

Supplementary Material

Quantitative Evaluation of Soil Water and Wind Erosion Rates in Pakistan

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Supplementary R-factor

$$\bar{R} = \sum_{k=1}^{24} \bar{R}_{hmk} \quad (1)$$

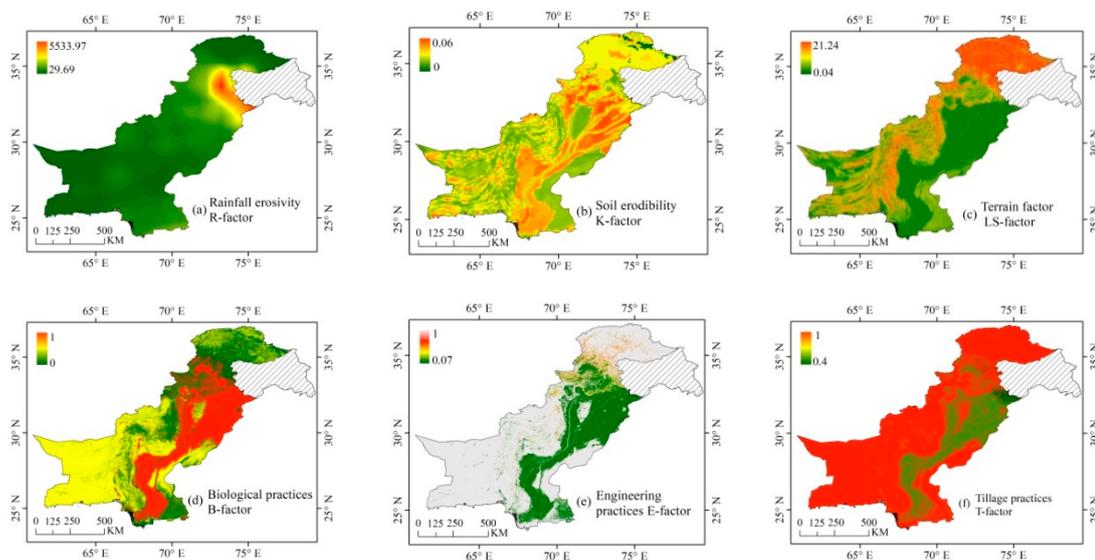
$$\bar{R}_{hmk} = \frac{1}{N} \sum_{i=1}^N \sum_{j=0}^m (\alpha \cdot P_{i,j,k}^{1.7265}) \quad (2)$$

$$\overline{WR}_{hmk} = \frac{\bar{R}_{hmk}}{\bar{R}} \quad (3)$$

where \bar{R} represents the average annual rainfall erosivity ($\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{a}^{-1}$). k represents 24 half months and ranges from 1 to 24. \bar{R}_{hmk} represents the rainfall erosivity of the k -th half-month ($\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{a}^{-1}$), N represents the number of years, and j represents the number of erosive precipitation days of the n -th year. $P_{i,j,k}$ represent the mean erosive rainfall on the j -th day, k -th half-month, and i -th year. \overline{WR}_{hmk} represent the percentage of the rainfall erosivity of the k -th half-month to the average annual rainfall erosivity.

Supplementary Figure S1

Soil water erosion—machine learning covariate maps: (a) rainfall erosivity factor (R), (b) soil erodibility factor (K), (c) terrain factor (LS), (d) biological practices factor (B), (e) engineering practices factor (E), and (f) tillage practices factor (T)



Rainfall erosivity factor (R) (Supplementary Figure S1a): The value range of the R - factor is 29.69–5533.97 ($\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{a}^{-1}$), and the mean value is 688.36 ($\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{a}^{-1}$). Spatially, there is a trend of increasing and then decreasing from north to south, with higher values centered around Islamabad on the Potohar

Plateau, near the town of Menghera on the upper India River Plain, Sialkot, and Lahore, which are associated with heavy summer monsoon rainfall (July to September), and where the annual precipitation exceeds 2000 mm. The lower values were found in the northern mountainous regions, the plateau in Balochistan Province, and other areas of intense topographic variation, outside the center of strong summer convection, where rainfall is little and heavy rainfall events are rare, with annual precipitation generally below 800 mm.

