

Global Dimensions of Vulnerability to Wind and Water Erosion

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ABSTRACT

The global assessment of wind and water erosion reported in this empirical study employs a simplified model considering only soil and climatic variables. The purpose is to obtain global and regional estimates of areas of land susceptible to different intensities of erosion. By relating to population densities, the areas of high risk for water erosion are demarcated on maps and they help to identify regions that require additional attention to conservation. The actual intensity of erosion is a function of many factors, the most important of which is the level of management as determined partly by the socioeconomic status of the land users. The relationship between erosion vulnerability and the inherent land quality (ILQ) is employed to compute magnitudes of global soil loss through water erosion.

The annual potential yield of sediment through water erosion from 72.5 million km² of global land area considered in this study is about 130 billion metric tons. In the arable lands of the world, which are those belonging to land quality classes I through VI, water erosion may contribute about 67 billion metric tons of sediment. In the susceptible drylands, which are the areas most prone to desertification, water erosion could yield about 92 Metric tons, which are about 71% of the total global soil loss.

INTRODUCTION

Erosion is a natural land forming process that is accelerated through human activities. Land surface disturbance ranging from traffic moving over the land to the extreme situation of deep tillage results in disruption of the natural soil structural elements, loosening of particles, and their eventual displacement. In the absence of chaotic events such as sheets of water moving across a desert, water

induced erosion is minimal under natural conditions. Erosion rates are strongly related to density and duration of vegetative cover of the soil (Francis and Thorne, 1990). With disturbance, onset of erosion is mostly a function of slope and kinds of soil; the antecedent moisture content and raindrop intensity are additional modifiers.

The art and science of soil conservation has developed essentially around the central theme of managing wind and water erosion. Numerous field experiments have been reported in the literature and continue to be reported on studies of evaluating water erosion under conditions of different soil cover, slopes, and other variables. Assessments of permanent micro-watersheds have yielded additional information on the variables that affect the quantity and rates of soil loss. Few attempts have been made to estimate soil loss on watersheds or other large areas. The need to make such estimates led to the development of the Universal Soil Loss Equation (Wishmeier and Smith, 1978) and later the Revised Universal Soil Loss Equation (Renard, 1997).

The first global assessment of human-induced water and wind erosion was made by Oldeman et al. (1990) in the framework of the Global Assessment of Land Degradation (GLASOD) Project of the United Nations Environment Program. Maps and information from this study, with minor modifications are reproduced in the Atlas of Desertification (Middleton and Thomas, 1997). Their estimates of land area susceptible to wind and water erosion are given in Table 1.

In the GLASOD estimate, only the susceptible lands from the dry sub-humid, semiarid, and arid parts of the world were considered. Hulme and Marshe (1990) define these climatic zones based on the Aridity Index (AI). AI is the monthly sum of the ratios of precipitation to potential evapotranspiration (P/PET) – dry sub-humid areas have a ratio of <0.65, semiarid areas have a ratio of <0.5, arid areas have a ratio of <0.2, and hyper-arid areas have a

Table 1. Distribution of susceptible dryland water and wind erosion in the continents. Source: Middleton and Thomas (1997).

REGION	WATER EROSION (million ha)			WIND EROSION (million ha)		
	Dry Subhumid	Semiarid	Arid	Dry Subhumid	Semiarid	Arid
Africa	25.1	59.2	34.8	1.6	30.7	127.5
Asia	54.9	69.9	32.7	15.1	52.1	85.9
Australasia	4.1	26.3	39.3	0	6.4	9.5
Europe	34.7	12.8	0.6	17.4	17.3	4.0
N. America	10.7	24.4	3.3	6.8	27.3	3.7
S. America	11.5	20.6	2.5	5.9	16.4	4.6
Total	141.0	213.2	113.2	46.8	150.2	235.2
TOTAL		467.4			432.2	

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P/PET ratio of <0.05. The susceptible drylands by definition exclude the humid and hyper-arid areas as defined by AI. The Aridity Index is a very crude assessment of climate and errors are introduced by using this simplified approach. Assessment of “human-induced erosion” was made by opinions of a large number of persons, many of whom had little or no actual data. Despite this, the GLASOD assessment is the only estimate of human-induced degradation.

