# REVITALISATION OF SAN FRANCISCO RIVER IN BRAZIL USING GEOMATS

**Victor Gustavo Chiari[1] & Gerardo Fracassi[2]**

[1] *Civil Engineering, Maccaferri do Brasil Ltda. (e-mail: victor@maccaferri.com.br)*
[2] *Civil Engineering, Maccaferri do Brasil Ltda. (e-mail: fracassi@maccaferri.com.br)*

**Abstract:** The main problem, besides the existence of social inequality, faced by the low-income earning Brazilian population are the living conditions. Most of the time this is due to the lack of resources. The San Francisco River, 2830 kilometers long and located between the states of Minas Gerais and Alagoas, is extremely important, both economically and culturally. For this reason, the river is the biggest means of transportation for the agricultural activities of the people who live in that area. Recent studies prove that in many places this important river has been degrading with time. Due to the lateral displacements that have occurred by the constant erosion in the margins, the river is becoming wider and shallower day by day. This reduces the navigability and, consequently, the commercial activities.

The proposal for the "Revitalization of San Francisco River" foresees a search for an effective margin protection system at low cost and using local available technology and resources. This paper introduces the main solution applied in this river using geomats. These are manufactured with an open three dimensional synthetic mat consisting of randomly placed filaments of polypropylene and a double twisted hexagonal mesh. This technique promotes protection against margin erosion and guarantees excellent interaction between soil and material. In addition, the stabilisation of the surface cover and the confinement of soil particles promotes the growth of vegetation. The roots of the vegetation which anchor the geosynthetic material to the slope and the wire mesh increases the resistance of the soil against small displacements.

**Keywords:** erosion control, geomattress, degradation, polypropylene, revetment, vegetation.

## INTRODUCTION

The San Francisco River, affectionately known as “The Old Chico”, is one of the most important hydrographic basins of Brazil. This is primarily because of its hydraulic importance rather than by the development generated for regions through which it passes. It contains an area of about 640 thousand km² and occupies 7,40% of the Brazilian territory (Figure 1). Its origins are in Serra da Canastra in the State of Minas Gerais, located in the southeast of Brazil. Then it continues flowing northwards for 2830 km crossing the State of Bahia, and making it’s northern boundary in the State of Pernambuco, and dividing the States of Sergipe and Alagoas, draining finally in the Atlantic Ocean in the northeast region of the country. In this region is located the Polígono das Secas, which is well-known as a region that has areas that are annually prone to droughts and possesses the highest concentration and highest rates of social exclusion in the country.


**Figure 1.** Location of the basin of San Francisco River related to the Brazilian territory

The San Francisco River is the main artery for socioeconomic connection between the southeast and the northeast of Brazil. It is the largest single variable influencing prosperity of the entire region, which is currently the largest producer of tropical fruit in the country. Moreover, the river is used to distribute these goods, supplying a population of about six million habitants who live in this area.

This paper has as the main objective to present the Plan of San Francisco River Revitalization, which was initiated in Barra in the State of Bahia located in the northeast of Brazil. This plan aims to find feasible and economic options that would allow for reduction of the level of erosion of banks along the river degraded by the action of rainfall, the stream flow and effect of waves, and hence to stabilize the fluvial bed.

**DESCRIPTION OF THE PROBLEM**

Emphasizing the importance of the San Francisco River and what its impact represents to Brazil, recent studies have shown that it has been degrading over time. Examining this river in detail, the width of its bed has changed in recent times by hundreds of meters (between 10 and 15 metres annually), making it wider and shallower day by day. This progressive degradation is due to the erosive nature of the banks, the transportation of solids and effluents, which form sand banks in the middle of the river and contribute to the instability of the present islands. This is a continually self-feeding process and is detrimental to the sustainability of countless productive activities. In addition it is reducing local navigability of the river. The impact is made worse by the disordered occupation of the riverbanks of the San Francisco River by the population who live in the region. This provokes ancillary deforestation and this removes additional protection for the surface of the soil to limit erosion.

It is understood that the process of erosion, including the displacement and transportation of soil which redistributes soil and sediment particles, causes big environmental impacts, inhibiting the water flow and altering the slope of the riverbanks, stimulating an accumulation of sand (Pereira 1999).

