Chapter 2

Bedload and Suspended Sediment of a Watershed Impacted by Dams

Jose Ramon B. Cantalice, Wagner Luis da Silva Souza,
Yuri Jacques Agra Bezerra Silva, Sergio M.S. Guerra, Alex Mauricio Araújo,
Douglas Monteiro Cavalcante and
Cinthia Maria Cordeiro Atanazio Cruz Silva

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61478

Abstract

Sediment transport relates to suspended sediment and bedload. The suspended sediment plays the most important role on the land-ocen sediment flux. On the other hand, the bedload should be considered in order to assess the impacts of dams on sediment transport and sediment yield. Recent effects of dam construction have been widely reported. The sediment load has been reduced by more than 75% for major rives, such as Nilo, Orange, Volta, Indus, Ebro, Kizil Irmark, Colorado, and Rio Grande and more than 40% of its lux is trapped within large dams. In addition, the multiple trapping through sequential dams has impacted the sediment transfer from terrestrial to coastal zone, triggering the coastal erosion. In terms of sediment retention and transport, China stands out the most impacted country by dams, followed by United States, and continents such as Europe, Africa, and South America. Based on the foregoing, the impact of dams on sediment transport and yield of an important Brazilian watershed with multiple dams will be the focus of this chapter. Thus, a three years field sampling (2009-2011) was carried out to measure the sediment yield of Capibaribe Watershed, and also its contribution to coastal erosion. The ratio between QB and SSQ ranged from 0.12% to 27.3% with 76% of all values lower than 5%. Usually, the bedload transport rate of a river is about 5–25% of the suspended sediment transport. This ranging sheds light on the lack of bedload reaching the coastal zone and it is likely one of the reasons to yield coastal erosion. The low rates can be attributed to the presence of dams which have been admitted to have a strong effect on sediment transport. The sediment yield was equal to 3.69, 4.36, and 6.7 t km-2 ano-1 in 2009, 2010, and 2011, respectively. In comparison with bedload yield, the suspended sediment yield was higher than 95% for all studied years. Therefore, the limited bedload supply – mainly responsible for construction of coastal landform – is likely contributing to the coastal erosion along part of the northeast region, Brazil. The multiple dams along the Capibaribe River watershed produce a deficit in sediment flux to coastal zone of Pernambuco State, Brazil, which relies on the low ratios between bedload and suspended sediment. As a result, it generates energy to coastal erosion of the Brazilian northeast.

Keywords: Capibaribe River, sediment yield, coastal processes

1. Introduction

Sediment transport relates to suspended sediment and bedload. The suspended sediment plays the most important role on the land–ocean sediment flux [1]. On the other hand, the bedload should be considered in order to assess the impacts of dams on sediment transport and sediment yield. Recent effects of dam construction have been reported by [1] and [2]. Based on data shown by [2], the sediment load was reduced by more than 75% for major rivers, such as Nilo, Orange, Volta, Indus, Ebro, Kizil Irmark, Colorado, and Rio Grande. The same author observed that more than 40% of sediment flux is trapped within large dams. In addition, the multiple trapping through sequential dams has impacted the sediment transfer from terrestrial to coastal zones [3].

According to [4], there is a correlation between dam construction and sediment supply (mainly sands) to coastal zone, triggering coastal erosion. In terms of sediment retention and transport, China stands out as the most impacted country by dams, followed by United States, and continents such as Europe, Africa, and South America. Based on the foregoing, a three-year field sampling (2009–2011) was carried out to measure the sediment yield of an important Brazilian watershed with multiple dams, and thus its contribution to coastal erosion.

Deforestation, uncontrolled grazing, and other destructive practices accelerate erosion with a concomitant increase in delivery of terrigenous sediments [5]. The sediment yield results from a complex interaction of several hydrogeological processes taking into account topography, soil characteristics, climate, land cover and use, catchment area, and dam-induced impacts [6]. In this sense, [7] says that after intense anthropogenic perturbations in the Changjiang (Yangtze) River basin, the riverine loads and compositions of materials into the Changjiang Estuary have greatly changed, resulting in dramatic deterioration in the Changjiang Estuary and adjacent sea environments and, even though water discharge has remained almost constant, the suspended sediment discharge was shown to be sharply decreased due to the construction of dams. Therefore, this chapter aims to assess the impact of dams on sediment transport and sediment yield of a Brazilian watershed.

2. Importance of sediment transport in watersheds

The sustainability of watersheds is strictly associated with sediment transport along their watercourses in which excessive sediment fluxes generated by extreme flows can destabilize river channels. As a result, sediment transport provokes damages to property and also public structure, narrows down the quality of water as well as increases flooding problems [8]. Comprehension regarding sediment transport in watersheds is useful for providing an adequate management of streams and reservoirs. Data on amount of sediment which has been transported by rivers is essential in the planning of hydraulic structures, such as dams, irrigation channels, while the features and amount of sediment transported from the drainage basins provides information to predict stream changes [9].

Several cities originated on the banks of rivers, mainly because water resources contribute to the development of the area under its influence. Recife is one of these cities which had the formation and expansion influenced by the Capibaribe River, the major water resource of the city [10]. Moreover, this river has a historical and economic importance for Pernambuco State (Brazil), where has been developing activities associated with sugarcane industry.

There are several problems related with sediment transport in watersheds. For instance, it increases the cost of water treatment; modifies the size of channel; acts as a carrier of bacteria and viruses; increases the transport of pollutants, chiefly the suspended sediment; narrows down the flow depth, damaging sea transport and increasing the possibility of floods. On the other hand, there are also benefits associated with sediment transport; for example, it decreases the erosion action of water in river runoff; improves the quality of water due to reduction of some pollutants; allows the chemistry reactions on sediment surface; carries organic matter, improving the aquatic life for some microorganisms [11].

3. Suspended sediment and bedload transport

Sediment transport in watersheds is classified into two groups: suspended and bedload transport. Suspended sediment is a term applied to particles which are maintained suspended by the vertical component of velocity in turbulent flux while it is transported by the horizontal component of velocity in the same flux. Furthermore, the suspended sediment transport is chiefly governed by the flow velocity, whilst the coarsest sediments might move only occasionally and remain at rest much of the time [9].