PURPOSE

The purpose of this study is to obtain an estimate of global land area, specifically in the susceptible drylands (UNEP, 1992), vulnerable to water and wind erosion. El-Swaify et al. (1982) called for “quantitative assessment of erosion extent, tolerance limits, and causative parameters.” Today there is a better understanding of factors controlling erosion and estimates of acceptable levels under different land uses. However, there is still an absence of erosion estimates of national, regional or global extent. In addition there is also an urgent need to locate critical erosion areas so that strategies for priority action can be launched. The actual rates of erosion are a function of on-site land quality characteristics, climatic attributes, and the kinds of land management technology that are applied. The management-input level cannot as yet be quantified for a global level assessment and is not considered in this analysis. However, population density is used as a proxy to estimate this, assuming that very high population densities are associated with proportionately higher amounts of soil loss. Exceptions to this occur in many of the developed countries of the world, which have taken appropriate action to conserve the soil resource.

METHODS

The current assessment considers ‘vulnerability to wind and water erosion’ based on global soils and climatic data. Using a geographic information system (GIS) a global soil map of the world is used as the starting point of the assessment. This map includes information on soil moisture and temperature regimes. Rainfall induced erosivity is an important parameter employed by several workers (Charreau, 1969, Fournier, 1960, Delwaulle, 1973,

Wishmeier and Smith, 1978, and El-Swaify and Cooley, 1981) to estimate soil loss. Available data on erosivity was related to soil moisture regimes to employ soil moisture regimes as proxies. Based on the knowledge of soil behavior under the prevailing climatic conditions, each soil unit was assigned a vulnerability class to water and wind erosion. Catastrophic events are excluded in this assessment. GIS analysis was used to make global estimates of the area occupied by each class.

Rates of soil loss under natural vegetation are generally low and there is a steady state with very little variation with time. Upon cultivation, the rates change dramatically. Conservation technology such as implementation of

mechanical structures and/or zero-till or minimum tillage reduces the amount of soil loss. However, a major factor is the period when the land is bare or devoid of vegetative cover and the number and intensity of storms at the onset of the rainy season. Databases that provide such information are just being assembled. In their absence, population density in combination with soil and climatic attributes is used to make estimates of rates of soil loss. This is done by overlaying a population density map on maps depicting vulnerability to wind and water erosion. A matrix (Table 2) was developed to estimate the water erosion rate based on population density and water erosion vulnerability. Published data from countries of the world are used to arrive at the assigned numbers. When no data were available, values were assigned to the cells based on soil and climatic attributes.

Table 2. Matrix to relate rates of erosion to population density classes.

Population Density Persons/Sq. km	Annual Water Erosion Rates (Metric tons/ha)			
	Vulnerability to Water Erosion			
	Low	Mode rate	High	Very High
<2	1	3	8	12
2-10	3	5	10	20
11-40	5	10	20	30
41-100	15	20	25	40
101-500	20	35	40	50
>500	25	50	75	80

Table 3. Matrix to relate rates of erosion to inherent land quality classes.

Inherent Land Quality classes	Annual Water Erosion Rates (Metric tons/ha)			
	Vulnerability to Water Erosion			
	Low	Moderate	High	Very High
I	2	4	6	8
II	3	5	8	11
III	4	8	12	17
IV	6	10	15	30
V	10	15	20	40
VI	15	20	40	60
VII	20	35	60	80
VIII	5	10	25	35
IX	1	4	6	10

Table 4. Comparison of land area in India impacted by erosion in present study with that of Singh et al. (1992).

