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# Water Erosion in Brazil and in the World: A Brief Review

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**Abstract:** Over the course of history soil erosion has been at the root of many problems, from small-scale local economic losses to the collapse of entire civilizations. Whether in rural areas, where erosion processes are more expressive and also visible, or in cities where its effects cannot be disregarded, erosion deserves attention and strategic studies. The objective of this article was to research and present a brief discussion about soil loss under the influence of rainwater surface erosion, focusing on Brazilian cases. The research shows high rates of soil loss, in many countries, especially in humid climates. Also highlighted are agricultural crops and dirt roads, the latter exhibiting erosion rates significantly higher than any agricultural activity. Besides particle entrainment, erosion is responsible for the removal of topsoil layers, reducing the fertility of agricultural areas, in addition to causing siltation of reservoirs and eutrophication of water bodies.

**Key words:** water erosion, sediment, silt

## 1. Introduction

Soils are materials resulting from the weathering of rocks, either by mechanical disintegration (agents such as water, wind, vegetation and temperature) or chemical decomposition, water as the main agent, such as mechanisms of attack, oxidation, hydration, carbonation of vegetation and chemical effects [1]. These processes usually operate simultaneously and in certain places, and under specific weather conditions they can overlap one another. From the agricultural point of view, the function of soil "[...] is to sustain plants, providing them with nutrients, water and air so that it completes its life cycle" [2].

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With anthropogenic influence, which occurs since the beginning of civilizations and causes the movement of large areas of land surface, accelerated soil erosion has reached dangerously high rates, affecting the economy, food independence and other factors inherent in human development.

The study of soil erosion processes uses sedimentological methods. The hydrosedimentological cycle shows the displacements of solid particles and their interaction with the environment, due to the action of water. The different phases of this cycle are defined as: breakdown, erosion, transportation, sedimentation, deposition and consolidation of sediments [3].

In this study only the erosion stage (or sediment yield) will be discussed — more specifically erosion caused by the action of water. This discussion is conducted as a literature review, covering soil loss studies in Brazil as well as in international cases.

## 2. Erosion — General Concept

Zachar (1982) [4] and Silva et al. (2003) [5] states that the term erosion originates from the Latin verb *erodere* (to gnaw). Erosion is "[...] the process of

detachment and accelerated dragging of soil particles [...]" [6]. According to K. Suguio [7], erosion is described as a natural process of wearing away the earth's surface through the action of physical, chemical and biological processes.

Another concept of erosion is described by N. O. Carvalho (2008) [8], as the "[...] separation and removal of rock particle and soil by water, wind or other effects, in which various phenomena are predominant in this process." It is described by R. Fendrich et al. (1997) [9] as "[...] the breakdown, transportation and deposition of materials from surface and deep soil horizons, leading to its degradation". These authors argue that this begins at the surface layer, deepening until a consolidated rock or soil layer is found.

According to S. J. C. Simões and E. M. Coiado (2001) [10] erosion is a set of processes in which the wearing away of earth or rock material occurs. According to the authors, this phenomenon varies according to its causative agents, the main ones being: water, wind, ice and gravity. They classify erosion in two ways; natural and accelerated, where the former occurs in normal conditions and cannot be controlled. Accelerated erosion, however, is difficult to be eliminated and has higher rates than natural erosion.

The main factors which influence sediment yield are rainfall, topography, type, land use and cover, and the characteristics of the sediments, among others [11]. Similarly, R. Bellinazzi Junior, D. Bertolini and F. Lombardi Neto (1981) [12] reported that the main factors that influence erosion are climate, soil, topography, vegetation cover and human action.

Erosion processes are complex and can be caused by various agents, such as rain and river waters and winds, among others. According to these authors, the most worrying type is water erosion, particularly due to the ease of segregating and transporting materials, especially in humid climate regions [5].

Erosive agents can be classified as active and passive. The following are some of the active agents highlighted: water, temperature, wind, snow and the actions of microorganisms, animals and human beings. The main passive agents are: topography, gravity, soil type, vegetal cover and anthropogenic practices [8]. Table 1 summarizes the main types of erosion.

Among the many types of erosive processes, as shown in Table 1, according to A. M. Silva, H. E. Sculz, and P. B. Camargo [5] and N. O. Carvalho (2008) [8] water erosion is the most worrisome as it causes sediments to detach more easily.

