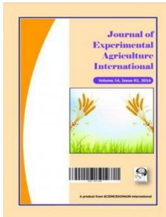

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Magnitude and Spatiotemporal Variation of the Erosion on the Slope of the Lower São Francisco River, Northeastern Brazil

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Authors' contributions

This work was carried out in collaboration between all authors. Author IPR designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors FSRH and MMR managed the analyses of the study. Authors JBL and RNAF managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Streams are under erosive processes such as hydrodynamic adjustment. After the construction of a sequence of hydroelectric dams for power generation, the São Francisco River experienced an increase in erosion processes, mainly on the riverbank of its lower course. The objective of this work was to quantify the magnitude and spatial and temporal variation of the erosive process. For

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this purpose, the erosion pins method was used on a vertical slope composed of Entisol, which was monitored monthly during the year 2013, alongside the acquisition of hydrological and meteorological data. The total soil loss was 35.26 m³, while the monthly magnitude of soil loss ranged from 0.00 to 24,300 mm yr^{-1}, totaling 475,396.1 mm yr^{-1}. The hydrodynamic and geometric characteristics of the watercourse, such as discharge and the proximity of the riverbank from the thalweg, are cited as the main causes of this erosion process.

Keywords: Mass failure; flow; soil loss.

1. INTRODUCTION

The dynamics of a watercourse depend on several variables, in particular, the interaction between physical, meteorological, and edaphic factors and the vegetation, and are also associated with previous anthropic interventions, such as the construction of dams on its canals, which changes the natural conditions [1,2,3,4].

Changes in fluvial dynamics accentuate the erosive processes in the riverbed and margins of the fluvial canal [5]. The mass movements that have occurred in the marginal slopes of the lower São Francisco have an important role in the evolution of the erosive process, and have socio-economic implications resulting from the loss of productive areas.

The river naturally presents a geomorphologic dynamic that seeks to achieve equilibrium between erosion and deposition. The suppression of riparian vegetation associated with the regulation of river flow has been gradually causing the destabilization of the marginal slopes and triggering erosion, because the slopes are composed of soil with very low cohesion. Constant wave action removes material from the base of the slope (undermining the base), leaving it unstable, and with no support [6].

The use of the São Francisco waters for the generation of electrical energy through hydroelectric projects has affected its fluvial dynamics and triggered several socio-environmental problems, mainly by the regulation of flow. The most serious consequences have appeared in the lower course of the river, in the region that separates the states of Sergipe and Alagoas, affecting above all the agro-ecosystems on its margins [4,7].

This region, declared by the environmental agency Conservation International as one of the 25 world hotspots with high conservation priority because of its ecological importance [8], has the suppression of riparian vegetation as one of its main environmental problems.

The exposure of those deforested slopes, composed of soil with very low cohesion, associated with local meteorological conditions and the hydrological variables of the watercourse, has resulted in great loss of soil mass as a consequence of the erosive processes acting on the slope margins [9,7].

Although it is a natural phenomenon of fluvial canal adjustment, the marginal erosion is accentuated by both anthropic activities and the hydrological characteristics of the canal itself. The operation of dams that regulate the river flow stands out among the anthropic activities [2,10,3].

Regulation of the São Francisco flow causes the water body to maintain the same level for long periods, causing waves to break always at the same location, where the force exerted by the current on the margins has an aggravated effect on the level of the riverbank and promotes the removal of soil particles [11,4]. The hydrological characteristics that most directly affect the stability level of the margins, the progression rate, and the duration of the marginal erosion are the flow dynamics in the proximity of the slope, the canal geometry, the waves caused by the wind, and climatic and biological factors [12].

The main factors that affect the processes of erosion, transport, and sedimentation in a river are: current speed; the physical characteristics of the sediments, specifically their size, density, and shape; topography changes or obstacles in the riverbank; river flow variations, which in turn are directly related to climatic variations [13].

The aim of this work is to quantify the magnitude and spatiotemporal variation of erosion rates on the right margin of the lower São Francisco River and to understand the main causes and controls of this variation.