It is essential to carry out an isokinetic and point-integrating suspended sediment sampling. The lack of accuracy and frequency in suspended sediment concentration measurements is usually associated with mistakes in suspended sediment flux estimates, chiefly because a large share of annual suspended sediment is transported in a short period of time, generally corresponding to a few flood events during the hydrological cycle [12]. Thus, high-intensity sampling associated with an adequate sampling is fundamental for evaluating the suspended sediment transport in watersheds. These details are essential because the suspended sediment concentration allows to calculate the suspended solid discharge, which in the most cases represents 95% of the total solid discharge, ranging in function of watercourse, flow velocity, flow depth, sediment grain-size, runoff type, cross section position, and so on [13, 14].

The bedload moves near the streambed, contrary to suspended sediment which predominantly moves in suspension. It is normal to observe these particles moving, rolling, and sliding in contact with the streambed, while a third sort of motion is known as saltation. Nevertheless, occurrences of high-intensity flows maintain momentarily the bedload in suspension [8], usually ranging from 5 to 25% of suspended sediment transport [15]. In addition, the movement of coarser sediments is controlled by selective transport capacity, which indicates the concentration of different sizes of sediments in the cross section.

Frequently, to assess the life expectancy of Brazilian reservoirs, bedload flux has been estimated by using formulas (e.g., the Einstein equations) or by assuming that bedload represents a fixed percentage of the suspended load. In Brazil, as with most countries of South America, little information is available about suspended sediment flux, especially for smaller rivers. Information about bedload flux is extremely rare and, when it does exist, is limited to a few case studies [16]. In this sense, they observed in a step-pool stream representative of the conditions on the basalt scarps of southern Brazil that the bedload flux–streamflow relationship was adequately described by a potential mathematical function. When considering the bedload flux–streamflow relationship, the flux ranged from a minimum of 0.24 g m^{-1} s^{-1} for a streamflow of 0.53 m^3 s^{-1} to a maximum of 44 g m^{-1} s^{-1} for a streamflow of 1.3 m^3 s^{-1}. The percentage of bedload/suspended load varied between <1% and 60%, and this variation was strongly associated with peak flow.

[17], for a river from semiarid zone of Brazil, reported other such cases. They reported that suspended sediment and bedload discharges in sand-bed rivers shape semiarid landscapes and impact sediment delivery from these landscapes, but are still incompletely understood. Moreover, they also observed that the Exu River ratio of bedload/suspended sediment ranged from 4% to 12.72% and the highest values were noted in the period of largest flow rates during the rainy season.

4. The sediment flux from continent to the ocean

Land–ocean transfer of sediment by rivers is a key pathway for material transfer on earth [1], and according to [18], crucial to this understanding is knowledge of the ambient flux of sediment transported by rivers, as rivers contribute 95% of sediment entering the ocean.

According to [19], analysis of anthropogenic impoundment is important to both the earth sciences and their applications. These include emerging studies of global water resources which require an assessment of storage volumes available for flow stabilization, and also a global-scale understanding of the role of reservoirs also provides a key toward articulating the role of humans in riverine nutrients. Still reported by [19], estimation of the true global flux is also made difficult by insufficient treatment of the countervailing influences of increased sediment mobilization from anthropogenically induced soil erosion and of decreased delivery caused by flow diversion and sediment trapping in reservoirs.

Early attempts to generate estimates of the total flux of suspended sediment from the land to the oceans faced major problems in terms of lack of data for many major rivers and for extensive areas of the globe. Faced with this paucity of data, it was necessary to extrapolate existing information to ungauged areas. In the case of the work of Fournier in 1960, the overrepresentation of rivers with limited database resulted in a suspended sediment yield of 51.1 x 10^9 t, which was undoubtedly an overestimate [20].

Sediment flux to the coastal zone is conditioned by geomorphic and tectonic influences within the world's drainage basins, but also by geography of the basin (location and climate), geology, and human activities. These often counterbalancing factors have complicated our understanding of what controls sediment discharge to the global ocean [21]. Despite these complications, the importance of understanding fluvial delivery of sediment is beyond question. Understanding the redistribution of continental substrate through weathering and erosion is one of the fundamental goals of geological sciences [22-24].

[25] wrote that erosion and sediment dynamics play a key role in the functioning of the earth system and have important implications for human exploitation of the system and the sustainable use of its natural resources. They must therefore be seen as having a highly significant socioeconomic dimension. Soil erosion is integrally linked to land degradation, and excessive soil loss resulting from poor land management has important implications for crop productivity and food security and thus for the sustainable use of global soil resource. Against this background, changes in erosion rates and sediment transport by the world's rivers can have significant repercussions at a range of levels.

From a global perspective, changes in erosion rates have important implications for the global soil resource and its sustainable use for food production. Changes in land–ocean sediment transfer will result in changes in global biogeochemical cycles, particularly in the carbon cycle, since sediment plays an important role in the flux of many key elements and nutrients, including carbon. At the regional and local levels, changes in erosion rates can have important implications for the sustainability of agricultural production and food security. Equally, changes in the sediment load of a river can give rise to numerous problems. For example, increased sediment loads can result in accelerated rates of sedimentation in reservoirs, river channels, and water conveyance systems, causing problems for water resource development, and adverse impacts on aquatic habitats and ecosystems. Conversely, reduced sediment loads can result in the scouring of river channels and the erosion of delta shorelines as well as causing reduced nutrient inputs into aquatic and riparian ecosystems, particularly lakes, deltas, and coastal seas [26]. Because of their close links to land cover, land use, and the hydrology of a river basin, erosion and sediment transport processes are sensitive to changes in climate and land cover and to a wide range of human activities. These include forest cutting and land-clearance, the expansion of agriculture, land use practices, mineral extraction, urbanization and infrastructural development, sand mining, dam and reservoir construction, and programs for soil conservation and sediment control [27].

5. Impact of dams on trapping sediments

At the heart of the current debate on dams is the way choices are made, and the different opinions and perspectives that are expressed – or denied expression – in the process. The World Commission on Dams considers that the end of any dam project must be the sustainable improvement of human welfare. This means a significant advance of human development on a basis that is economically viable, socially equitable, and environmentally sustainable. If a large dam is the best way to achieve this goal, it deserves our support. Where other options offer better solutions, we should favor them over large dams. Thus, the debate around dams challenges our view of how we develop and manage our water resources. Large dams have fragmented and transformed the world's rivers. The World Resources Institute (WRI) found that at least one large dam modifies 46% of the world's 106 primary watersheds. The extent to which river flows have been changed varies around the world. The United States and the European Union regulate the flow of 60–65% of the rivers in their territories, though the amount varies from basin to basin. Spain has 53 km^3 of storage behind large dams and regulates 40% of its river flow, varying from 71% in the Ebro River basin, to 11% in the basins on the Galicia coast. In Asia, just under half of the rivers that are regulated have more than one large dam [28].