### *2.1 Brief History of Erosion*

> "Erosion, a deadly disease of the soil, ruthlessly destroys the living layers of the earth and on it installs hardened and barren furrows and plaques which are no longer fixed to the roots or the helpful bacteria, nor the creeping plants, the grains, or seeds, which carry within the annunciation of life."

These are the first words in the preface (signed by Dante Costa) of the book "Erosion in Brazil" [13], at a time when research on soil erosion was beginning to emerge worldwide. However, the destructive power of this phenomenon, which impaired populations and weakened major regions, was already known.

The processes of erosion and sediment transport of soils have occurred throughout geological eras, assisting in the modelling of mountains, valleys and plains in the world. However, human action has catalyzed these events and on account of human action the current erosion rates are 100 times greater, if only the geological events were to be considered [8]. This author also states that:

> "[...] The erodibility of natural material is strongly hindered by disturbances in the soil structure due to inappropriate treatment, either in agricultural practices or in inadequate land use in engineering works. The protective soil layer (vegetation) is weakened by fire, cutting, plowing, etc. Besides producing detrimental sediments, erosion causes serious damage to agricultural lands, reducing soil fertility and productivity" [8].

Soil erosion, which has always existed and modelled the Earth's surface for billions of years, is known as natural or geological erosion. Erosion by human action, which causes visible and dangerous impacts, is known as accelerated (or anthropogenic) erosion. The references used in this paper are related to accelerated soil erosion.

**Table 1 Main Types of Erosion**

| Aeolic | Fluvial | Surface water | Mass removal | Caused by human or anthropogenic actions | Extreme events |
|---|---|---|---|---|---|
| Dust | Excavation | Rain erosion or by collision | Creep or crawl | In several construction works | By floods |
| Air transported | Margin erosion | Sheet or laminar erosion | Solifluction | By deforestation | By earthquakes |
| Transported on surface | Bed erosion | Erosion by diffuse flow, by gully, or finger-like grooves | Dislodgement of earth or sliding | In agriculture by tilled soils | By volcanism |
| | | Erosion by intense diffuse runoff | Surface slip or slope rupture | By livestock trampling | By tornadoes and others |
| | | Concentrated flow erosion (gully) | Subsurface flow | | By climatic variability |

Source: Adapted from [8].

The disappearance of many communities due to strong soil degradation is reported by A. B. Primavesi (1952) [14] (it should be noted that soil erosion was an underlying factor in these events). According to the author, the agricultural wealth of ancient Egypt relied on the fertile lands of the Nile River, today the Sahara Desert (Northern Africa). Libya, Algeria and Tunisia, which during the Roman Empire contained very fertile soils, are currently arid-desert areas with very poor soils. Also according to the author, the rich empires of the Incas (the region that is now South America), the Aztecs (Mexico) and other indigenous peoples collapsed as a result of soil depletion, in part because of corn monoculture.

Regions that are currently desert or semi-desert are often associated with long periods of negligent human occupation. The devastation of previously vegetated areas, in most cases, leads to soil erosion and to the decline of cities and agglomerations. There is a direct relationship between productive soil conditions and the prosperity of a population [15].

From the Gallic era, through the Middle Ages to the mid-nineteenth century, France was being deforested. The economist and politician Auguste Blanqui, realizing the damage that soil erosion had caused, sought to reverse the process by drafting a guidance document (delivered to the Academy of Moral and Political Sciences). The arable lands were being destroyed by floods [13].

China's Loess Plateau has recorded exponential annual soil losses since about 220 bc, partly due to demographic pressure [16]. In mountainous areas of the humid tropics, specifically in the Himalayas and the Andes, population pressure has forced marginal lands into cultivation, causing soil erosion.

Continents like America and Australia were victims of "heroic and daring" conquerors, who above all else aimed at immediate profits. Thus, lands were transformed and devastated, generating more cases of soil erosion [13].

One of the main factors responsible for the decline of various civilizations was soil erosion, triggered by unrestricted deforestation and the depletion of nutrients in previously fertile lands (which would be abandoned to then occupy other more fertile areas). In addition, a number of countries currently face hard times because of erosion. Among them China, Iceland and the USA [17].

Soil erosion has been the cause behind rural depopulation in some regions of the world. In the mountains of Haraz (Yemen, southwest of the Saudi Peninsula), land abandonment occurred at the beginning of the twentieth century, due to severe droughts in 1940 and between 1967 and 1973 [18].