2. MATERIALS AND METHODS

2.1 Description of Study Area

The experimental site consists of a soil classified as Fluvisol, according to the Brazilian System of Soil Classification [14], and is located on the right margin of the São Francisco river River (UTM coordinates N= 8.868.789,506 and E = 736.583,864), in the municipality of Amparo de São Francisco, Sergipe. The climate of the region is warm and semi-humid, with an annual average temperature of 25°C, a rainy season that occurs in winter, between March and September, and precipitation ranging from 800 to 1.300 mm.

The marginal slope has a width of approximately 80 m, with a 27° inclination, resulting from the setup of experiments in natural engineering carried out in 2010, when vetiver (*Chrysopogon zizanioides* (L.) Robert) seedlings were planted. When these experiments were set up, the slope was vertical and had no protection because of the erosion process.

2.2 Collection of Soil Loss Data

For the quantification of soil loss on the face of the slope, we used the method of erosion pins [15], which consists of periodic measurements of the exposure of metallic pins inserted into the face of a slope. Although it is simple, it has been widely used because it is a reliable and low-cost method to measure this variable in vertical slopes [16,13,17].

Before insertion in the slope, the pins were painted with a layer of red lead paint for protection against corrosion, and two layers of paint with a color similar to the color of the soil, to mask them in the margin and protect them from vandalism. At the extremity of each pin, we attached an aluminum identification tag.

In total, 99 steel pins of 1.0 m length × 0.006 m diameter were installed, distributed in 24 horizontal lines, equally separated by 3.0 m horizontally and 0.5 m vertically, forming a regular 3.0 × 0.5 m matrix.

Monthly measurements were taken between January 2013 and January 2014, for a total of 13 time-points. When a pin was lost because of soil loss or any other reason, the lost pin was replaced, and its entire length registered as soil loss [17].

The erosion magnitude was calculated after each measurement according to Eq. 1:

$$EM = \frac{L_1 - L_0}{t} \quad (1)$$

where:

EM- erosion magnitude (mm year^{-1})

L_1- length of the exposed part of the pin at the time of measurement (mm)

L_0 - length of the exposed part of the folded pin after the measurement (mm)

t- time between each measurement (year)

The volume of lost soil was determined by multiplying the length of the exposed pin by its representative area: 1.5 m^2 (3.0 × 0.5 m).

2.3 Collection of Precipitation Data

The time series of precipitation data were obtained from the conventional pluviometric station of Propriá (coordinates UTM 8,869,978.450 N and 738,388.286 E, Datum SAD69, Zone 24S), managed by the National Waters Agency (NWA) and operated by the Company of Research on Mineral Resources (CRMR), between January and December 2013; the daily information was used to plot a histogram of cumulative monthly precipitation, which was compared to the climatologic normal (1961–1991) for the season [18].

In order to verify the influence of precipitation on the marginal erosive processes in the experiment area, the precipitation data were analyzed against the retraction rates of the margin.

2.4 Collection of Data on Quota, Flow, Flow Speed, and Area of the Wet Section

The historic series containing data on flow and quota were obtained from the conventional pluviometric station of Propriá (coordinates UTM 8.869.978,450 N and 738.388,286 E, Datum SAD69, Zone 24S), managed by NWA and operated by the CRMR, referenced to the year of 2013; the quota data was tied to RN IBGE 2541U, located on the right shoulder of the bridge that connects the municipalities of Propriá, in the State of Sergipe, to Porto Real do Colégio, in the State of Alagoas, approximately 15 km downstream of the experimental site.