[2] reported that globally, greater than 50% of basin-scale sediment flux in regulated basins is potentially trapped in artificial impoundments. If we consider both regulated and unregulated basins, the interception of global sediment flux by all registered reservoirs (≅45000) is conservatively placed at 4–5 Gt $year^{-1}$ or 25–30% of the total. There is an additional but unknown impact due to still smaller unregistered impoundments (≅800000). The [2] results demonstrate that river impoundment should now be considered explicitly in global elemental flux studies, such as for water, sediment, carbon, and nutrients. From a global change perspective, the long-term impact of such hydraulic engineering works on the world's coastal zone appears to be significant but has yet to be fully elucidated.

[1] reported the nonstationary nature of sediment flux to ocean. The sediment loads of many rivers are known to be changing in response to, for example, land clearance and land use change, which can cause increased sediment loads, and the construction of dams, which can trap sediment that would previously have been discharged to the oceans. They should, therefore, not be viewed as a static measure of the functioning of the system, but rather as providing a snapshot of the functioning of an ever-changing system. In the case of Nile River, for example, a near zero sediment load was observed owing to the situation after the construction of the Aswan High Dam. Other estimates of reduction in sediment discharge of some rivers impacted by dams are showed in Table 1.

In Brazil, also there is reduction in sediment load of Sao Francisco River, that drains ca. 8% of the territory of Brazil. The available data suggest that the construction of the Sobradinho Dam in 1978, which impounded a vast reservoir extending over 4220 km^2, and several other hydropower dams with a total generating capacity in excess of 10000 MW, reduced the annual sediment output from this large (645000 km^2) basin by about 80%, from ca. 11 Mt $year^{-1}$ to ca. 2 Mt $year^{-1}$ [1].

6. Sediment delivery in the shoreline and coastal erosion

Among the most important and dynamic natural environments worldwide, the approximately 440000 km long coastal area is one of a small group of systems where several human, animal,

River	Country	Reduction in sediment load (%)
Nile	Egypt	100
Orange	South Africa	81
Volta	Ghana	92
Indus	Pakistan	76
Don	Russia	64
Krishna	India	75
Ebro	Spain	92
Kizil Irmak	Turkey	98
Colorado	USA	100
Rio Grande	USA	96

Showed by [1] and based on data from [2].

Table 1. Estimates of sediment trapped by dams in some rivers of the world

vegetal, and geomorphologic activities interact. Its invaluable landscape and ecological richness make it a very desirable zone to develop social, industrial, and recreational infrastructure. On the other hand, coastal zones are attacked by different natural phenomena, mostly from hydro-meteorological origin, such as waves, wind, tides, and rainfall which can reach extraordinary magnitudes during the occurrence of events like hurricanes and tsunamis. The direct consequences of these extreme events are flooding (derived from mean sea level rise) and beach erosion (as a result of the increase in current velocities and wave energy); a combination of both of these causes land loss, damage to infrastructure and natural habitats, ecological imbalance, health problems in the population, and instability in economic activities. The phenomena mentioned above are commonly grouped under the generic term of “dangers,” and the combination of these with the vulnerability of the natural and/or artificial elements found at the coast gives the risk of a specific coastal area. In the last decade, the interest shown in the assessment of risks comes from the evidence of an increase in the magnitude of natural dangers, added to the expansion of human activities in coastal zones which results in a higher level of risk [29].

The coastal zones of Latin America have many landforms and environments, including sedimentary cliffs, deeply incised estuaries, headlands, barrier coasts and low lying, muddy coastal plains. These forms will respond differently to the expected changes in climate and associated sea level rise, which may produce coastal erosion in the future. Considering the coasts of Latin America overall, erosion is not yet a serious threat, although it is widespread and it is severe in some parts [30].

[31] says that the coastal zones of Latin America feature a wide range of landforms. Expected climate change will bring about sea level rise and the different landforms will respond in different ways. Therefore, according to [30], it is necessary to explore the potential vulnerability of the distinct coastal types in response to climate change. Since risk to people is a key factor in vulnerability, the risk is greatest in the urbanized coasts, where the greatest impacts are expected to be caused by floods. However, the absence of long-term observations of oceano-

graphic data and detailed topo-bathymetric data presents a major difficulty for the evaluation of different risk scenarios at local level and consequently for the application of strategies aimed at minimizing these impacts on the population. In addition [30], tectonic subsidence is often a cause of regional vulnerability, as well as that which occurs in areas of permanent loss of sediments, owing to deforestation or to fragmentation of coastal ecosystems (e.g., sand dune vegetation, mangroves), to land use changes (mostly for agriculture and cattle ranching, and focal urban sprawl) and to sediment deficits caused by the presence of infrastructure (dams in the watersheds, jetties, and groynes).

Martínez et al. [32] presents an analysis of the erosion processes in Matanchén Bay located on the Pacific Coast of Nayarit State, Mexico. They said that at the beginning of the 1940s an unexplained growth in the beach at the northern tip of the bay was observed, while 40 years later, and up to date, erosion processes began adversely affecting small businesses in the area. The primary causes of the erosion are the anthropogenic modifications in the bay and its surroundings, which include the construction of a hydroelectric dam system, new transport infrastructure, tourist facilities, a harbor, and several dredging works in the existing port. In this paper, the evolution of the coastline at Matanchén Bay and its surroundings is analyzed for the first time and the actual coastline is compared to that predicted under the assumption that no countermeasures against the erosion are adopted.

[33], describing the northeast of Brazil, observed that the coastline is generally receding. This is noticeable along several stretches of the coast of Pernambuco, but is felt mostly in the area of the Recife metropolitan area. Here, as in many other places, urban encroachment and the construction of infrastructure along the coast, coupled with sea level rise processes, has led to a “coastal squeeze,” which results in the loss of coastal habitats.