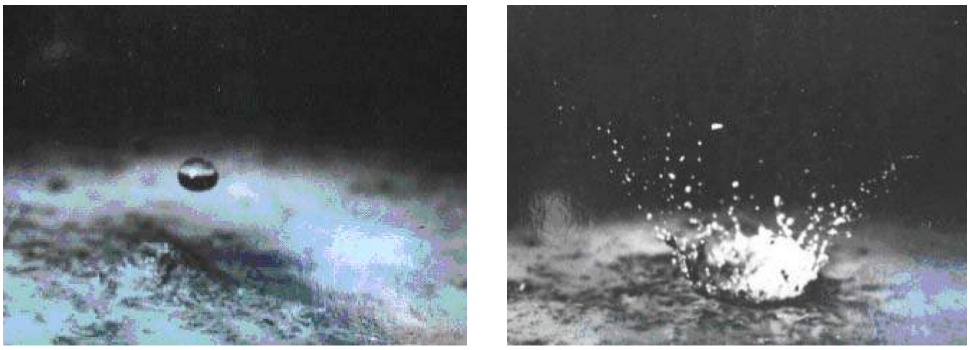
However, the adoption of effective measures of preventative and corrective control of this disordered erosion depends on a correct understanding of the processes related to the dynamics of hydraulic operation. The margins or riverbanks of the San Francisco River have no protection, which contributes to the erosive processes that occur by natural causes (e.g. by the action of rainfall, stream flow and even by the effect of waves).

**Erosive process caused by rainfall**

Erosive process related to rainfall has a global importance, especially in regions with a tropical climate such as the northeastern region of Brazil. More importantly, Brazil is a country where the pluviometric indices are much more elevated than in other regions of the planet. The disordered occupation of the margins of San Francisco River leading to deforestation, results in reduced vegetative coverage that allows rain water to directly impact the surface of the ground.

*The splash effect*

The physical action of a splash (Figures 2 and 3) or splashing (Guerra and Guerra 1997) is the initial phase of the erosive process caused by a drop of rainwater that contacts particles of soil. This generally leads to rupture of the aggregates allowing particles to be transported by the superficial flow. Moreover, the aggregates enter the pores of the surface of the soil generating a hampering effect and consequently decreasing porosity and increasing the surface flow of the water. In the same way, susceptibility to erosion depends on the relationship between the erosive capacity of the rainfall drops through its kinetic energy and the flows of the surface and sub surface.



**Figures 2 and 3.** Details of a drop of rain on the surface of soil causing the splash effect

*Kinetic energy of rain*

The kinetic energy of the rain determines the erosivity of the terrain, which is the ability of the rain to cause erosion. The determination of the erosive potential depends mostly of the erosivity parameters of the soil and also on the characteristics of the drops of the rain, which vary over time and space. The key parameters include the total precipitation, the intensity, moment and the kinetic energy of the rain. Moreover, an additional factor that can increase erosivity is aeolian action (i.e. if rain is driven by strong winds).

*Rupture of the aggregates*

The rupture of aggregates can be considered the initial stage of the erosive process of the soil. This rupture initiates on direct impact of raindrops with the ground. Aggregates are broken and can form very small particles that enter existing pores in the soil. This results in reduction of the porosity of the soil and the superficial flow increases. It has been verified through sounding and batimetries executed in September 2005, that the soil present in the margins of San Francisco River is silt-sandy, which is characteristic of soil in the semi-arid region of Brazil and which is susceptible to action of erosion. According to Wischmeier & Mannering (1969), soils with these characteristics, often used for agriculture and without the care of handling, are more susceptible to erosion when they loose organic matter. This factor affects directly rupture of the aggregates. Organic matter incorporated in the soil increases the cohesion between particles making the soil more stable, increases retention in the presence of water, makes it more porous thus decreasing the erosive potential, and guarantees the indispensable nutrition required for the growth of the vegetation.

*Crust formation and hampering of soils*

Due to rupture of the aggregates caused by the impact of drops of rain, a crust forms on the surface of the soil. This happens almost instantaneously generating hampering of the soil, complicating the infiltration of water and, as a consequence, increasing the superficial flow and the possibility of soil loss. According to Thornes (1980) infiltration occurs quicker in aggregates that are large and granulometricly stable, and this decreases the action of superficial flow. When aggregates are broken and the surface of the soil compacts, these crusts offer larger resistance to the action of splash, however the speed of the superficial flow increases and it can cause significant damage in the contacted areas of the ground. As soon as the infiltration indices are reduced, puddles form on the surface of the soil.