Erosion Classes	Area ('000 km ²)	
	This study	Singh et al. (1992)
Low	870	801
Moderate	359	1,406
High	635	805
Very High	590	243
	2,453	3,255

technology is applied. Even in the former systems, if the land is used for padi cultivation during the rainy season or The assumption in Table 2 is that if areas are highly vulnerable to water erosion, high erosion rates result if the population density is also high. This is true in low-input low- output systems, but less valid where conservation irrigation is available for cropping during the dry season, the assumption is not correct. To assess soil loss as a function of the inherent land quality classes (Eswaran et al., 1999), the matrix of Table 3 was developed based on published erosion rates in some countries. Due to the paucity of data, values for most of the classes were interpolated to represent relative magnitudes. This matrix is used later to compute magnitudes of soil loss from water erosion.

To test the validity of the empirical model employed to evaluate water erosion, data sources from India were used. Singh et al., (1992) reported on erosion rates in India using information from small runoff plots, small and large watersheds, and sedimentation in reservoirs. Erosion rates were measured with the Universal Soil Loss Equation (Wishmeier and Smith, 1978) and the results were plotted on a map. Table 4 compares the data of Singh et al. (1992) with the estimates from this study. The study of Singh et al. (1992) includes the very dry and cold areas of India, which are excluded in the present study.

Results and Discussion

Table 5 is a summary of the susceptible dryland areas subject to wind and water erosion on a global basis. Globally there are about 19 million km² (41% of susceptible dryland) of land vulnerable to water erosion. The hyper-arid and cold regions are excluded in this estimate. There are about 17 million km² or 37% of the drylands that are vulnerable to wind erosion. The hyper-arid, cold, and humid areas were excluded for the wind erosion estimate. According to the GLASOD (Oldeman et al., 1990) estimate, 8.3% of the susceptible dryland areas are degraded due to human-induced water erosion and 13.2% experience accelerated wind erosion due to human interventions.

Table 6 is a summary of the global land areas subject to wind and water erosion. Globally there are about 56 million km² (43% of ice-free land) of land vulnerable to water erosion in the slightly arid to humid areas of the world. The hyper-arid and cold regions are excluded in this estimate. There is about 33 million km² or 25% of the landmass that is vulnerable to wind erosion. The hyper-arid, cold, and humid areas were excluded for the wind erosion estimate.

The distribution of the lands vulnerable to water and wind erosion is shown in Figs. 1 and 2. Lands of high to very high vulnerability, those most susceptible to erosion,

Table 5. Estimates of susceptible dryland areas vulnerable to water and wind erosion. See Middleton and Thomas (1997) for susceptible dryland definition.

EROSION VULNERABILITY CLASS	WATER EROSION		WIND EROSION	
	AREA Million km ²	Percent	AREA Million km ²	Percent
LOW	5.15	11.2	3.64	7.9
MODERATE	5.76	12.5	3.74	8.1
HIGH	3.31	7.2	5.92	12.9
VERY HIGH	4.44	9.6	3.75	8.1
Total Vulnerable Area	18.66	40.5	17.05	37.0
Dry	23.38	50.8	23.17	50.3
Depositional/minimal	3.92	8.5	5.75	12.5
Cold	0.06	.1	0.06	.1
Total Susceptible Drylands	46.02	100	46.02	100

Table 6. Estimates of global land areas vulnerable to water and wind erosion. Note: the humid areas were included for the water-erosion estimate but not for the wind erosion. The 40 million km² of the humid areas are assumed to have negligible wind erosion

EROSION VULNERABILITY CLASS	WATER EROSION		WIND EROSION	
	AREA Million km ²	Percent	AREA Million km ²	Percent
LOW	17.33	13.3	9.25	7.1
MODERATE	15.39	11.8	6.32	4.8
HIGH	10.97	8.4	7.80	5.9
VERY HIGH	12.21	9.3	9.33	7.1
Total Vulnerable Area	55.91	42.8	32.70	25.0
Dry	37.77	28.9	37.77	28.9
Depositional/minimal	16.59	12.7	40.00	30.6
Cold	20.36	15.6	20.36	15.6
Total Ice-free Land Area	130.63		130.63	