Still in Pernambuco State, Brazil, [34] showed the main processes that are involved in the erosion of Maria Farinha Beach, a beach of great ecological and socioeconomic importance and they observed that the erosion problem at Maria Farinha Beach is complex and difficult to solve, since the problem has multiple causes, including the construction of coastal defenses. As it affects several municipalities, the problem is exacerbated. Wave propagation simulations have shown that the combination of high spring tides and high waves significantly impact the coast of Maria Farinha. The comparison between the numerical model results and the profile data indicates that under these conditions the beach profile where erosion is observed is more exposed to wave energy than the beach profiles showing accretion. Three possible solutions are suggested – the construction of a submerged breakwater, the deployment of a sand bypassing system and the relocation of buildings on the beach front. Due to the diverse beach usage, the implementation of a sand bypassing system is recommended. The option of doing nothing would cause continued erosion in the critical area taking into account the presence of urbanized areas, often irregular, all along the beach. The case of Maria Farinha Beach indicates the necessity of better understanding coastal processes and thorough planning prior to coastal development. It is highlighted that, if preventive efforts had been made in the past, prior to development, such as establishing a buffer zone or a setback line, much of the erosion on Maria Farinha Beach would have been avoided.

According to [35], beaches are of great significance as recreational areas, but from a geological perspective, the beach has a value as a natural defense system for the coast, which is exposed to the constant risk of erosion due to the action of waves and tides. Problems of beach erosion have become prevalent in northeast Brazil as a result of unplanned coastal development. Urbanization in conjunction with historic soil occupation and use, including the landfill of mangrove areas, the practice of soil sealing (which prevents drainage), combined with the local meteo-oceanographic characteristics, have caused a growing erosion problem and have contributed to a reduction in the resilience of the beaches. These authors using simulation methods to coastal erosion in Candeias Beach, in the southern area of the breakwater, observed that sediment transport to the south is even greater than if there was no protection to the coastline because there is no sediment source in the area that could replace the sediment that is being moved to the south. As a result, this could dramatically reduce the sediment availability in the area, leading to more beach erosion in the future. On the other hand, there is an improvement related to modifying the former breakwater. By opening up the gaps, wave-current transport was restored, thereby eliminating the sediment trap created by the installation of the original breakwater.

[36] presented the recent changes in sediment flux of the five largest rivers of East and Southeast Asia to Pacific Ocean and observed that the Yellow, Yangtze, Pearl, Red, and Mekong Rivers are important contributors of sediment to the western Pacific Ocean, and concluded that these rivers are of vital importance not only for providing water resources to more than 700 million people in six countries, but also for delivering large amounts of terrigenous sediment (~2000×10^9 kg/yr) to the coastal and shelf seas of the western Pacific Ocean, accounting for ~10% of the global sediment flux to the ocean. Freshwater, sediment, and nutrients discharged by these rivers play important roles in local and regional geomorphology and the biogeochemical cycle of the regional ocean. Although the rivers vary in their local geography, geology, and climate, human interventions of the past several decades have greatly modified the river systems. The present sediment flux from these five rivers has declined to ~600×10^9 kg/yr, equivalent to levels before widespread human interventions. Although the total freshwater discharge to the ocean remains almost unchanged, the stress on water resources for individual rivers continues to grow. Still, [36] reveals large anthropogenic changes in sediment flux from all five rivers to the western Pacific Ocean and summarizes their recent trends comparing the time-series data on water discharge and sediment flux to signals of climate oscillation and historical human activities. From this comparison it is concluded that the short-term variation (interannual scale) of sediment flux is dominated by climate oscillations such as the El Niño/La Niña cycle that affect the regional distribution of rainfall and thus the sediment yields from the river basins, and that the decrease in sediment flux on the decadal scale is controlled by human interventions including entrapment in reservoirs and human-influenced changes in soil erosion. The Yellow and Yangtze Rivers dominate the decline in sediment flux from both natural and anthropogenic impacts, as they are the largest contributors of sediment to the regional ocean. For the Mekong River, the sediment from the upper Mekong Basin is entrapped by reservoirs, and the increased sediment load in the lower Mekong arises from human interventions such as mismanaged land reclamation. As rapid development continues in East and Southeast Asia, human interventions in the large river systems will become still more intensive. Consequently, the continuing decline in river sediment flux to the ocean will put the mega-deltas at risk of destruction, adding to other severe challenges from regional environmental change.

7. Material and methods

The Capibaribe River watershed, 7557 km^2 in area, crosses from the end of semiarid area until the east coast. Climate in the portion located in the semiarid region is As' type, according to the Köppen classification, known as dry, with dry summer and the largest rainfall taking place between April and July, ranging from 550 mm to 700 mm annually. Toward the portion located in the east coast, the climate is classified as Ams' type with the largest rainfall taking place between May and July, ranging from 1700 mm to 2500 mm annually [37].

The amount of sediment supplied to the studied cross sections is influenced by nonconservationist agricultural activities, which trigger the erosion process, mainly represented by the occurrence of interrill and rill erosion. All these sources of sediment are affected by the dam's distribution along the Capibaribe River, which are predominantly located upstream of the studied cross section (Figure 1).

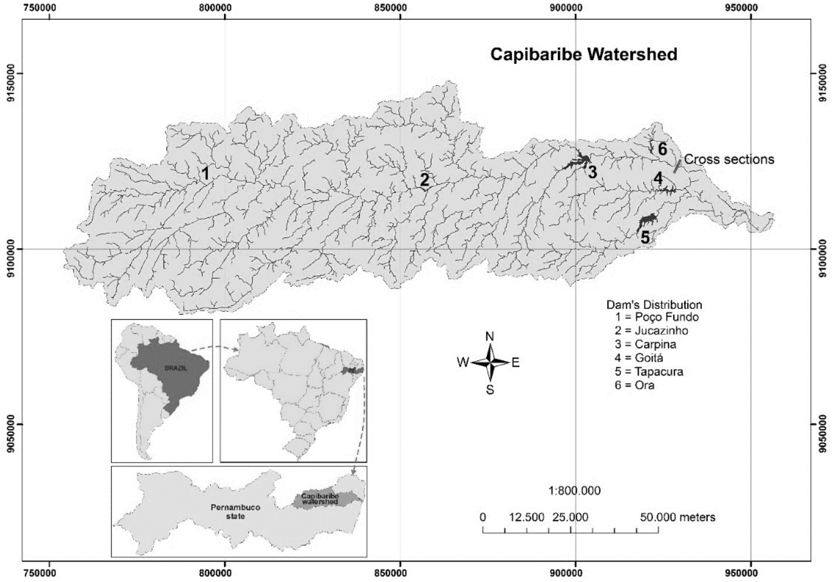

Figure 1. Location of Capibaribe watershed in the context of South America, dam's distribution and cross section in the studied river reach. Note: (Poço Fundo – Area = 854 km^2/volume = 27 x 10^6 m^3; Jucazinho – Area = 3918 km^2/volume = 327 x 10^6 m^3; Carpina – Area = 1828 km^2/volume = 270 x 10^6 m^3; Goitá – Area = 450 km^2/volume = 52.9 x 10^6 m^3; Tapacurá – Area = 360 km^2/volume = 94.2 x 10^6 m^3 and Ora (data not available).