*Infiltration and puddle formation on the surface of the soil*

When raindrops have direct contact with the soil, they are stored in small furrows or directly in the soil. During a torrential rain event, the empty void spaces between particles are filled by water, which reduces the rates of infiltration compared to the original state of the soil. It can lead to the loss of apparent cohesion and after a certain time the soil cannot absorb any more water as it becomes saturated. All of these factors give rise to the last phase that precedes superficial flow, which is puddle formation on the surface of the soil.

*Superficial flow of water*

After the desegregation of the particles, the saturation of the soil and the consequent formation of puddles, superficial flow occurs. Water reaches a relatively fast trajectory and is able to transport soil particles by means of the hydraulics force of its flow. Depending on the force of this flow, two kinds of erosion are possible. Laminate flow is caused by intensity of the drops of rain resulting in progressive removal of the present soil surface and along linear flow channels. Erosion rates can be increased in slopes with high river bed gradient (above 34°) with disintegration of soil aggregates.

Figure 4 shows the entire trajectory that rainfall water runs through following its impact on the soil surface. It demonstrates the beginning of the process of ravine formation, which is caused by concentration of the superficial flow and hence erosion at a point. The total amount of erosion caused by the accumulation of the superficial and subsuperficial flow (groundwater) results in erosion over a larger area. This demands an effective solutions at low cost and this makes intervention works often impracticable.

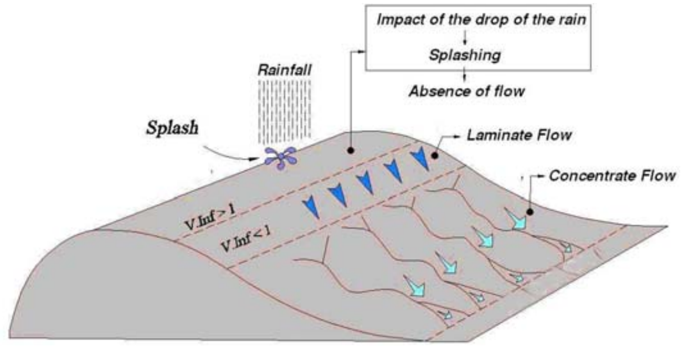



**Figure 4.** Mechanism of the erosion caused by action of the rainfall

**Erosive process caused by flow stream**

In spite of the fact that the San Francisco River does not have flow rates of water that cause great impact when in contact with its banks or margins, the flow stream is responsible for depriving the banks of vegetation cover. With the slope unprotected, the flow of water causes drag on soil particles and this can cause collapse of the silt-sandy soil that forms the margins of the river and this results in erosion.

**Erosive process causes by the effect of waves**

Besides the erosive processes previously cited, the margins of San Francisco River are subject to wave impact generated by wind action, and sometimes generated by local navigation activity (i.e. wash). The collision of waves in the margins of the river cause mass movement in a large quantity of big blocks, thus promoting bank destabilization. This effect is increased by the deforestation of ancillary woods on the river margins.

**PLAN OF SAN FRANCISCO RIVER REVITALIZATION**

The problems of San Francisco River in its margins (Figures 5 and 6) and riverbed were identified after several expeditions undertaken to understand the cultural factors in the area but primarily to gain understanding of environmental conditions and to investigate potential interventions. Also it had been noticed that the erosive process was not generalized along the whole fluvial course and is conditioned by the demographic density, along with the geotechnical and hydrographic characteristics in the locations studied.

**Figures 5 and 6.** Erosion in the margins of San Francisco River

In 1998, the Government of the State of Bahia made a formal contract with CESP – Companhia Energética de São Paulo, with the purpose of accomplishing interventions and the consequent revitalization in the margins of San Francisco River. The initial idea was to perform interventions similar to those used on the Paraná and Tietê Rivers. These are both located in the State of São Paulo and demonstrated multiple examples of stabilization works that were an enormous success in Brazil. In December 2001, a covenant between the Environment Department, National Agency of Waters, and the Government of the State of Bahia was signed with the aim of developing the Plan of San Francisco River Revitalization through conducting a field test. To execute this work, a contact was formed with FUNDESPA – Fundações de Pesquisas e Estudos Aquáticos.