Fig. 1 Water Erosion Vulnerability

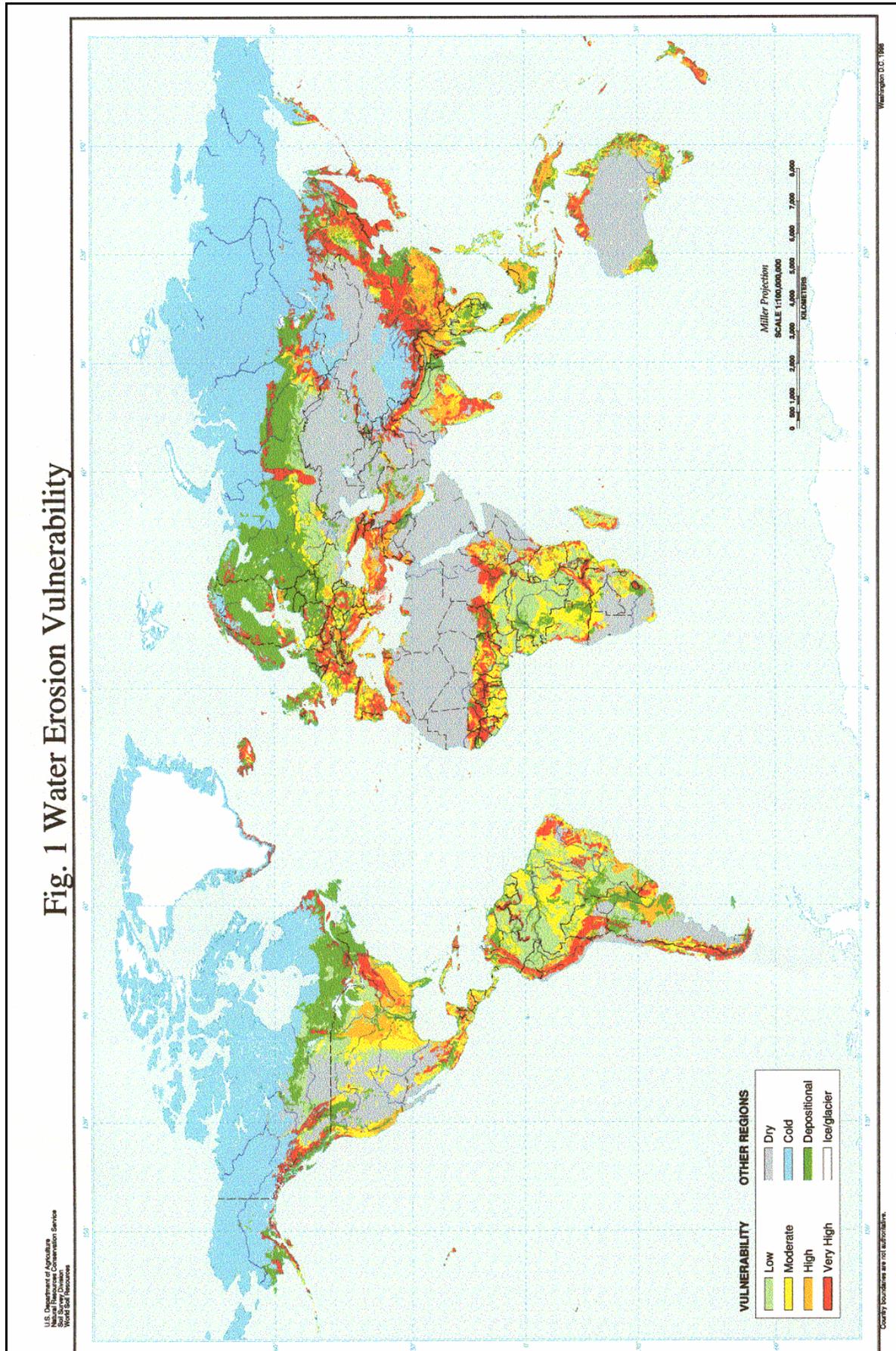


Figure 1. Water erosion vulnerability.