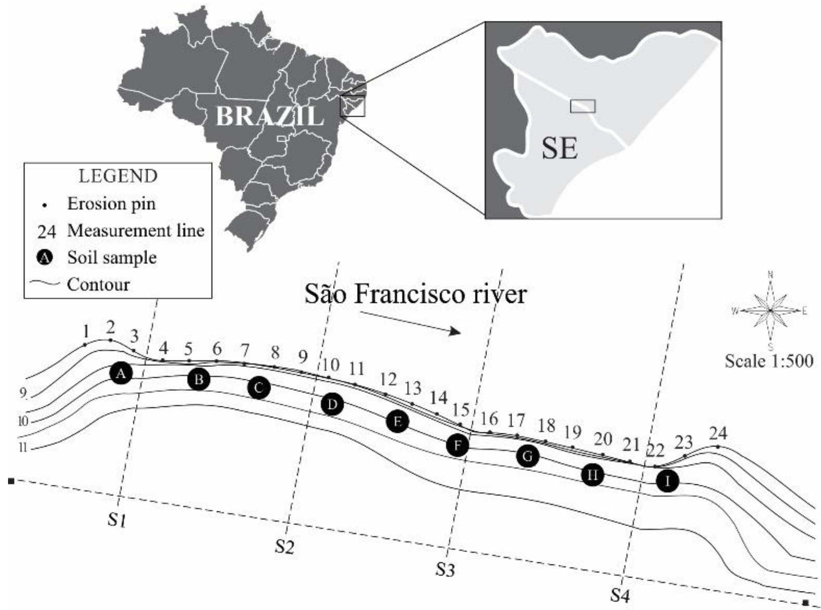


Fig. 1. Positions of the transversal sections, pin setup lines, and soil sample points

The average flow speeds were obtained using Eq. 2:

$$\overline{V} = Q/A \qquad (2)$$

where:

$\overline{V}$– average flow speed (ms^{-1})
Q – measured flow ($m^3\ s^{-1}$)
A – area of the measured section (m^2).

The area of the wet section became known after a bathymetric assessment between the right margin and a fluvial island in front of the experiment site. Using a baseline on the river margin, four sections transverse to the main riverbank and equally spaced 18 m apart were determined (Fig. 1).

3. RESULTS AND DISCUSSION

The erosion process, characterized by the disaggregation and transport of soil particles, was dominant in the accretion process of the margin, characterized by the deposition of sediments, in 99% of the measurements. This demonstrates that, in the evaluated period, this part of the river experienced intense margin excavation activity.

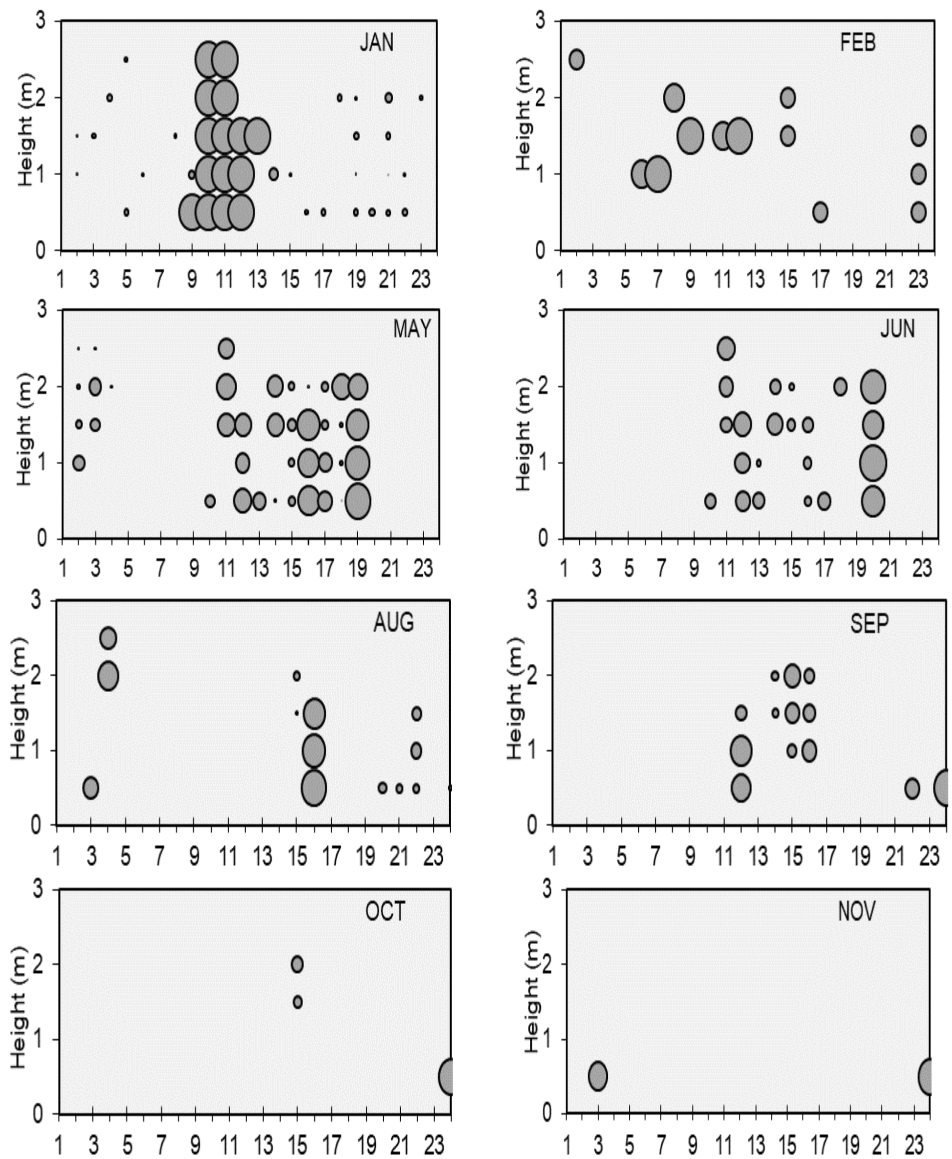
Of the 99 pins placed on the slope, 74 reflected erosion in some of the measurements carried out during the evaluation period. At the end of the analysis period, a total volume of 35.26 m³ of soil had been eroded (Table 1). Although this is a significant value for the length of the marginal stretch, it is low compared to the values observed by [6] when investigating the erosive process a few kilometers away from the experiment site.