Numerous studies currently portray soil erosion in many parts of the world, often due to inadequate use and management of agricultural lands. These actions can cause reservoir siltation events, loss of soil fertility and increased land management costs, in addition to lower fertility rates, among other factors.

*2.2 Water Erosion*

Notwithstanding the importance of all types of erosion (due to soluble salts or minerals, wind, river, surface water, mass removal, animal or human action and extreme events), in this paper the research was directed to the effects of surface erosion caused by natural rainfall: rainfall erosion. This occurs through the collision of rain drops with the soil surface. A breakdown of particles, which occurs when the surface is bare, shifts the place of origin (erosion by collision). Water erosion is defined by N. M. C. Mafra (2010) [19] as "[...] basically a series of transfers of matter and energy generated by an imbalance of the water/soil/vegetation cover system, which results in a progressive loss of soil".

Laminar erosion occurs during heavy rainfall, when a water saturated surface soil is beyond its infiltration capacity. From this point, there is a smooth and uniform wear throughout the ground. In some cases small channels are formed due to slope gradient changes. This type of erosion — a more advanced stage of laminar erosion — is known as stream erosion and occurs in soft soils and plowed fields, especially those with high silt content. It also occurs in soils with slope inclinations of 4% and higher [9].

According to Roose (1967) [20] cited by R. P. C. Morgan (1997) [18], experimental studies applied in Senegal show that (between 1959 and 1963) 68% of soil loss was due to rainfall events between 15 and 60 mm and the frequency of these events took place 10 times per year. The studies of Morgan et al. (1986) [21], cited by R. P. C. Morgan (1997) [18] in Bedfordshire (England), indicated that between 1973 and 1979, 80% of the erosion was due to 13 events, although most of the soil loss (21%) recorded was due to an event of 57.2 mm.

Edwards and Owen (1991) [22], cited by R. P. C. Morgan (1997) [18], analyzed 28 years of data of nine small watersheds that receive rotating corn-wheat-pasture-grazing crops (4 years) in Coshocton, Ohio (USA). They found that the three biggest events, with return periods longer than 100 years, accounted for 52% of erosion, with 92% of losses related to the corn crop development time.

Extreme events may also have long-time duration consequences. Nossin (1964) [23], cited by cited by R. P. C. Morgan (1997) [18], reported that a change in the equatorial rain associated to the northwest monsoons caused in Kuantan, Malaysia, rainfall of 631 mm on December 28, 1926, and 1194 mm between the 26 and 29, causing massive erosion and landslides. The damage caused by this event could still be seen 35 years later.

Erosion and land-use change are strongly related. Combining historical and geomorphological analysis has proved that erosion is a natural process. However, its time-space intensity distributions are factors resulting from the interaction of physical and human circumstances [18].

A review of the book "Dirt: The erosion of civilizations" by David R. Montgomery, E. A. Davison (2007) [20] reports that this topic (soil erosion) could not be more timely, given the recent and intense large-scale corn expansion (in the US) and sugar cane (in Brazil), key productions in the energy and food sectors. All of this at a time when finite global resources and areas of arable (and good quality) lands are increasingly smaller.

This author mentions that soil fertility, that is, the natural capital of a region and the longevity and prosperity of a civilization appear to go hand-in-hand.

*2.3 Effects of Erosion*

Erosion can be a determining factor to a region's economic success or decline. Regions that were once agricultural and prosperous, and which had their fertile lands degraded due to erosion, saw its population slowly decrease and its economy decline [8]. According to the author, the effects of erosion are the onset of all sediment-related problems in the environment. The first and most harmful effect of erosion is the loss of soil fertility. Also according to the

author, of the number of problems arising due to the erosion of soils, the following are highlighted:

- Erosion in the headwaters of rivers can cause the destruction of the headsprings;
- A greater risk of desertification;
- The removal of topsoil in agricultural regions causes soil depletion;
- Soil detachment, landslides and slopes can cause severe damage, including deaths;
- Erosion can alter water flows, surface runoff and river channels;
- When there are landslides into rivers, the landslide material deposited in the bed alters the river channels;
- Floods produce grooves in undesirable places;
- There are cases of erosion around structures, which can cause irreversible damage.

Surface runoff can also carry seeds and agrochemicals to nearby crops, which in addition to generating economic damage, can also pollute headstreams and water bodies. Another circumstance caused by erosion is the increased need to use fertilizers and soil correctors, all of which require greater activities of agricultural machinery [24].

