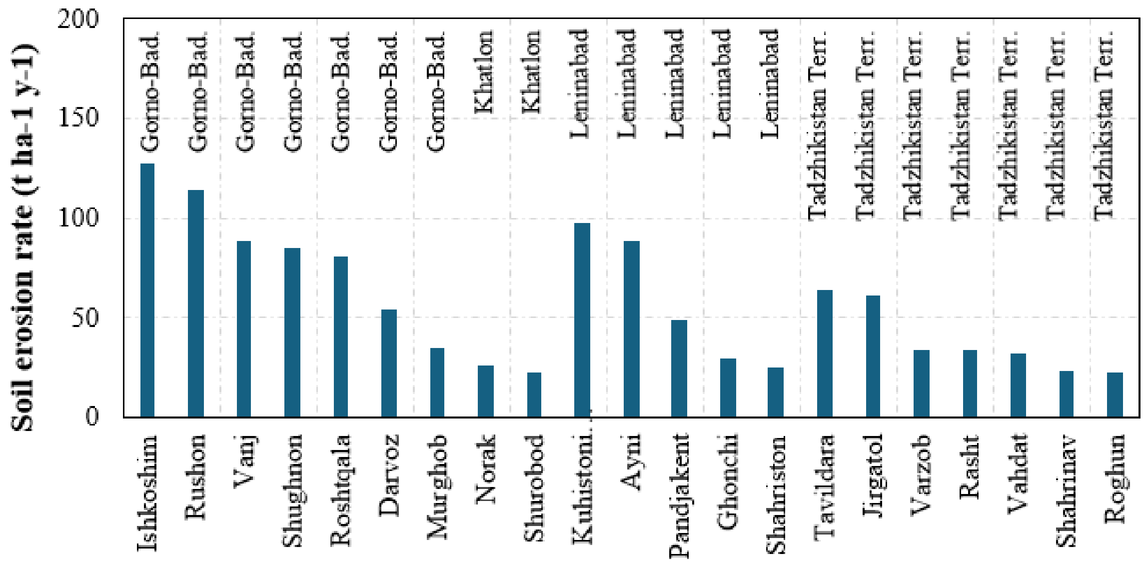

Figure 6. The top eighteen districts with the highest soil erosion rate (t ha-1 y-1)

Conclusions

This study provides a spatially explicit assessment of soil erosion using the Revised Universal Soil Loss Equation (RUSLE) and rainfall variability assessment across Tajikistan. The soil erosion assessment was done by integrating RUSLE with a Geographic Information System (GIS) on a Google Earth Engine (GEE) platform. The findings reveal that 34% of the country faces “severe” to “excessive” soil erosion, caused by steep topography, land use practices, and declining rainfall trends. The rainfall analysis also indicates a widespread decline in annual rainfall for the last three decades across 77% of the country, with significant variability ranging from 15% to 30.4%, which presents further challenges to sustainable land management and agricultural productivity. This widespread pattern of decreasing precipitation across most of the country highlights a concerning trend toward drier conditions, which could have serious implications for water availability, agriculture, and drought vulnerability. The results underscore the importance of localized climate adaptation and water resource management strategies to address the growing risks associated with declining rainfall in Tajikistan. A serious plan is needed in the regions such as Gorno-Badakhshan and Khatlon, where erosion rates and rainfall declines are most pronounced.

The integration of high-resolution spatial data with the RUSLE model enables targeted planning and prioritization of soil conservation interventions. Policymakers, land managers, and development partners can use these insights to allocate resources efficiently and design region-specific climate adaptation and land restoration strategies. Future studies could enhance this work by incorporating field data, sediment transport processes, and land management scenarios under projected climate change conditions.

Acknowledgments: This research is made possible by the support of the FAO FLOUR project to the International Center for Agricultural Research in the Dry Areas (ICARDA). The contents are the sole responsibility of the authors and do not necessarily reflect the views of the donor.

Reference

Klytchnikova, I.I. et al., 2024. Tajikistan-Climate-Smart Agriculture Profile for Tajikistan: Scaling Up Agricultural Solutions to Boost Productivity and Address Climate Change-Summary Report.

Montanarella, L. et al., 2015. The Status of the World’s Soil Resources (Technical Summary). Food and agriculture organization of the united nations.

Qin, Y., He, J., Wei, M., Du, X., 2022. Challenges threatening agricultural sustainability in central Asia: Status and prospect. International Journal of Environmental Research and Public Health, 19, 6200.

Shigaeva, J., Wolfgramm, B., Dear, C., 2013. Sustainable Land Management in Kyrgyzstan and Tajikistan: A Research Review.