This field tests (Figure 7), is located between the cities of Barra and Xique-Xique, in the State of Bahia, and has an extent of 12 km. The aim was to test at real scale some realistic applicable alternatives to the eroded margins. The objectives were to stabilize and revitalize the banks environmentally, using low cost options, little maintenance and where possible, using technologies and available resources in the location, and generating employment for the people who live in the region. These interventions are related to total revitalization of the fluvial flow and with the aim of increasing the depth of the San Francisco River thus guaranteeing continuous navigation of embarkation points, which are used to transport all the agricultural goods produced by the local habitants.

The measures tested for the protection of these margins included slope construction with low inclination (between 15 and 27 degrees) protected by geosynthetics materials, and including planted vegetation. Specific vegetation selection was controlled by the location in relation to the river level.


**Figure 7.** Location of the field tests.

## TECHNICAL CONSIDERATIONS

The process of superficial erosion that affects constantly the margins of the San Francisco River and contributes to formation of ravines and large amounts of erosions is made worse by the disordered occupation of the population who live in that area, devastating the local vegetation and consequently the ground that is totally unprotected against the impact of raindrops, stream flow and impact of waves. The Plan of Rio San Francisco River Revitalization focused on a search for solutions with low environmental impact with the objective of providing fast growth of vegetation.

**Importance of the vegetation**

Vegetation has been used as the prevention and control of erosion for centuries, beginning with the Chinese, Roman and Incas civilizations as the pioneers. Vegetation coverage and the presence of soils in slopes contribute to attenuation of erodibility rates and help to maintain humidity and facilitate infiltration of water in the terrain. It has several beneficial effects relating to geotechnical, ecological, economic and even aesthetic aspects; however each one has specific factors.

*Geotechnical*

- Protection of the margins against the erosion caused by impact of raindrops, stream flow, and waves;
- Increase the stability of the slope by the establishment of a soil-root matrix and by modifications in the humidity proportion;
- Protection against the action of wind and displacement of the soil;
- Enrichment of the organic material of the soil, decreasing its shear;
- Reduction of the speed of water flow.

*Ecological*

- It smoothes temperature and humidity changes of air close to the surface of the soil;
- Optimization of the hydraulic relationships in the soil-plant-atmosphere system;
- Reduction of extra-transpiration rates;
- Improves the quality of water;
- Create refuges for micro-faunas and insects.

*Economic*

- Reduction of construction and maintenance costs;

*Aesthetic*

- Harmonization and improvement of the landscape;
- Reduction of the visual impact with the increase of the green area.

**Geosynthetics used for prevention and control of superficial erosions**

Geosynthetics can be defined as polymeric industrialized products, whose properties can result in geotechnical improvements. They perform mostly functions of: reinforcement, filtration, drainage, protection, and separation, flow control (impermeable barriers) and superficial control (Vidal 2002).

Their utilization in this specific field of application has experienced a significant advance since the 1990s, providing adequate protection of soils even though the local factors (e.g. river bed gradient, geotechnical characteristics, pluviometric indices, use and occupation of the terrain, etc) produce adverse erosive processes. Basically, geosynthetics should act as retainers of the fines coming from the underlying soils or of the erodible material transported. In addition, they can reduce overland flow speeds and can help absorb the energy of the impact of raindrops. Currently, geosynthetic products and applications range from prevention to control of superficial erosion and have a wide range of applications with new solutions being developed constantly. It suggests clearly that any kind of solution with erosion prevention and control purposes constituted by synthetic materials should be installed on a stable geotechnical slope.

According to Theisen (1990) geosynthetics for erosion prevention and control are classified as temporary (TERMs, temporary erosion and vegetation materials) that are wholly or partly degradable elements and that have the function of preventing and controlling erosion of the protected location until the vegetable coverage can be established, and in addition, promoting the germination of seeds for the fast development of the vegetation. Theoretically, TERMs are subdivided in two groups: ECMNs (erosion control meshes and nets) constituted by geogrids or geonets, both constructed with biaxial orientation and ECBs (erosion control blankets) constituted by blankets of biodegradable vegetable fibers.