Soil erodibility factor (K) (Supplementary Figure S1b): The mean value of the K-factor is 0.034 ($t \cdot \text{hm}^2 \cdot \text{h} \cdot \text{hm}^{-2} \cdot \text{MJ}^{-1} \cdot \text{mm}^{-1}$), ranging of 0–0.06 ($t \cdot \text{hm}^2 \cdot \text{h} \cdot \text{hm}^{-2} \cdot \text{MJ}^{-1} \cdot \text{mm}^{-1}$). The regions with the highest values correspond to the cropland, where cambisols are the predominant soil type. Cambisols are not well resistant to erosion, and frequent cultivation causes the soil to become loose. They also have a high soil silt (SL) content and a low soil organic carbon (SOC) content, which have a higher K and increase the risk of soil erosion. The lowest values are observed in the high mountainous regions of the north, where the soil type is dominated by cryosols, which freeze year-round to strengthen the erosion resistance of the soil. In the west, the vast wilderness is covered with calcisols and gypsisols, a soil type rich in secondary carbonates in semiarid regions that are suitable for crop growth and have lower soil erodibility, while the desert regions have lower rainfall and severe drought, which inhibit the growth of vegetation and have medium soil erodibility (about 0.03). Northern mountain forests were rich in highly reactive, leached soils with many luvisols, strong cohesion, excellent fertility, with lower soil erodibility.

Topographic factor (LS) (Supplementary Figure S1c): The mean value of the LS - factor was 4.67, with a range of 0.04–21.24. The maximum value (21.24) was 4.5 times greater than the mean value, showing a significant difference in the spatial

distribution of LS-factor. The spatial pattern shows a gradual decrease from northeast to southwest, which is attributed to the rugged terrain, large elevation changes, steeper slopes, and longer slope length, all of which result in higher LS-factor values in the north and west. While the center and southern regions are wide plains, the slope is gentle, and the LS-factor value was lower.

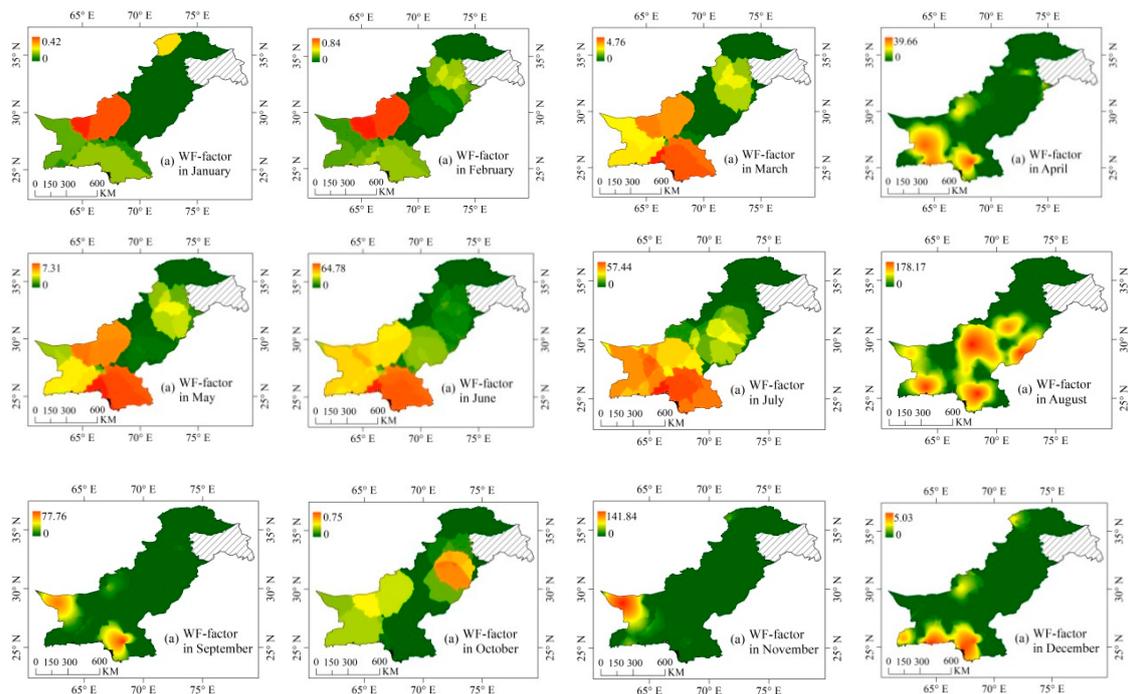
Soil and water conservation practices (BET) (Supplementary Figures S1d, S1e, S1f): The mean value of the B - factor was 0.31, with a value range of 0–1. The spatial pattern of B - factor was closely related to land use, and the B values showed a gradual increasing trend according to bare land, forest, grassland, and cropland. In Addition, the B-factor value gradually decreases as vegetation cover increases, with the mean value of the B-factor for low vegetation cover (0.379) being 4.3 times greater than the mean value of the B - factor for high vegetation cover (0.089); indicating that increasing vegetation cover can significantly reduce the B-factor value. Land use type and vegetation cover are affected by a variety of factors, including rainfall, temperature, and terrain; therefore, the spatial distribution of the B - factor is the result of multiple factors acting together.