Erosion problems, cited by I. Santos (2001) [25] directly affect Brazil's agricultural development. According to the authors, of every 1 kg of grain produced in the country, between 6 to 10 kg of soil is lost due to erosion. The problem of erosion often undermines agriculture, dilapidating fertile soil layers [26].

Similarly, F. F. Pruski (2009) [24] states that erosion results in the need for increased use of fertilizers and soil correctors, requiring more products and higher activity of agricultural machinery. It should be mentioned that besides removing certain nutrients and fertilizers needed for good plant growth, these materials can be carried to water bodies, hence causing numerous problems.

Sediments are often responsible for the transport of pesticides, nutrients, organic wastes and organisms [27]. Thus, L. M. Costa and A. T. Matos [28] discuss the issue of fertilizers and soil correctors as sources of water pollution. In their paper they present some interesting data from Brown (1989) [29] on the evolution of fertilizer use in relation to grain yield (Table 2).

Table 2 shows elucidating numbers regarding the escalating demand for fertilizers worldwide, between the 1950s and 1990s. For an inexpressive grain yield (only twofold), the agricultural sector had to increase by almost 10 times the amount of fertilizers applied.

The quantification of erosion processes is important because these phenomena cause numerous environmental, economic and social problems. Among them, N. O. Carvalho (2008) [8] mentions: destruction of headsprings (erosion in the headwaters), increased risk of desertification, removal of fertile topsoil (soil depletion), death and destruction of constructions (detachment, landslides and slope gradients).

### *2.4 Soil Loss Rates*

Erosion rate is expressed in volume (or weight) of eroded material per unit area and time, and the soil loss rate (or erosion rate) is that "in which from a given area the soil is eroded" [9].

According to R. P. C. Morgan (1997) [18], the *in situ* effects of erosion are particularly important and evident in agricultural areas under cultivation. These areas have soil fertility decrease, as well as available moisture loss, structural degradation, and material dragged to river beds and reservoirs.

**Table 2 Global Use of Fertilizers and Mean Grain Production**

| Year | Fertilizers (millions - t) | Production (t) |
|---|---|---|
| 1950 | 15.1 (100) | 1.05 (100) |
| 1960 | 24.2 (160) | 1.30 (124) |
| 1970 | 59.2 (392) | 1.35 (128) |
| 1980 | 111.3 (737) | 1.90 (181) |
| 1990 | 142.9 (946) | 2.20 (209) |

Source: Brown (1989).

Regarding erosion, A. C. Rebouças, B. Braga, & J. G. Tundisi (1999) [30] stated that:

"[...] Depending on soil type, land slope and cultivation, rainfall with intensity above certain magnitudes can cause surface soil erosion, carrying solid particles, natural or artificial nutrients, exhausting or destroying soil and degrading water bodies" [30].

The authors also cite a list of annual soil losses for a number of crops. Besides these, they emphasize erosion of peri-urban roads, as shown in Table 3. The dirt roads, in Table 3, show high erosion potential due to constantly being bare, and often receiving stormwater from adjacent areas due to poor topographic planning.

These findings show that such bare areas may have erosion rates 4 times more prone to the susceptible crops (castor beans) pointed in this survey.

In the state of São Paulo, of the existing 250 thousand kilometers of transit roads, 220.00 km are dirt roads [31]. Therefore, in this state only 12% of the roads are paved. It should be noted that São Paulo is the state with the highest economic concentration in Brazil (32.6%) [32].

In erosion studies of sugarcane cart-roads, G. D. A. Scarpinella (2012) [33] estimated soil losses (through experiments in a sugar cane farm) that ranged from 60.6 to 90.1 $t.ha^{-1}.year^{-1}$. This author also found that on average the cart-roads correspond to 5.21% of the sugarcane areas installed in the study area. Through a quick estimate of the area planted with sugarcane in Brazil, considering an average width of 3 meters of the cart-roads and a planted area of 9.835.169 ha [34], it can be stated that the sugarcane cart-roads correspond to approximately 1.7 million linear kilometers. Other major crops such as soybeans, corn and coffee also have cart-roads in their formations, increasing susceptibility to erosion in such passages.