8. Velocity measurement

During the campaigns in the Capibaribe River, the flow velocity was determined by rotating current meter (Figure 2), which is based on the proportionality between the angular velocity of the rotation device and the flow velocity.

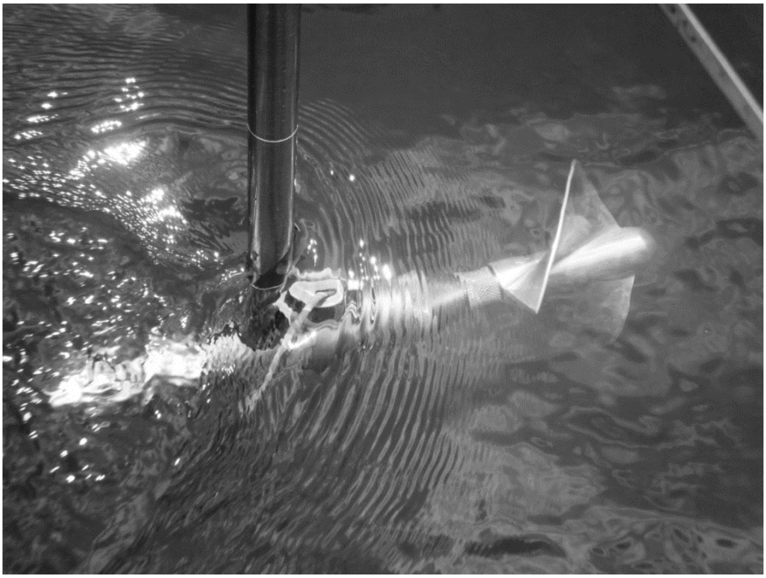

Figure 2. Rotating-element current meter used in the Capibaribe River.

The positions to which the rotating-element current meter was adjusted in each vertical in function of the flow depth are described in Table 2.

Positions	**V (m s^{-1})**	**h (m)**
0.6h	$V = V_{0.6h}$	< 0.6
0.2 and 0.8h	$V = (V_{0.2h} + V_{0.8h})/2$	0.6 - 1.2
0.2; 0.6 and 0.8h	$V = (V_{0.2h} + 2V_{0.6h} + V_{0.8h})/4$	1.2 - 2.0
0.2; 0.4; 0.6 and 0.8h	$V = (V_{0.2h} + 2V_{0.4h} + 2V_{0.6h} + V_{0.8h})/6$	2.0 - 4.0
s; 0.2h; 0.4h; 0.6h; 0.8h and b	$V = (V_s + 2(V_{0.2h} + V_{0.4h} + V_{0.6h} + V_{0.8h}) + V_b)/10$	> 4.0

s: surface; V_s: surface velocity and b: bottom of the river.

Table 2. Measurement of average flow velocity according to flow depth

In other words, the flow velocity was acquired by counting the number of revolutions of the propeller in a measured time interval, which was thirty seconds for all campaigns. The depth-average velocity was obtained in the cross section through a measurement velocity profile. In some campaigns, mainly during low water discharges, the Hidromec mini model was used due to low flow depth.

9. Water discharge measurement

At first, the width of the cross sections was measured by affixing a measuring tape parallel to the flow surface and transverse to the direction of flow from the left bank of the stream to the right bank and the flow depth of each vertical was obtained by specific measuring rule. The cross sections were divided into a series of vertical lines with the same width, varying according to the total width of the water flow at the moment of measuring, according to the equal-width-increment (EWI), method proposed by [9].

The water discharge was determined by computing the product of the mean flow velocity (m s^{-1}) and the area of influence (m^2) for each segment in the section and then summing these products over all segments (Equation 1).

$$Q = \sum Q_i = \sum A_i . V_i \tag{1}$$

where Q is the water discharge (m^3 s^{-1}), Q_i is the water discharge in each vertical segment (m^3 s^{-1}), A_i is the influence area of the vertical segment (m^2), and V_i is the average flow velocity in the influence area of each vertical segment (m s^{-1}).

10. Sampling of suspended sediment and bedload

Direct sampling was performed from 2009 to 2011 in the downstream cross section, which was divided into a series of 8–10 verticals with the same width. For suspended sediment sampling, the sampler US DH – 48 model (Figure 3) was used according to equal-width-increment (EWI), proposed by [38]. Furthermore, the US DH-48 sampler features a streamlined aluminum casting 13 inches long that partly encloses the sample container. The container, usually a glass milk bottle, is sealed against a gasket recessed in the head cavity of the sampler by a hand-operated, spring-tensioned, pull-rod assembly at the tail of the sampler. This instrument was calibrated with an intake nozzle, l/4 inch in diameter [11].