The mean value of the E-factor was 0.75, with a range of 0.1025–1. The lower the E value, the greater the advantages of engineering practices. The low-value regions of the E-factor were found in the Indus plain and the cropland on both sides of the Indus in Sindh province, while the high-value regions were found in the northern mountains, the Kharan desert in the southwest, and the Thar desert in the southeast. This spatial distribution is determined by the quality of engineering practices, land use type, and slope characteristics. This study classifies cropland into rainfed cropland and irrigated or post-flooding cropland and assigns the E-factor in combination with slope, which is a newly developed method of E - factor assignment.

The mean value of the T-factor was 0.88, with a value range of 0.40–1. The spatial pattern was associated with agriculture and exhibited a progressive rise in values from northeast to southwest along the cropped region, which was mostly influenced by precipitation and temperature. From the north to the south of Pakistan, rainfall steadily declines, and the rice is replaced by drought-tolerant and drought-resistant maize and wheat. Different tillage practices are used to cultivate various crops, and these methods have varying impacts on soil erosion.

Supplementary Figure S2

WF factor values from January to December in Pakistan

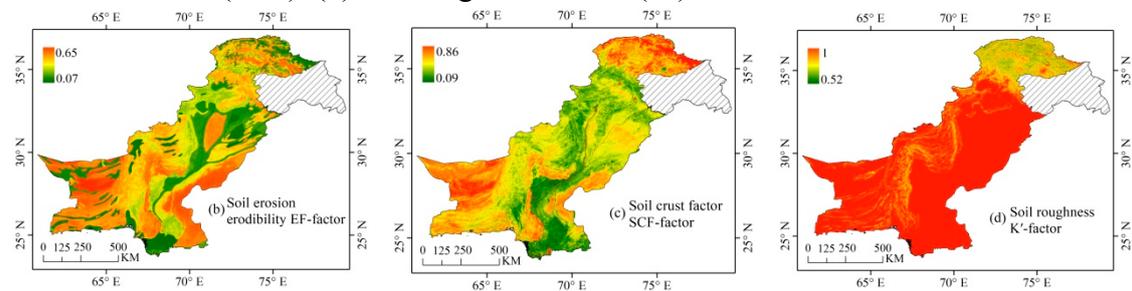


Weather factors (WF) (Supplementary Figure S2): The value range of the WF factor from January to December was 0–178.17, with the higher values mostly found in the India River Delta, Thar desert, and Kharan desert, and the lower values

concentrated in the northern mountainous and India River Plain regions. The higher WF values in the India River Delta are primarily attributable to the greater regional temperature, higher evaporation, and lower soil water content, which make them susceptible to wind erosion. The higher WF in the Kharan desert was primarily attributable to the stronger wind speed in July and August, which can reach up to $12.31 \text{ m}\cdot\text{s}^{-1}$, and the mountainous areas in the north were crisscrossed by high mountains, which have a certain inhibiting effect on wind. According to the inter-annual statistics, the values of the WF factor were greater from June to August, the mean value of the WF factor was 20.94 in August, 13.77 in July, and 13.51 in June; in contrast, the WF factor values were lower from December to February, with the lowest WF-factor mean value being 0.08 in January.