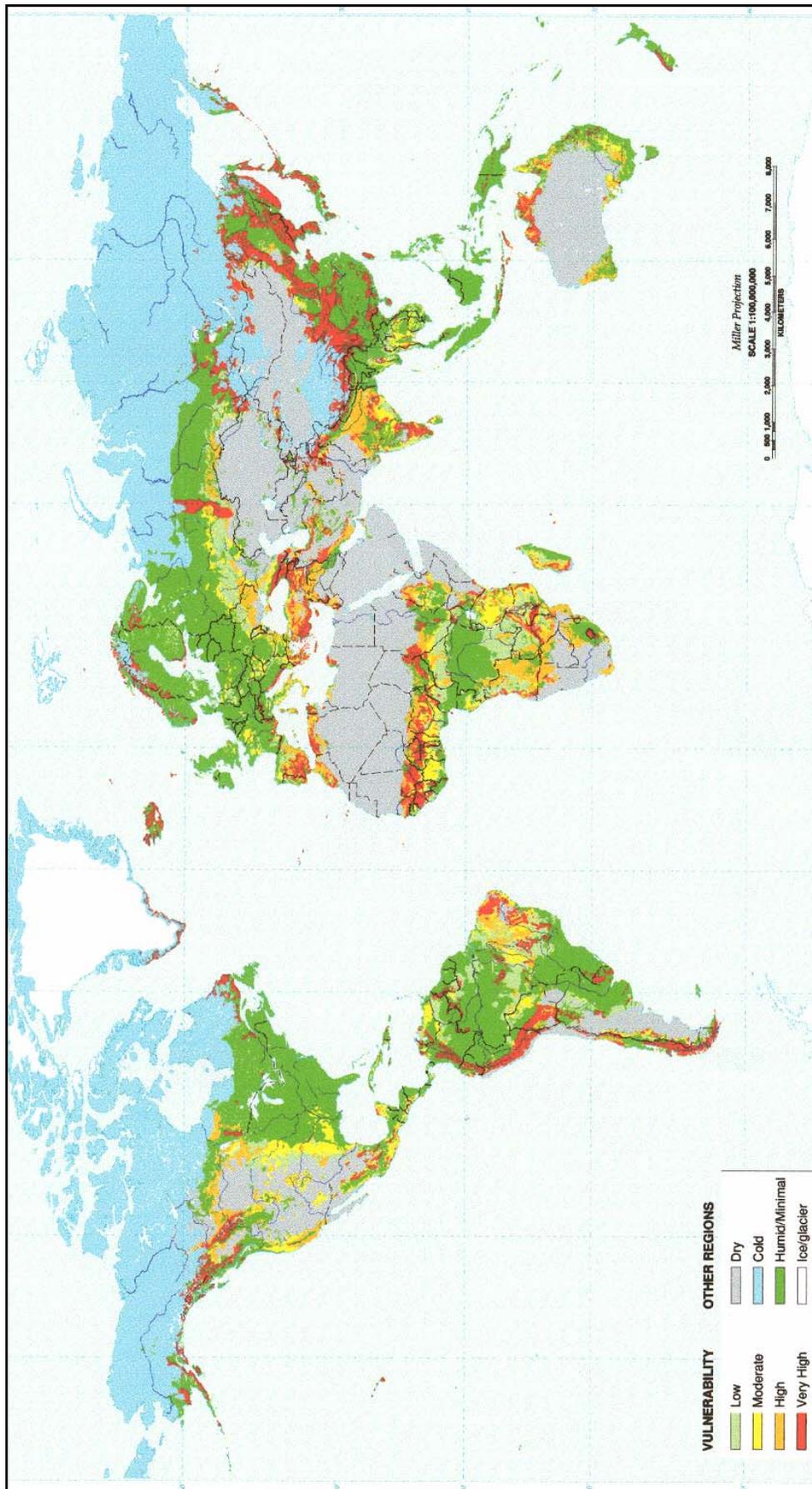


Figure 2. Wind erosion vulnerability.