Moreover, during the sampling, the descending and ascending transit rate must be the same along the traverse of each vertical, resulting in a volume of water proportional to the flow in each vertical [9]. The transit rate depends on several features, such as sample volume collected, size of the nozzle in sampling equipment, depth of the sample taken, and flow velocity [39]. Thereby, according to [40], the transit rate was expressed as:

$$V_t = V_i . K \tag{2}$$

where V_t is the transit rate (m s^{-1}) and K is the constant of variable proportionality according to each different nozzle used, which was 0.4 for the ¼” nozzle of the sampler. Nevertheless, the information used during sampling was not the transit rate, but the time for the sampler to

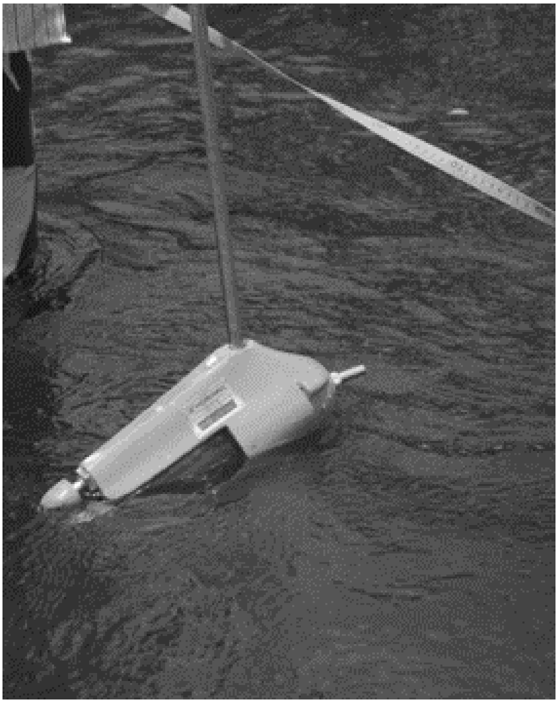

Figure 3. Suspended sediment sampling (sampler - US DH-48) in the Capibaribe River.

descend to the streambed and return to the water surface, calculated by the expression proposed by [14, 40]:

$$t = \frac{2h}{V_t} \tag{3}$$

where t represents the minimum time of the suspended sediment sampling (s). A small distance was subtracted from the value of h to account for the fact that the equipment would not contact the streambed (10 or 15 cm).

All collected samples in each segment (vertical) of the cross sections in the Capibaribe River were individually preserved to determine the Suspended Sediment Concentration (SSC) in Soil Conservation Engineering Laboratory at UFRPE, which was determined through the ratio between the suspended sediment mass and liquid volume of the sample, according to evaporation method [38]. The concentration values in each vertical segment that made up the section were determined, and the suspended sediment discharge values (SSQ) were determined by the addition of the product of the suspended sediment concentration (SSC_i) and the respective water discharge (Q_i) from each vertical segment [42]:

$$SSQ = \sum \left(SSC_i Q_i \right) 0.0864 \tag{4}$$

where SSQ is the suspended solid discharge (t day^{-1}) and 0.0864 is a constant for unit adjustment. The bedload was obtained by means of the US BLH 84 sampler. For checking the accuracy of suspended sediment sampling, the Box Coefficient (BC) – ratio between average of suspended sediment concentration and suspended sediment concentration at each vertical – was calculated, following that proposed by [43]:

$$QB = \sum \frac{m}{wt_2} L_x 0.0864 \tag{5}$$

where QB is bedload discharge (t day^{-1}), m is the mass of sediment from bedload transport in each vertical (g), w is the width of nozzle which is considered 0.075 m, t_2 is the sampling time of bedload transport (30 s), and L_x is the distance among verticals (m). In addition, the sediment yield was calculated (t km^{-2} ano^{-1} or t ha^{-1} ano^{-1}).

11. Results and discussion

The rating curve relating water discharge (Q) and flow depth (h) provided a determination coefficient equal to 0.81, considering the direct measurements campaigns carried out with Q ranging from 0.25 to 11.60 m^3 s^{-1} (Figure 4). The reasonable adjustment was acquired due to the higher amplitude of Q evaluated. Thereby, the number of measurements and also the variation between minimum and maximum values improve the effectiveness of the rating curve [11].

The relation between suspended sediment concentration (SSC) and Q provided a low determination coefficient equal to 0.21 (data not shown), demonstrating the large complexity and variability associated with the SSC measurements. Furthermore, this behavior represents the effects of dams. In the same way, [44] working in the Capibaribe Watershed obtained low adjustment between SSC and Q discharge (R^2 equal to 0.14). Moreover, the high variability between SSC and Q was emphasized by [45], which obtained a high variability of regression coefficients. These results are associated with the dynamic relation between Q and SSC, becoming essential to keep manual sampling to decrease the mistakes linked with SSC estimation and improve the effectiveness of the rating curves [42].

On the other hand, the rating curve relating SSQ (dependent variable) and Q (independent variable) showed a good adjustment with determination coefficient equal to 0.86 (Figure 5). Nevertheless, this behavior cannot be understood as the same way of the rating curve which relates the Q and h due to the high complexity linked with suspended sediment transport. Indeed, it is possible to observe the momentary behavior of the SSQ instead obtaining this variable only with the Q even if a high number of measurements had been carried out. According to Horowitz [46], this approach is acceptable for a suspended sediment concentra-

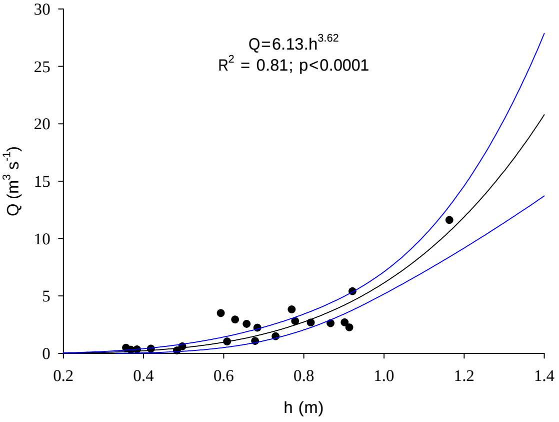

Figure 4. Rating curve of direct measurement campaigns performed under conditions in the Capibaribe River.

tion rating curve. Nonetheless, it is inadequate for a suspended solid discharge rating curve, chiefly because the Q is used for obtaining the SSQ. Accordingly, it is common to observe the increase in determination coefficient, but without increasing the importance of the rating curve relating Q and SSQ.

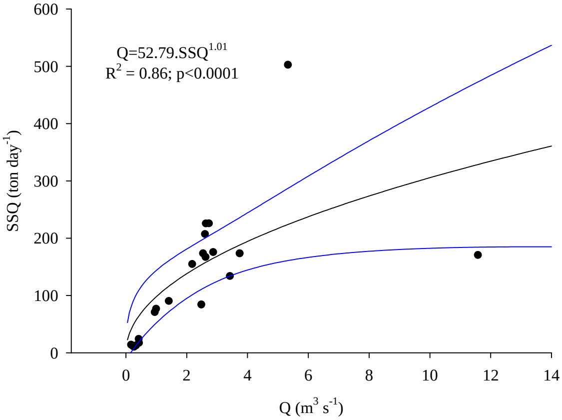

Figure 5. Suspended sediment rating curve of Capibaribe watershed.