The transverse section, S2 (Table 2), showed the most significant loss, with a total of 23.74 m³ (67% of the total) of eroded soil, while sections S3 and S4 showed 6.38 and 4.09 m³ of eroded soil, 18 and 12% of the total soil loss, respectively; S1 had the lowest volume of eroded soil, 1.05 m³, which was only 3% of the total soil loss.

In terms of magnitude, which expresses the intensity of the phenomenon, the monthly soil loss varied between 0.00 and 24.300 mm year^{-1}, totaling 475.396,07 mm year^{-1}, with the highest values observed in sections S2 and S3 in the month of January, while the months of March, April, July, and December did not show any soil loss. Such spatial variability of the erosive process, even in a short margin stretch such as the one analyzed, can be explained by the high level of variability in the resistance parameters because of the expected stratification of the margins in cohesive layers in the monitored sections (Table 2), which is a characteristic of Neossolo Fluvico. Similar behaviour was observed by [12] and [19], where the spatial variation of the soil loss was attributed to the soil granulometry.

The erosive process occurred mainly in the middle third and in the base of the slope, because of falling soil blocks and in the form of undermining, which constitutes the removal of soil particles by an erosive agent, which in this case was water. This result indicates that the chief erosive agent of this stretch of the river is located in the quotas closest to the water level. Moreover, monthly measurements enabled us to observe that the erosive process had a spatial and temporal variability (Fig. 2).

The highest values of sand fraction occurred in sections S2 and S3, where the soil loss was more significant. This result can be clearly explained by the weak soil aggregation attributed to this granulometric component. This material, geotechnically weak, has high values of internal particle friction angles, resulting in a large number of empty spaces in the soil, which confers to the sand layers a lower resistance to the erosive processes. Similar behaviour was observed by [20], who found the rupture speed in sandy soils to be between three and ten times higher than that of soils with high contents of silt and clay when submitted to conditions similar to those of the present study.



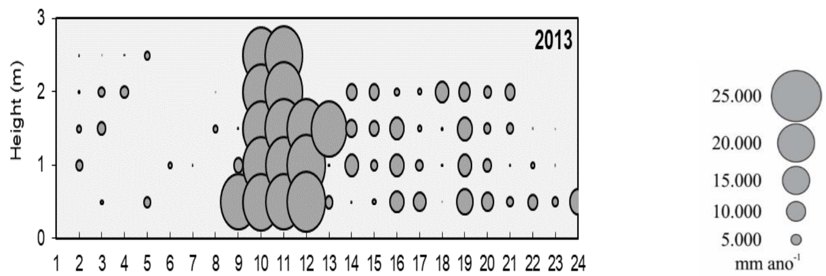


Fig. 2. The magnitude of the erosive process along the 24 measurement lines during the evaluation period

Table 1. The volume of eroded soil (m³) from the 24 measurement lines at the experiment site in 2013