**Table 3 Soil Losses Associated with Agricultural Use in the State of São Paulo/SP/Brazil (in $t.ha^{-1}.year^{-1}$).**

| Annual crops | Soil losses | Temporary crops | Soil losses |
|---|---|---|---|
| Cotton | 24.8 | Sugar cane | 12.4 |
| Peanut | 26.7 | Castor beans | 41.5 |
| Rice | 25.1 | Cassava | 33.9 |
| Bean | 38.1 | Permanent crops | Soil losses |
| Corn | 12 | Coffee | 0.9 |
| Soybean | 20.1 | Orange | 0.9 |
| - | Soil losses | Pasture | 0.9 |
| Peri-urban roads | 175 | Reforestation | 0.4 |

Source: Adapted from Telles (1999) [35] and Ref. [30].

Nearly 99% of the food supply comes from the earth, associated with freshwater. Given this number, the erosion caused by rain and wind are threats to soil yields and hence to society [36]. Approximately 80% of the arable land area in the world sustains from moderate to severe erosion processes. And 10% mild to moderate soil erosion [37].

Crops and pastures are susceptible to erosion. However, crop areas are more susceptible in relation to pasture areas, because the soil is frequently exposed and plowed, hence bare and thus exposed to the actions of wind and rain. Soil loss (through erosion) and water (due to lower infiltration and higher runoff) has caused an annual loss of approximately U$400 billion throughout the world [38].

In the last 40 years approximately 30% of the world's arable lands have become unproductive and much of these former agricultural areas have been abandoned [39, 40].

According to calculations by the United Nations (UN) soil degradation in the world accounts for 2 billion hectares, an area equivalent to the size of the United States and Canada.

Global soil degradation indices have increased yearly by 20 million hectares [41].

The regions which are most susceptible to erosion in the world are in semi-arid and sub-humid regions, highlighting China, India, western United States, center Russia and the Mediterranean countries. Other high erosion-intensity areas are mountainous terrains, such as most of the Andes, Himalayas, Kara Korum (border between Pakistan, China and India), part of the Rocky Mountains and the Rift Valley (in Africa) and volcanic soil areas (Java, southern islands of New

Zealand, Papua New Guinea and parts of Central America) [18].

In a review of soil erosion, Young (1969) [42], and R. P. C. Morgan (1997) [18] reported that in regions under natural conditions, soil loss rates for moderate relief terrains are 0.0045 $t.ha^{-1}.year^{-1}$. For more irregular terrains this rate increases to 0.45 $t.ha^{-1}.year^{-1}$. On the other hand, farmed lands have a significantly higher rate, compared to the previous ones: between 45 and 450 $t.ha^{-1}.year^{-1}$.

According to Table 4 we can compare that erosion rates for bare soils can reach higher values in the same lands, considering the possibility of some coverage on its surface.

There have been reports of soil loss by laminar erosion in Brazil from as early as 1940 when Marques (1949) [43] and J. Bertoni, F. Lombardi Neto [6] pointed to an annual loss of approximately 500 million tons. Today, due to the intense use and expansion of the agricultural frontier, it is believed that soil losses are higher than this value, with extremely serious situations in some Brazilian states [25].

In Brazil, according to Agência Nacional de Águas (2009) [55], it is estimated that the loss of nutrients by erosion have resulted in a loss of US$ 3.6 billion/year. If, in addition to this we take into account "the effect of erosion on land depreciation and other costs, such as road maintenance, water treatment and reduced useful life of reservoirs", this loss would be US$ 6 billion/year. The greater the exposed soil, the greater the risk of erosion.

**Table 4 Erosion Rates in Some Countries ($t.ha^{-1}.year^{-1}$).**

| Country | Natural | Cultivated | Bare |
|---|---|---|---|
| China | 0.1-2 | 150-200 | 280-360 |
| USA | 0.03-3 | 5-170 | 4-9 |
| Australia | 0.0-64 | 0.1-150 | 44-87 |
| Costa | 0.03-0.2 | 0.1-90 | 10-750 |
| Nigeria | 0.5-1 | 0.1-35 | 3-150 |
| India | 0.5-5 | 0.3-40 | 10-185 |
| Ethiopia | 1-5 | 8-42 | 5-70 |
| Belgium | 0.1-0.5 | 3-30 | 7-82 |
| UK | 0.1-0.5 | 0.1-20 | 100-200 |

Source: Boardman (1990) [44]; Bolline (1978) [45]; Browning et al. (1948) [46]; Edwards (1993) [47]; Fournier (1972) [48]; Hurni (1993) [49]; Jiang, Qi e Tan (1981) [50]; Lal (1976) [51]; Morgan (1985a) [52]; Roose (1971) [53]; Singh, Babu and Chandra (1981) [54], cited by Morgan (1997).