A multimodal dominant discharge was observed, with peaks of suspended sediment concentration lagging behind, taking place at the same time as well as after extreme flow events (Figure 6). The first two trends of sediment concentration in relation to hydrograph are typical of semiarid environment and may be related to low flow or short distance of transport from erosion site. Despite being most common in the semiarid environment, the lag far behind the peak of suspended sediment concentration related to the flow might be linked to the flow events provoked by high intensity rainfall, which resulted in more losses of soil particles in the downstream cross section [47].

In some instances, the low suspended sediment concentration may be linked to dilution effects provided by the high water discharge that was observed in the first peak (Figure 6). This behavior may be related to trapping sediments along Capibaribe River, due to dam effects. The mean suspended sediment concentration value, equal to 662 mg L^{-1}, is higher than values reported for other Brazilian rivers [48, 49] as well as world rivers under dam effect, such as Pérola and Yellow [7].

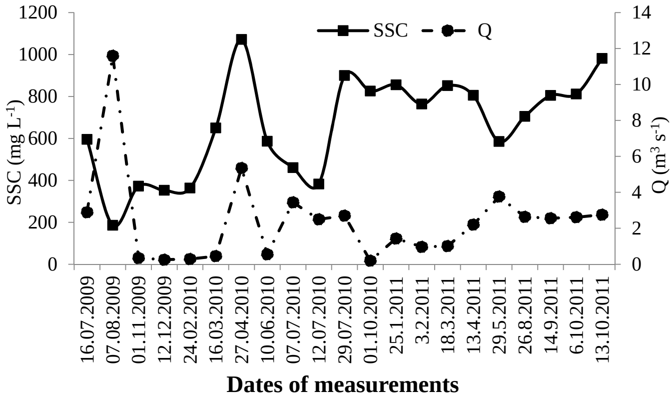

Figure 6. Hydrographs and sedigraphs at the studied site of the Capibaribe River.

Considerable variation of water discharge and sediment concentration values, ranging from 0.19 to 11.6 $m^3 s^{-1}$ and 185.23 to 1071.55 mg L^{-1}, respectively, were observed; nevertheless, the values of individual suspended sediment samples showed adequate Box Coefficient (BC), ranging from 0.67 to 1.5 – acceptable limits suggested by [43]. Therefore, the sediment concentration samples from the Capibaribe River were considered sufficiently accurate. The SSQ ranged from 9.48 t day^{-1} to 501.56 t day^{-1} (Table 3).

The ratio between QB and SSQ ranged from 0.12% to 27.3% with 76% of all values lower than 5%. Usually, the bedload transport rate of a river is about 5–25% of the suspended sediment transport [15]. This ranging sheds light on the lack of bedload reaching the coastal zone and it is likely one of the reasons to yield coastal erosion. The low rates can be attributed to the presence of dams which have been admitted to have a strong effect on sediment transport, which evidenced the reduction on sediment supply at Reno River, but without quantifying this process due to the lack of assessment before dam construction. The presence of dams has been known to have a strong effect on sediment transport [50].

The sediment yield was equal to 3.69, 4.36, and 6.7 t km^{-2} ano^{-1} in 2009, 2010, and 2011, respectively. In comparison with bedload yield, the suspended sediment yield was higher than 95% for all studied years. According to [51], these values are low, but this behavior is in agreement with that observed by [41]. Both national [52] and international studies [53] have shown the reduction of sediment yield due to dam construction. Therefore, the limited bedload supply – mainly responsible for construction of coastal landfor – is likeli contributing to the coastal erosion along part of the northeast region, Brazil.

Dates of measurements	SSC	BC	SSQ	QB	QB/SSQ
	(mg L^{-1})	(no dimensional)	(t day^{-1})	(t day^{-1})	(x100)
Jul-09	595	0.99–1.50	175	0.22	0.12
Aug-09	185	0.79–1.50	170	3.41	2.01
Nov-09	372	0.85–1.32	12	0.68	5.71
Dec-09	353	0.72–1.30	10	0.2	1.9
Feb-10	363	0.68–1.20	9	0.9	9.94
Mar-10	649	0.84–1.20	16	0.18	1.1
Apr-10	1071	0.90–1.10	501	7.76	1.55
Jun-10	586	0.87–1.30	23	0.22	0.93
Jul-10	460	0.97–1.43	133	9.77	7.35
Jul-10	382	0.92–1.50	83	9.46	11.37
Jul-10	899	0.67–1.37	225	3.44	1.53
Oct-10	826	0.85–1.29	13	2.53	27.3
Jan-11	855	0.86–13	89	0.19	0.21
Feb-11	764	0.86–1.40	70	0.18	0.26
Mar-11	851	0.93–1.25	76	0.14	0.18
Apr-11	805	0.83–1.18	154	0.57	0.37
May-11	585	0.74–1.36	172	2.14	1.24
Aug-11	705	0.67–1.13	166	5.82	3.51
Sep-11	805	0.85–1.08	172	2.97	1.72
Oct-11	811	1.05–1.26	206	5.32	2.58
Oct-11	981	0.86–1.12	225	3.85	1.71

Table 3. Suspended sediment concentration (SSC), suspended sediment discharge (SSQ), Box Coefficient (BC), and ratio between QB and SSQ of samples from the Capibaribe River in 2009, 2010, and 2011

12. Conclusions

The multiple dams along the Capibaribe River watershed produce a deficit in sediment flux to coastal zone of Pernambuco State, Brazil, which relies on the low ratios between bedload and suspended sediment from Capibaribe River. As a result, it generates energy to coastal erosion of the Brazilian northeast.

Acknowledgements

The authors would like to acknowledge the financial support by Fundação de Amparo a Ciência e Tecnologia do Estado de Pernambuco (FACEPE), Edital FACEPE 12/2008 – ESTUDOS E PESQUISAS PARA POLÍTICAS PÚBLICAS ESTADUAIS EROSÃO COSTEIRA – SEGURANÇA PÚBLICA – DENGUE FACEPE/SECTMA/SEPLAG/SES.