Section	Pin line	Volume of lost soil (m³)	Volume of lost soil per section (m³)*
S1	1	0.00	1.05 (3%)
	2	0.19	
	3	0.38	
	4	0.33	
	5	0.12	
	6	0.03	
S2	7	0.00	23.74 (67%)
	8	0.04	
	9	1.62	
	10	7.64	
	11	8.48	
	12	5.96	
S3	13	1.74	6.38 (18%)
	14	0.91	
	15	0.73	
	16	1.97	
	17	0.58	
	18	0.46	
S4	19	1.70	4.09 (12%)
	20	1.08	
	21	0.30	
	22	0.32	
	23	0.06	
	24	0.62	
Total			35.26 (100%)

** Values in parentheses represent the overall percentage of lost soil*

[21] stated that the material that composes the margins of the Brahmaputra River in India is highly susceptible to erosion because of its high humidity level, low contents of silt and clay, and a poorly graduated sand fraction.

The erosion rates of the experimental site appear not to be correlated with the precipitation in the region since more than 83% of the soil losses did not occur during the rainy season (Fig. 3). [22], as well as [4], concluded that precipitation in this region is of low intensity, and when associated with soils that have good drainage capacity, hampers the occurrence of laminar erosion.

The geometry of the riverbank changed along the experimental site, indicating intense geomorphological activity along this stretch of the river, which in turn explains the different distances between the right margin of the river and the thalweg in each section.

Table 2. Soil granulometry in sections 0 - 20, 20 - 40, and 40 - 60 cm

Soil granulometry		Section								
		S1		S2			S3		S4	
Collection point		A	B	C	D	E	F	G	H	I
					0 - 20 cm					
Granulometric fractions (g kg^{-1})	Sand	436	947	478	746	860	584	588	532	475
	Clay	286	2	215	26	84	142	166	189	205
	Silt	278	51	307	228	56	274	246	279	320
					20 - 40 cm					
	Sand	368	883	926	904	582	558	458	529	476
	Clay	325	24	18	49	154	180	231	225	236
	Silt	307	93	56	47	264	262	311	246	288
					40 - 60 cm					
	Sand	423	955	475	889	649	616	547	351	515
	Clay	304	1	248	50	126	226	262	314	228
	Silt	273	44	277	61	225	158	191	335	257

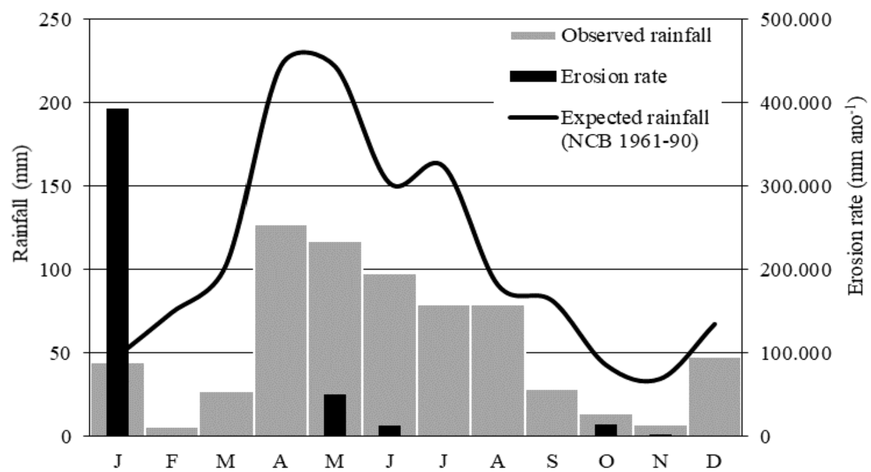


Fig 3. Histogram of monthly precipitation in 2013, expected rainfall at the conventional pluviometric station of Propriá [18], and cumulative monthly erosion rate in 2013 at the experiment site

It is possible that the irregularity of the riverbank was caused by both the turbulence of submerged flow, resulting in the friction between the liquid portion and the riverbank sediments, and the variation in the speeds of the submerged flow close to the margin in the different sections, consistent with the findings of [23], as well as [24].