Supplementary Figure S3

Soil wind erosion—RWEQ factor maps: (b) soil erosion erodibility factor (EF), (c) soil crust factor (SCF), (d) soil roughness factor (K')



Soil wind erosion erodibility factor (EF) (Supplementary Figure S3b): The EF factor has a range of values between 0.07 and 0.65, with an average value of 0.44. Higher values were concentrated in the southwestern Karan Desert, followed by the Thar Desert in the southeast, and another in the transition zone from the eastern plains to the western mountains, with EF values of around 0.4 in other regions. This spatial pattern of EF factor was mostly associated with soil type.

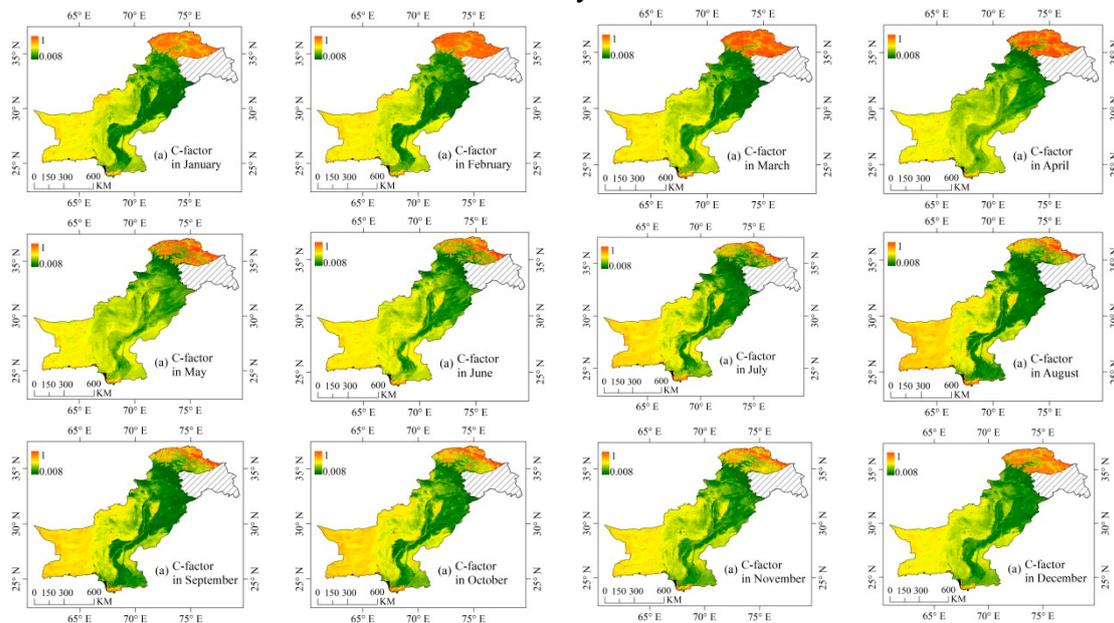
Soil crust factor (SCF) (Supplementary Figure S3c): The SCF factor values range from 0.09 to 0.86, with an average of 0.35. Higher values were concentrated in

the southwestern desert region and the Thar Desert in the southeast, where the soil clay and soil organic matter contents were lower. Lower values were found in the central plains and southern coastal regions, where soil clay and soil organic matter content were greater, moisture conditions were reasonably favorable, the soil was well-developed, and SCF factor values were much lower. The existence of soil crust decreases the concentration of erodible particles, lessens the abrasive impact of soil particles, aids in the stabilization of sand dunes, and prevents and weakens soil wind erosion.

Soil roughness factor (K') (Supplementary Figure S3d): The value of the K' factor ranges from 0.52 to 1, and the mean value was 0.98. The regions with the highest values were found in the central plains and Kharan desert, while the regions with the lowest values were concentrated in the northern mountains, where the topography is more complicated and less susceptible to wind erosion.