A second group of geosynthetics with the same function are denominated as permanent (PERMs, permanent erosion and re-vegetation materials) which are polymeric elements not-degradable with good tensile strength and that work not only as reinforcement of the root system of the vegetation, but also aid vegetative growth. PERMs are subdivided in two distinct categories: geosynthetics biotechnical-related, TRMs (turf reinforcement mats) which are blankets of three-dimensional matrix of polymeric fibers used for the reinforcement of the vegetation, which is already developed to resist the action of water flow, and the support system has a strength greater than the maximum required just to support the vegetation, in addition to helping it grow. Aligned to this concept are ECRMs (erosion control and re-vegetation mats) which are blankets with the same characteristics as the aforesaid material, however with soil added to accelerate the development of the vegetation. The second PERMs category include biologically active materials supported in geocell systems, concrete block systems, wood, stone riprap or gabions. Table 1 provides a summary of the classification.

**Table 1.** Geosynthetic erosion control material (after Theisen 1990)

| TERMs | PERMs | |
|---|---|---|
| | **Biotechnical-related** | **Hard armor-related** |
| Erosion control meshes and nets (ECMNs) | Erosion control re-vegetation mats (ECRMs) | Geocell |
| | | Concrete block system |
| Erosion control blankets (ECBs) | Turf reinforcement mats (TRMs) | Wood |
| | | Stone riprap |
| | | Gabions |

**GEOCOMPOSITE PROTECTION**

During the Plan of San Francisco River Revitalization study many solutions have been proposed to cure definitively the erosive problems in the margins of the river, however, due to the factors imposed by the sites, not all of them could be installed.

Geocomposite protection examples are outlined in this paper (Figures 8 and 9). These geomats are manufactured with an open three dimensional synthetic mat consisting of randomly placed filaments of polypropylene welded in all of their points of contact and incorporated in a double twisted hexagonal metal mesh with a plastic coating that inhibits its corrosion when in contact with water. Aligned to the TRM concept, this geomat minimises direct contact of raindrop splash with the surface creating an optimal environment for the growth of vegetation. The roots of the vegetation, which anchor the geosynthetic material on the slope, and the wire mesh, increase the resistance of the soil against small displacements. Besides these characteristics, these geomats also have a function to reduce the speed of fluvial flow and hence they reduce erosion risks at river margins. Each component of this geomat has a specific function and the composite behaviour is enhanced.


**Figures 8 and 9.** Details of the geomat applied in the San Francisco River

The San Francisco River Basin does not experience high water flow rates. According to the statistics of the Government of the State of Bahia, its average flow is approximately 2700 m³/s, and it has an average speed between 2.7 and 3.5 m/s. In reference to Figure 10 these are low enough for installation of the TRM geocomposite protection, which after vegetation, tolerates admissible speed up to 4.50 m/s.

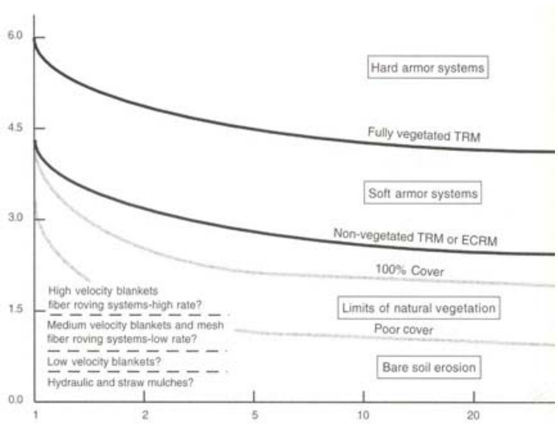



**Figure 10.** Admissible speeds of the geomat

**Installation of geosynthetic material at the field test sites**

Before beginning the field tests, significant care was taken regarding selection of the kind of vegetation that would be developed at the sites. As a result, native vivariums have been installed strategically in sites with easy access to aid work on ancillary reforestation of the margins of the San Francisco River.

Due to the previous erosion in the margins of the river, initially it was planned for preparation of the slopes with mechanical equipment to an inclination of 27 degrees with the purpose of forming an uniform surface. The second stage consisted of forming a trench 1.00m below the top of the slope with dimensions of 0.50m x 0.50m to anchor the geomat and to allow for local drainage, thus preventing rainwater from infiltrating beneath the geomat leading to formation of ravines below the protection.