Estimates of Hernani et al. (2002) [56], cited by Pruski (2009) [25], project for Brazil annual losses of 822.7 million tons of soil in areas occupied by crops and pastures. Other estimates indicate that Brazil loses about 822 million tons of soil per year and 170 billion cubic meters of water [57].

Zoccal (2007) [32] estimates that 80% of the cultivated area in the state of São Paulo (Brazil) is affected by some form erosion, causing a loss of 200 million tons of soil annually. Rebouças, Braga, and Tundisi (1999) [31] report that in 1993, only in São Paulo, there was a loss of 193 million tons of soil because of inadequate land use.

Hernani et al. (2002) [58] cited by S. Ahrens (2005) [59], reported that in the early 1990s, Brazil lost on average 600 million tons of soil per year (due to inadequate land use and erosion). Of this amount, 70% comes in the form of sediments in watersheds and water bodies, causing siltation and pollution.

Fig. 1 illustrates the details on the potential for sediment production in Brazil, in order to create subsidies for managing hydropower reservoir plants [60]. This study was based on methodologies for mapping the risk of erosion and siltation, such as Campagnoli (2002) [61], Instituto de Pesquisas Tecnológicas (2000) [62] and Diniz (1998) [63]. Fig. 1 shows the main result of this study.

Fig. 1 illustrates and corroborates the fact that vegetation cover is the best guarantee to minimize erosion. The predominant green zone on the map, which corresponds to very low sediment production, is characterized by its natural vegetation cover (Amazon forest). Although rainfall is significant in this region, the natural cover (as shown in Table 3) provides the best protection against water erosion.

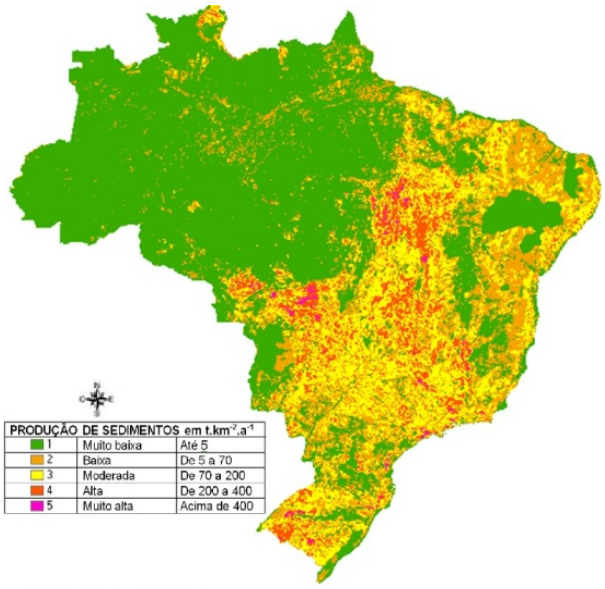


**Fig. 1 Map of Potential Sediment Production in Brazil [60].**

At any rate, the highest soil losses caused by erosion can be attributed mainly to anthropogenic action, by the deforestation of large areas, lacking adequate attention to the destructive potential of natural processes. After the deforested areas, the lack of care, concern and information can bring erosion to other land areas. Types of erosion, such as laminar erosion (which occurs often without the farmer's awareness) are economically and environmentally damaging, due to the "washing away" of nutrients and soil depletion.

## 3. Final Remarks

Anthropic factors are seen as the main drivers of erosion, due to the interference they generate, the mismanagement of land, and in some cases possibly due to the ignorance about the effects of soil erosion. For thousands of years, with the emergence of settlements and civilizations, man has experienced all sorts of losses from exploring the land. There is currently technical and scientific knowledge, prediction tools and soil erosion measurement equipment, all of which can reduce soil loss rates, even in regions that have the highest susceptibility to erosion.

In this sense, it is observed that erosion problems are found in all parts of the world and deserve adequate attention, especially because such problems directly affect agricultural production, reducing soil fertility. In water bodies, erosion causes siltation and affects the distribution of water supply to the population or even accomplishing the other multiple uses.

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