Greater riverbank depth (10.7 m) was observed in section S3, which presented the highest granulometric irregularity. The smallest distance between the thalweg and the right margin was found in section S2 (Fig. 4), where it contributed to the highest soil loss rate in this section. This occurred because it is the deepest area of the riverbank, where the nucleus with the most top flow speed and turbulence confers a higher supply of kinetic energy to the margin soil. In physical terms, this energy is the main component of the destabilisation process on the marginal slopes.

The flow oscillated during the evaluation period, with peaks in January, April, and August of 2013 (Fig. 5).

The operation governs the fluvial discharges along the regulated stretch of the São Francisco River at the dams constructed for energy generation [4]. This anthropic factor, although beyond the scope of the present work, must be taken into account, since it directly affects river flow, and consequently, flow speed.

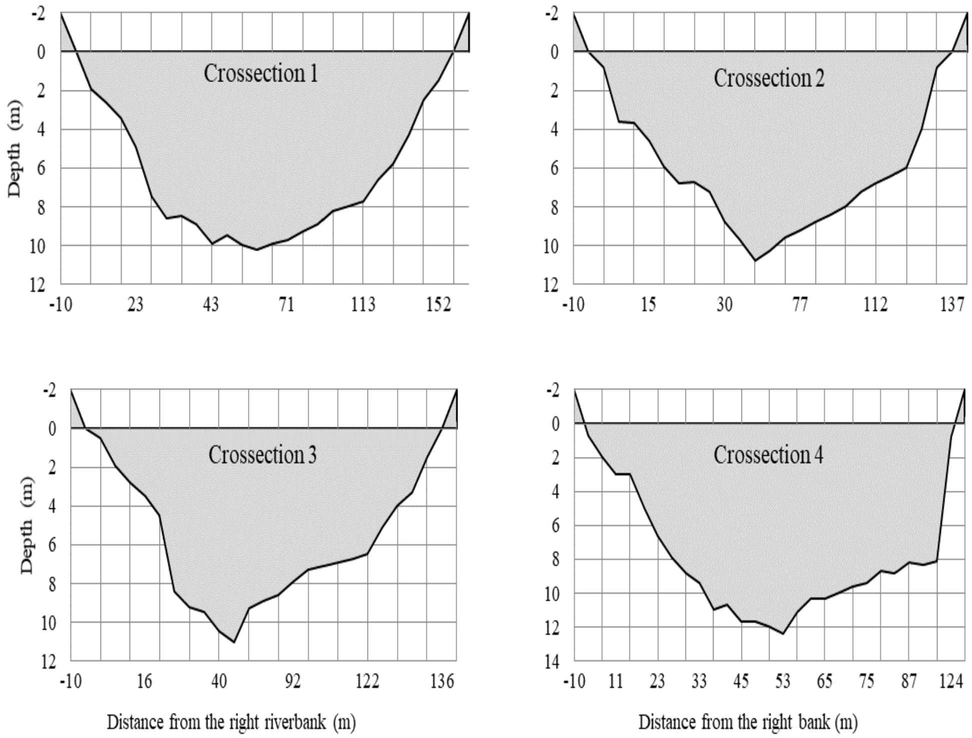


Fig. 4. Transverse profiles of the experimental site in the four bathymetric sections

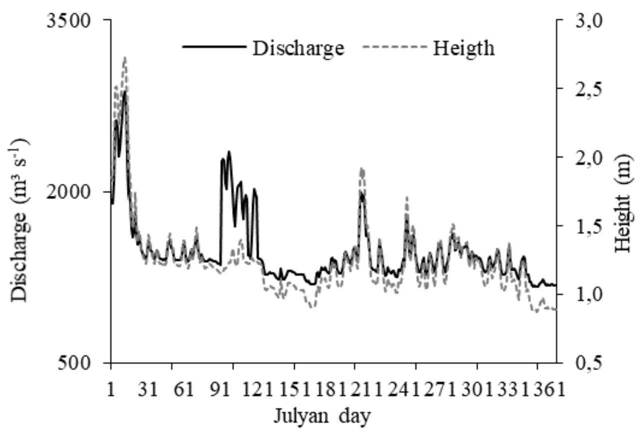


Fig. 5. Values of flow and quota observed at the experiment site

The flow increase reflects the increase in flow speed, a factor that explains the higher erosion rates during the flooding periods when the flow is higher than in other periods.