Steel pegs in the form of an 'L' were used to pin the geomat. The geocomposite protection was first anchored at the trench and then opened and unrolled (Figure 11). The geomat was installed along the slope using a standard peg configuration with an average distribution of four pegs per square meter. This is a function of the slope inclination. The objective of the anchorage of the material on the slope is to guarantee adhesion of the blanket to the surface, and hence preventing removal of soil material through the superficial flow. In addition, to avoid open points in the geocomposite, an overlapping joining seam was made with an overlap of 0.15 m in both longitudinal and transverse directions (i.e. the upstream revetment superimposed the downstream revetment in response to the river flow direction). The geomat was hand sown with a variety of seeds prepared with native plant seeds and fertilizers.

**Figure 11.** Geomat being unrolled on the slope

**Figure 12.** Geocomposite protection installed on the slope

Tactically the field tests was planned for execution during the driest period of the San Francisco River Basin (between June and October 2007), so that the geocomposite protection could be totally installed (Figure 12) on dry soil. Sprinklers were used to irrigate the slope. The result was exceptional and vegetation has been developed in just two months (Figures 13 and 14). In addition to the vegetation that developed normally, the plants extracted from the natural vivarium seeds that had been planted along the geocomposite revetment in the openings of the double twisted hexagonal mesh, also showed excellent results.

**Figures 13 and 14.** Vegetation developed in two months

## CONCLUSIONS

Execution of the initial part of the field tests of the Plan of San Francisco River Revitalization has been a success. It has enabled observation of several methodologies used in the margins of this important Brazilian river. The example presented in this paper is for the use of geocomposite protection and this demonstrated the best results of those evaluated. The study reported is only the first of several that are to be performed on Brazilian rivers that currently do not have environmental protection and require repair. There is a continuing search for a low cost solution, with consideration of productivity rates that can generated, and most importantly for a solution that provides employment for the low income population.

## ACKNOWLEDGEMENTS

The authors wish to express their sincerest acknowledgements to Maccaferri do Brasil, Ms. Karen Henriques Giamboni, Mrs. Sandra Spadaccia Chiari, Mr. Natalino Chiari, Eng. Petrucio Jose dos Santos Junior, and Eng. Jaime da Silva Duran, without their assistance this paper would not be possible.

**Corresponding author:** Mr Victor Gustavo Chiari, Maccaferri do Brasil Ltda, Dom Gabriel Paulino Bueno Couto Highway, km 66, Jundiaí, São Paulo, 13201-970, Brazil. Tel: +55 11 4589-3258. Email: victor@maccaferri.com.br.

## REFERENCES

Brighetti, G., Martins, J.R.S. & Bernardino, J.C.M. 2002. Coating of water channels and courses (Revestimentos de canais e cursos d´água). Maccaferri, Jundiaí, Brazil.

Guerra, A.T. & Guerra, A.J.T. 1997. New geological-geomorfologich dictionary (Novo dicionário geológico-geomorfológico). Bertrand Brasil, Rio de Janeiro, Brazil.

Guerra, A.J.T., Silva, A.S. & Botelho, R.G.M. 1999. Erosion and preservation of the soils: Concepts, themes and applications (Erosão e conservação dos solos: Conceitos, temas e aplicações). Bertrand Brasil, Rio de Janeiro, Brazil.

Koerner, R.M. 1998. Designing with geosynthetics, 4th edition. Prentice Hall, New Jersey, USA.

Pereira, A.R. 2006. Determination of the soil loss (Determinação da perda de solo). Deflor Bioengenharia, Belo Horizonte, Brazil.

Theisen, M.S. & Carroll, R.G.,Jr., 1990. Turf reinforcement – The soft armor alternative, Proc. 21st Conf. Prof. Instl. Erosion Control Assoc., Steamboat Springs, CO, 255-270.

Thornes, J.B. 1980. Erosional process of running water and their spatial and temporal controls: a theorical view point. In:Soil erosion. M.J. Kirkby and R.P.C Morgan (Eds.), 129-182.

Vertematti, J.C. 2004. Geosynthetics Brazilian Manual (Manual brasileiro de geossintéticos). Edgard Blucher, Brazil.

Vidal, D.M. 2002. Application in pavements (Aplicação em pavimentos). Aeronautich Technological Institute, São José dos Campos, Brazil.

Wischmeier, W.H. & Mannering, J.V. 1969. Relation of soil properties to its erodibility. Proceedings of Soil Science Society of America, 33, 133-137.