Fig. 3 Risk of Human Induced Water Erosion

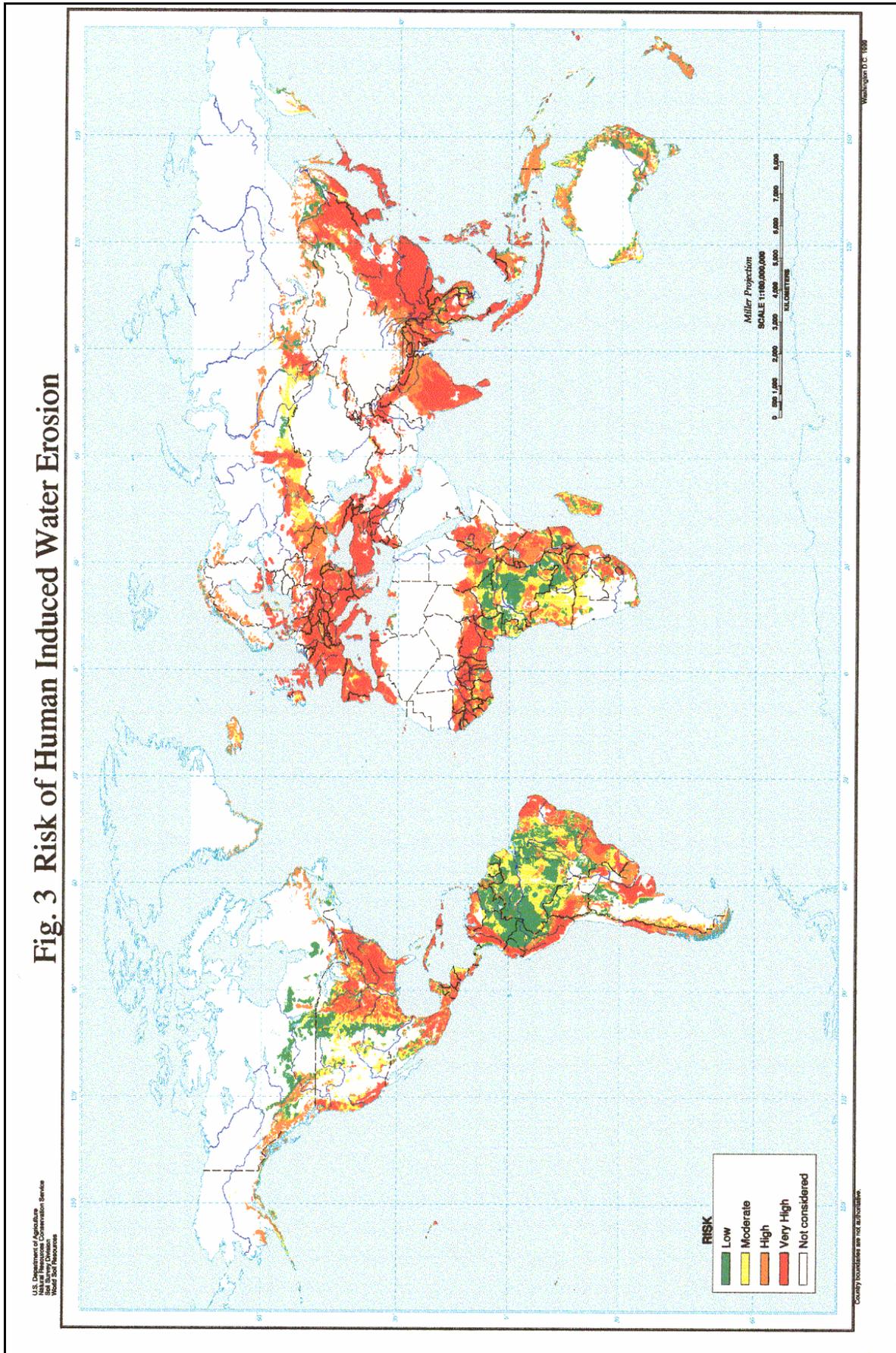


Figure 3. Risk of human induced water erosion.

Table 7. Vulnerability to erosion in relation to inherent land quality. Note: The extreme drylands in ILQ class IX and extreme cold lands in ILQ class VIII are excluded.