Supplementary Figure S4

C factor values from January to December in Pakistan



Vegetation cover factor (C) (Supplementary Figure S4): The C factor, which ranged from 0.008 to 1, was inversely linked with soil wind erosion intensity and

vegetation cover. Higher values were concentrated in the northern mountains and Kharan desert, and lower values were found in the central plains. The C values varied with the seasons, with the highest mean value of 0.24 in December and the lowest mean value of 0.18 in September, but the spatial pattern was similar. The C factor values increase from the south to the northwest as vegetation cover decreases, reaching about 1 in the northern mountainous and southwestern desert regions, which indicated that these regions have lost their wind erosion inhibitory impact due to the absence of vegetation.

Supplementary Table S1

Average soil water erosion rate for each land use type				
Land use	Soil water erosion rate ($t \cdot km^{-2} \cdot a^{-1}$)	Annual precipitation (mm)	Rainfall erosivity factor (R) ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot a^{-1}$)	Tillage practice factor (LS) (dimensionless)
Bare land	194.66	179.81	247.45	3.94
Rainfed cropland	747.73	521.53	1439.51	3.34
Post-flooding or irrigated cropland	222.73	312.04	1069.023	0.46
Grassland	451.52	300.27	475.89	9.09
Desert sparse	238.96	238.51	556.21	2.29
Forests	1859.87	822.96	1599.11	13.97
Shrub	359.15	368.26	577.66	6.94

Supplementary Table S2

Soil erosion each administrative unit in Pakistan				
Administrative unit name	Soil water erosion rates ($t \cdot km^{-2} \cdot a^{-1}$)	Soil water erosion amount ($\times 10^7 t \cdot a^{-1}$)	Soil wind erosion rates ($t \cdot km^{-2} \cdot a^{-1}$)	Soil wind erosion amount ($\times 10^8 t \cdot a^{-1}$)
Azad Jammu & Kashmir	2942.28	3.22	0.12	0.000013
Balochistan	299.51	10.25	3751.07	12.67
Gilgit-Baltistan	576.59	3.96	0.09	0.00006
Khyber Pakhtunkhwa	1053.15	10.65	12.01	0.02
Punjab	377.36	7.73	559.91	1.15
Sindh	212.97	2.97	2809.93	3.87

Supplementary Table S3

Statistically comparison between local scales conducted studies in Pakistan and Current study

Reference	Study area	Soil water erosion rate ($t \cdot km^{-2} \cdot a^{-1}$)		
		Local study	Gilani study [19]	Current study
Ashraf et al., (2017) [23]	Rawal watershed	1030	791	2196.58
	Ghabbir watershed	2200	25	731.94
Abuzar et al., (2018) [21]	Simly watershed	1400	10.34	3688.25
Ullah et al., (2018) [25]	Potohar region	1910	103	1278.89
Ashraf et al.,(2020) [22]	Soan river basin	840	126	1517.29

Supplementary Table S4

Comparison of soil water erosion classification in Potohar Plateau

Classification ($t \cdot km^{-2} \cdot a^{-1}$)	Percentage in Ullah (%)	Percentage in current study (%)
0 - 200	69.25	14.70
200 - 500	15.35	17.83
500 - 2000	13.34	42.37
>2000	2.06	25.10

S1. Plausibility of soil water erosion rates

S1.1 Comparison with Gilani et al. (2021) evaluated the soil water erosion map of Pakistan

The following are the causes of the mean differences. (a) The spatial resolution of Gilani et al.'s (2021) [19] study was 1000 m, but the area of Pakistan is about 881,913 km², so higher resolution (30 m to 100 m) data is more suitable for analysis. The current study, which uses 30 m resolution data, is more in keeping with the accuracy requirements. (b) The R-factor in the study of Gilani et al. (2021) [19] was calculated based on annual precipitation and did not account for the influence of extreme precipitation, which may have underestimated the value of the R-factor. In this study, the R-factor was calculated based on semimonthly precipitation, which can