In the same way, the low river quota oscillation in February, March, April, May, June, October, November, and December, when the value varied between 1.0 and 1.5 m, may have contributed to the destabilisation of the marginal slope. [6] attributed the margin retraction at certain stretches of the river to the permanence of the water flow with a constant speed, with a minimal quota variation, for an extended period.

From the point of view that geotechnical properties determine the failure mechanism of the slope and that the deposition and erosion processes of the margins are controlled by fluvial

Table 3. Geometric and hydrological parameters in the study area

Section	Wet area (m)	Damp perimeter (m)	The distance between the right margin and the thalweg (m)	Maximum flow speed (ms^{-1})	Minimum flow speed (ms^{-1})
S1	107.91	158.03	60.0	26.6	11.0
S2	97.22	134.04	42.0	29.6	12.2
S3	98.96	137.80	63.0	29.0	12.0
S4	99.41	130.09	53.0	28.9	11.9

processes [2,3,11], that is, geomorphological aspects, we can confirm the relevance of the hydrodynamic and geometric characteristics of the canal to the magnitude of the erosive process.

The geometric parameters such as wet area, wet perimeter, and hydraulic radius had little variation among the sections, with S2 having the lowest values of the damp area and damp border.

Considering that the volume of water that passed through each section was equivalent, section S2 consequently presented the highest values of maximum and minimum flow speed (Table 3), reflecting a higher concentration of kinetic energy in contact with the soil particles both in the margin and in the riverbank, and increasing their chance of removal. Moreover, the fact that the distance between the right margin and the thalweg was smaller in section S2 allowed this kinetic energy to act closer to the margin in this section than in other parts.

Associating the rates of soil loss in section S2 with the geometric and hydrological parameters, especially the maximum flow speed, we observed that this section presented the highest flow speed, an obvious consequence of the smaller area of its wet part.

It is possible to deduce that the high flow speed observed in January 2013, when a higher flow occurred, increased the flow turbulence in the proximity of the right margin, especially in section S2.

It is worthwhile mentioning that the flow speed can be considered a primordial factor for the evolution of the erosion rates in the months that had flow peaks, since in general, its increase occurred proportionally to the volume of eroded soil, mainly when the slope consisted of predominantly sandy material, similar to the findings of [25].

The results found by [26] suggest that the values of marginal erosion rate are higher in canals of rivers where the flow speeds are higher, which in the present work occurred closer to the right margin than to the fluvial island. Therefore, we suppose that the rates observed in section S2 are also related to an increase in the erosion capacity of the riverbank.

It appears that the most plausible hypothesis to explain the magnitude and variation of the erosive process in this experiment site is the relationship between the flow speed and the weak engineering properties of the material that composes the margin.

4. CONCLUSIONS

The observed magnitude of soil loss was considered small compared to results from other studies carried out in the same area. The erosive process varied both spatially and temporally and developed in the lower and middle thirds of the slope, in the form of wind erosion on the base of soil blocks. The hydrodynamic and geometric characteristics of the canal were relevant to the erosive process, with the proximity to the thalweg being the leading cause of soil loss in section S2. The highest erosion rates were associated with months that had the highest flow values.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Zhai H, Cui B, Hu B, Zhang K. Prediction of river ecological integrity after cascade hydropower dam construction on the mainstream of rivers in Longitudinal Range-Gorge Region (LRGR), China. Ecological Engineering. 2010;36:361-372.