ILQ CLASS	WATER EROSION (Million km ²)				WIND EROSION (Million km ²)			
	LOW	MODERATE	HIGH	V. HIGH	LOW	MODERATE	HIGH	V. HIGH
I	1.22	1.41	1.39	0.02	0.72	1.04	1.00	0.02
II	1.43	1.19	1.85	1.82	0.08	0.60	0.25	0.34
III	2.42	1.69	0.41	0.17	1.29	0.80	0.70	0.07
IV	0.07	0.47	0.03	0	0.03	0.04	0.01	0
V	7.45	4.46	6.15	2.21	6.56	3.12	2.92	1.05
VI	4.57	6.01	0.89	0	0.47	0.58	2.82	0
VII	0	0.01	0	7.35	0	0	0	7.35
VIII	0.05	0.14	0.26	0.07	0.05	0.14	0.02	0.04
IX	0.12	0.01	0.01	0.55	0.04	0.01	0.06	0.05
Total	17.33	15.39	10.97	12.21	9.25	6.32	7.80	9.33

Table 8. Estimate of global annual water erosion soil loss as a function of land quality classes of potentially arable lands. LQI VII, VIII, and IX are not included in this table.

Land Quality Class	Annual Water Erosion Amount (billion Metric tons)				
	Vulnerability to Water Erosion				
	Low	Moderate	High	Very High	TOTAL
I	0.24	0.56	0.83	0.02	1.66
II	0.43	0.6	1.48	2.01	4.51
III	0.97	0.14	0.21	0	2.53
IV	0.04	0.47	0.07	0	0.58
V	7.45	6.69	12.29	8.85	35.28
VI	6.86	12.02	3.52	0	22.40
TOTAL	15.99	21.70	18.40	10.88	66.96

occur mostly in the poorer third world countries. In Africa, they are dominant in the region between the southern limit of the Sahara and the humid zone. In South Asia, the whole of India is highly vulnerable. India, in general, is comprised of an old geomorphic surface, uplifted and tilted with a current highly erosive climate. These physiographic conditions, coupled with a farming system that is essentially low-input with few conservation technologies, leads to high rates of human-induced water erosion. Erosion, with rates exceeding 30 Metric tons/ha/yr (Singh et al., 1999) is so rampant in the central part of the continent that large inselbergs are exposed in a north-south alignment. The highest erosion rates are probably along the east-west running Shiwalik hill tracts (estimated by Singh et al. (1992) as being about 80 Metric tons/ha/yr) but here it is largely coupled with tectonic uplifts.

Though peneplanation processes formed the large expanses of the Mid- to End-Tertiary erosion surfaces in Central and Southern Africa, they are not currently sites of intensive erosion. The flat nature of the present day surfaces does not promote intensive erosion under the prevailing climate. During the period of peneplanation, both the physiographic conditions and the climate must have been different and were perhaps similar to those in India today. It is difficult to validate a global assessment. However, it is possible to compare the results obtained in this study with estimates obtained for specific locations published in the literature. A synthesis of such data was compiled by El-Swaify et al. (1982) and is a valuable source of information

for comparison. Due to insufficient national estimates, the validation was only made for water erosion susceptibility.

To estimate the amounts of soil loss due to water erosion, land quality classes (Eswaran et al., 1999) were assigned erosion rates for each of the vulnerability classes. As indicated in the methodology, the amounts assigned (Table 3) were empirical values obtained from studies in different parts of the world. It is estimated by this procedure that the total global soil loss, in all lands excluding the extreme dry and the extreme cold, which is about 72.5 million km², through water erosion is about 130 Metric tons per year. Table 8 presents the estimates for each land quality classes (only I through VI), which represents most of the arable lands of the world. The total estimate of soil loss due to water erosion for the six classes is about 67 billion Metric tons. This is about 52% of the global annual soil loss.

As seen in Table 8, very high erosion losses arise from Class V and VI lands, which together account for over 86% of total soil loss from the arable lands. Much of Class V and VI lands occur in the inter-tropical areas that have high population densities and low inputs for land management as they can least afford appropriate conservation technology. Class V and VI lands are in general fragile ecosystems and also form the main challenges to institute sustainable agriculture. These lands are also one of the major sources of carbon emission to the atmosphere, which of course is enhanced through erosion.