effectively account for the erosive impact of extreme precipitation, so the value of the R-factor is generally greater than the results of Gilani et al. (2021) [19], and regional differences were more significant. (c) The K-factor in the study of Gilani et al. (2021) [19] was derived from the average value of the literature, with the range of 0 - 0.23. In this study, the K-factor was calculated using 250 m resolution Soilgrid data, and the range of values was 0-0.06, but usually the value of the K-factor should be 0.0X [49,87,88], indicating that the value of the K-factor in the study of Gilani et al. (2021) [19] may be high. (d) Gilani et al. (2021) [19] calculated the LS-factor using a 30 m-resolution SRTM DEM resampled to 1 km, which may have underestimated the LS-factor values, especially in the northern mountains. In this study, the LS-factor was calculated using the 30 m resolution SRTM DEM, and the mean value (4.67) was greater than the finding of Gilani et al. (2021) [19]. (e) The C and P factors in the study of Gilani et al. (2021) [19] were assigned according to the land use type, and the method was not rigorous enough, which is also the reason why the soil water erosion rate in the desert region of Balochistan, Punjab, and Sindh is essentially the same ($< 100 \text{ t}\cdot\text{km}^{-2}\cdot\text{a}^{-1}$). But the fact is that the Potohar Plateau and surrounding regions should have higher soil erosion rate because of the heavy rainfall and topographic relief. And the mountainous regions of Balochistan Province also have higher topographic relief and should have more severe soil erosion intensity than the desert and plain regions. The vegetation cover factor (B) in this study was calculated using high-precision land use interpretation data according to the assignment method of Borrelli et al. (2017) [6], the E-factor was assigned by taking land use and slope into

account in a comprehensive way, and the T-factor was assigned to different cultivation types according to cropping rotation system of global and the Guide of Soil Erosion Monitoring¹, indicating that this study was more comprehensive in calculated soil and water conservation practices (BET).

S1.2 Comparison with Borrelli et al. (2017) estimated the soil water erosion rate of global

There are three causes for the variance in average values: (a) Borrelli et al. (2017) [6] calculated soil water erosion rates with a raster resolution of 250 m, whereas the evaluated results of the current study have a raster resolution of 30 m. Large differences in raster resolution should be lead to statistical disparities. (b) Borrelli et al. (2017) [6] did not take into account the impact of rock fragments, and the consideration of bare rock may not be comprehensive. In fact, rock fragment cover and bare rock reduced soil water erosion. In the calculation results of Borrelli et al. (2017) [6], the soil water erosion rate value of the regions with more rock fragments and bare rock distribution in the northern high mountain region will be slightly higher than the results of the current study, indicating a high soil erosion region extending from the northeast to the southwest, which may be the difference between the calculation results of the two K-factors. (c) The sampling survey units used in the current study were high-precision interpreted data with more accurate information on soil and water conservation practices, and the results were closer to the actual soil water erosion rate on the surface, which was less than the potential soil erosion rate evaluated by Borrelli et al. (2017) [6] ($P = 1$).

¹ Center of Soil Conservation Monitoring of MWR, Guide to Soil Erosion Monitoring, 2021.6

S2. Plausibility of soil wind erosion rates

S2.1 The following were possible explanations

(a) Inconsistent temporal scales. Yang et al. (2021) [20] evaluated the soil wind erosion rates from 2001 to 2010, while the current study evaluated the soil wind erosion rates in 2018, and the difference in temporal resulted in variation in wind speed. For example, S3 Fig. 15, the daily wind speed in 2001 and 2006 - 2010 were about twice that of 2018, resulting in a significant variation in soil wind erosion rates. Yang et al. (2021) [20] found a decreasing trend in soil wind erosion rates from 2001 to 2010 in central Pakistan and a non-significant decreasing trend in the Kharan desert, which may be attributable to the management of the Pakistan government. (b) Yang et al. (2021) [20] did not take CaCO_3 content into account when evaluating the global soil wind erosion rates, which would have resulted in a greater value of the EF factor. (c) Differences in spatial resolution. Global and in this study, the resolution of soil wind erosion rates evaluation were 10 km and 250 m, respectively. In general, as the pixel size increases, the richness of gray image levels decrease, spatial heterogeneity will decrease, and many internal details are ignored, resulting in a simplified and coarse texture structure, which may cause statistical disparities in results. (d) The differing calculation methods of the wind erosion surface roughness factor (K') and vegetation cover factor (C) used by Yang et al. (2021) [20] and the current study may also contribute to some differences between the results of the two studies.