2. Dang TH, Coynel A, Orange D, Blanc G, Etcheber H, Le LA. Long-term monitoring (1960-2008) of the river-sediment transport in the Red River Watershed (Vietnam): temporal variability and dam-reservoir impact. The Science of the Total Environment. 2010;408:4654-64.
3. Egger G, Politti E, Woo H, Cho K, Park M, Cho H, Benjankar R, Lee N, Lee H. Dynamic vegetation model as a tool for ecological impact assessments of dam operation. Journal of Hydro-Environment Research. 2012;6:151-161.
4. Rocha IP, Holanda FSR, Araújo Filho RN, Casado APB, Bandeira AA. Meteorological and hydrological variables on occurrence of riverbank erosion along lower São Francisco river. Revista Brasileira de Engenharia Agrícola e Ambiental. 2013;17: 137-144.
5. Rosgen DL. A classification of natural rivers. Catena. 1994;22:169-199.
6. Holanda FSR, Santos CM, Casado APB, Bandeira AA, Oliveira VA, Fontes LCS, Rocha IP, Araújo-Filho RN, Góis SS, Vieira TRS. Análise multitemporal e caracterização dos processes erosive no Baixo São Francisco Sergipano. Revista Brasileira de Geomorfologia. 2007;8:85-94.
7. Holanda FSR, Ismerim SS, Rocha IP, Jesus AS, Araújo-Filho RN, Mello-Júnior AV. Environmental Perception of the São Francisco Riverine Population in Regards to Flood Impact. Human Ecology. 2009; 28:37-46.
8. Myers N, Mittermeier RA, Mittermeier CG, Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. Nature. 2000;403:853-858.
9. Holanda FSR, Santos LGC, Santos CM, Casado APB, Pedrotti A, Ribeiro GT. Riparian vegetation affected by bank erosion in the lower São Francisco river, Northeastern Brazil. Revista Árvore. 2005; 29:327-336.
10. Yao Z, TaW, Jia X, Xiao J. Bank erosion and accretion along the Ningxia–Inner Mongolia reaches of the Yellow River from 1958 to 2008. Geomorphology. 2011;127: 99-106.
11. Casado APB, Holanda FSR, Araujo Filho FAG, Yaguiu P. Bank erosion evolution in São Francisco River. Revista Brasileira de Ciência do Solo. 2002;26:231-239.
12. Henshaw A J, Thorne CR, Clifford NJ. Identifying causes and controls of river bank erosion in a British upland catchment. Catena. 2012;100:107-119.
13. Christofoletti A. Geomorfologia fluvial. 2. ed. São Paulo: Edgard Blücher. 1981;312.
14. EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária. Sistema brasileiro de classificação de solos. 3. ed. Rio de Janeiro: Centro Nacional de Pesquisa de Solos. 2013;353.
15. Wolman MG. Factors influencing erosion of a cohesive river bank. American Journal Science. 1959;257:204-216.
16. Lawler DM. The measurement of river bank erosion and lateral channel change: A review. Earth Surface Processes and Landforms. 1993;18:777-821.
17. Bąk L, Michalik A, Tekielak T. The relationship between bank erosion, local aggradation and sediment transport in a small Carpathian stream. Geomorphology. 2013;191:51-63.
18. INMET - Instituto Nacional de Meteorologia. Normais Climatológicas do Brasil 1961-1990. Brasília: INMET; 2009.
19. Grove JR, Croke J, Thompson C. Quantifying different riverbank erosion processes during an extreme flood event. Earth Surface Processes and Landforms. 2013;38:1393-1406.
20. Fox GA, Felice RG. Bank undercutting and tension failure by groundwater seepage: predicting failure mechanisms. Earth Surface Processes and Landforms. 2014; 39:758-765.
21. Arvind P, Rajib G, Deva B, Ananta, N, Chandan M. River bank erosion and restoration in the Brahmaputra River in India. The Clarion. 2012;1:2277-1697.
22. Fox GA, Wilson GV. The Role of Subsurface Flow in Hillslope and Stream Bank Erosion: A Review. Soil Science Society of America Journal. 2010;74:717-733.
23. Michalková M, Piégay H, Kondolf GM, Greco SE. Lateral erosion of the Sacramento River, California (1942-1999), and responses of channel and floodplain lake to human influences. Earth Surface Processes and Landforms. 2011;36:257-272.
24. Engel FL, Rhoads BL. Interaction among mean flow, turbulence, bed morphology, bank failures and channel planform in an evolving compound meander loop. Geomorphology. 2012;163-164:70-83.

25. Luppi L, Rinaldi M, Teruggi LB, Darby SE, Nardi L. Monitoring and numerical modelling of riverbank erosion processes: a case study along the Cecina River (central Italy). Earth Surface Processes and Landforms. 2009;34:530-546.

26. Biron PM, Robson C, Lapointe M F, Gaskin SJ. Comparing different methods of bed shear stress estimates in simple and complex flow fields. Earth Surface Processes and Landforms. 2004;29:1403-1415.

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