In the United States, the US Department of Agriculture Natural Resources Conservation Service (USDA, 1996)

Table 9. Global soil loss due to water erosion in relation to population density. Note that very cold and dry areas are excluded from the estimate. About 16.6 million km² of land (Table 2) is considered as depositional and contributes minimally to water erosion.

Population Density Persons/Sq. km	<i>Erosion amount (million Metric tons)</i>				
	<i>Vulnerability to erosion</i>				
	Low	Moderate	High	Very High	Total
<2	392	842	717	1,935	3,886
2-10	1,633	2,247	2,429	15,341	21,650
11-40	1,878	4,092	5,589	9,978	21,537
41-100	3,025	4,465	5,116	8,696	21,302
101-500	3,460	5,280	9,636	10,375	28,751
>500	1,029	873	2,148	1,779	5,829
Total	11,418	17,799	25,634	38,103	91,953

estimated that in 1982, 3.14 billion metric tons of soil were lost through wind erosion and 3.8 billion metric tons by water erosion. This total soil loss of about 7 billion metric tons was reduced through the Conservation Reserve Program (CRP) to about 5 billion metric tons by 1992. These estimates are only for cropland. In our study of the US, we estimated the potential soil loss through water erosion for land belonging to land quality Classes I through VI in the rating of Eswaran et al. (1999). The potential soil loss is about 6.5 billion metric tons. The actual soil loss of about 3.1 billion metric tons is about 48% of our estimated potential soil loss and this points to the success of implementing a conservation technology program. In India, the amount of soil loss computed from the data of Singh et al. (1992) is about 4.7 billion metric tons for the whole of India. In our study, we estimate about 4.3 billion metric tons of soil loss by water erosion for the area of India under consideration.

To demarcate risk of water erosion arising from land use, we overlaid the water erosion vulnerability map with a population density map. An estimate of amounts of soil loss that can be expected for each population density class is obtained. Fig. 3 shows the areas of high risk. Using the matrix in Table 2, the amounts of potential soil loss were calculated and presented in Table 9.

Table 9 suggests that the annual soil loss due to water erosion, in the regions of the world prone to desertification (55.91 million km²), is about 92 billion Metric tons. The average rate is about 16 metric tons ha⁻¹ yr⁻¹. Fig. 3 shows the distribution of these lands. Again, the major concentration of land with high erosion rates or erosion risks is in the poorer third world countries.

CONCLUSION

Lowdermilk (1953) has provided a good historical analysis of the rise and fall of civilizations and how this was related to the quality of land resources. Though there is good evidence for enhanced soil loss in poorer countries of the world there is no good estimate for global soil loss through wind and water erosion. The GLASOD (Oldeman et al., 1990) project recently, made the first attempt to evaluate human-induced land degradation. The land areas with high

erosion rates and their locations are already disheartening as they confirmed previous published observations.

In this analysis, we preferred to consider wind and water erosion more generically and attempted to locate vulnerable areas and provide estimates of global magnitudes. The assessment is necessarily empirical, since no global database exists. Therefore, assessments are largely dependent upon assumptions made in the method. The results, however, validate the widely held belief of the extensive nature of the problem and its seriousness. The 56 million km² of land vulnerable to water erosion has the capacity to yield about 92 billion metric tons annually of sediment that can have significant off-site damages. The on-site damage ranges from reduced soil quality to collapse of biodiversity and ecosystems. In many of the third world countries, food security is strongly linked to quality of land resources and these are the countries in risk of famine and civilian unrest due to extensive land degradation.

It is acknowledged that the weakness of this analysis stems from the lack of reliable data and consequently the use of assumptions that cannot be unequivocally proven. In the absence of national assessments and monitoring programs, we may have to make such judgments based on default values. This study offers evidence that soil erosion and the resulting degradation remains a threat to world food production. Accordingly, a global program to make assessments and monitor this process is urgently needed.

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