Author details

Jose Ramon B. Cantalice[1*], Wagner Luis da Silva Souza[1], Yuri Jacques Agra Bezerra Silva[1], Sergio M.S. Guerra[2], Alex Mauricio Araújo[3], Douglas Monteiro Cavalcante[2] and Cinthia Maria Cordeiro Atanazio Cruz Silva[1]

*Address all correspondence to: cantalice21@hotmail.com

1 Agronomy Engineering Department, Soil Conservation Engineering Laboratory, Rural Federal of Pernambuco University (UFRPE) Brazil, Recife-PE, Brazil

2 Rural Technology Department, Rural Federal of Pernambuco University (UFRPE), Recife-PE, Brazil

3 Fluid Mechanics Laboratory, Federal of Pernambuco University (UFPE), Recife, PE, Brazil

References

[1] Walling, D.E. 2006. Human impact on land-ocean sediment transfer by the world’s rivers. *Geomorphology*. 79(3), 192–216.

[2] Vörösmarty, C.J., Meybeckc, M., Feketea, B., Sharmad, K., Greena, P., Syvitski, J.P.M. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Global Planetary Change*. 39, 169–190.

[3] Zhang, Q., Xu, C.Y., Singh, V.P., Yang, T. 2009. Multiscale variability of sediment load and streamflow of the lower Yangtze River basin: Possible causes and implications. *J Hydrol*. 368, 96–104.

[4] Dias, A.J.M. 1993. Estudo de Avaliação da Situação Ambiental e Proposta de Medidas de Salvaguarda para a Faixa Costeira Portuguesa. *Geologia Costeira*. 26 p.

[5] Stender, Y., Jokiel, P.L., Rodgeres, K.S. 2014.Thirty years of coral reef change in relation to coastal construction and increased sedimentation at Pelekane Bay, Hawaii. *Peer J.* 2:e300, DOI 10.7717/peerj.300.

[6] Hovius, N. Controls on sediment supply by large rivers. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks*. Society of Sedimentary Geology, Special Publication 59, 3-16. 1998.

[7] Dai, H., Du, J., Zhang, X., Su, N., Li, J. 2011. Variation of riverine material loads and environmental consequences on the Changjiang (Yangtze) estuary in recent decades (1955-2008). *Environ Sci Technol*. 45(1):223-7. doi: 10.1021/es103026a.

[8] Frey, P., Church, M. 2011. Bedload: a granular phenomenon. *Earth Surf Process Landforms*. 36, 58–69.

[9] Edwards, T.K., Glysson, G.D. 1999. Field methods for measurement of fluvial sediment. In: *Techniques of Water-Resources Investigations of the U.S. Geological Survey (USGS)*. Reston, Virginia, book 3, chapter C2. 97 p.

[10] Mayrinck, O.M.A. 2003. Paisagem do rio Capibaribe: um recorte de significados e representações (Tese de Doutorado), Instituto de Geociências/Universidade Federal do Rio de Janeiro. 273 p.

[11] Carvalho, N.O. 2008. *Hidrossedimentologia Prática*. Editora Interciência. Rio de Janeiro, RJ. 599 p.

[12] Meybeck, M., Laroche, L., Durr, H.H., Syvitski, J.P.M. 2003. Global variability of daily total suspended solids and their fluxes in Rivers. *Global Planet Change*. 39, 65–93.

[13] Carvalho, N.O. 1994. *Hidrossedimentologia Prática*. Rio de Janeiro: CPRM. 374 p.

[14] Carvalho, N.O., Júnior, N.P., Santos, P.M.C., Lima, J.F.E.W. 2000. *Guia de Práticas Sedimentométricas*. ANEEL, Brasília – DF, 154 p.

[15] Yang, T.C. 1996. *Sediment Transport Theory and Practice*. New York. McGraw-Hill companies. 395 p.

[16] Merten, G.H., Minella, J.P.G. 2014. Bedload flux in southern Brazilian basalt scarp. *Sediment Dynamics from the Summit to the Sea* (Proceedings of a symposium held in New Orleans, Louisiana, USA, 11–14 December 2014) (IAHS Publ. 367, 2014). doi: 10.5194/piahs-367-185-2015.

[17] Cantalice, J.R.B., Filho, M.C., Stosic, B.D., Piscoya, V.C., Guerra, S.M.S., Singh, V.P. 2013. Relationship between bedload and suspended sediment in the sand-bed Exu River, in the semi-arid region of Brazil. *Hydrologic Sci J.* doi: 10.1080/02626667.2013.839875.

[18] Syvitski, J.P.M., Peckham, S.D., Thierry, R., Hilberman, M. 2003. Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. *Sediment Geol*. 162, 5–24.

[19] Vorosmarty, C.J., Meybeckc, M., Feketea, B., Sharmad, K., Greena, P., Syvitski, J.P.M. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Global Planet Change*. 39, 169–190.

[20] Walling, D.E., Webbe, B.W. 1996. *Erosion and Sediment Yield: Global and Regional Perspectives*. IAHS Publ. n 236, 1–19.

[21] Hay, W.W. 1994. Pleistocene-holocene fluxes are not the Earth's norm. In: *Material Fluxes on the Surface of the Earth* (Ed. by Panel on Global Surficial Geofluxes) Studies in Geophysics, National Academy Press, Washington, DC, pp. 15-27.

[22] Milliman, J.D., Meade, R.H. 1983. World-wide delivery of river sediment to the oceans. *J Geol*, 91, 1-21.

[23] Milliman, J.D. 2001. Delivery and fate of fluvial water and sediment to the sea: a marine geologist's view of European rivers. *Sci Marina*. 65 (Suppl. 2), 121-132.

[24] Syvitiski, J.P.M., Milliman, J.D. 2007. Geology, geography and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *J Geol*. 115, 1-19.

[25] Montgomery, D.R. 2007. Soil erosion and agricultural sustainability. *Proc Natl Acad Sci*. Vol. 04, n 13. Washington D.C., PNAS, pp. 268–272.

[26] Walling, D.E. 2009. The impact of global change on erosion and sediment transport by rivers: Current progress and future challenges. The United Nations World Water Assessment Programme. The United Nations World Water Development Report 3, *Water in a Changing World*, UNESCO, Paris, 29 p.

[27] Walling, D.E. 2005. Human impact on land–ocean sediment transfer by the world's rivers. *Geomorphology*. Vol. 79. Amsterdam, Elsevier, pp. 192–216.

[28] World Commission on Dams (WCD). 2000. *Dams and Development: A new Framework for Decision-Making*. Thanet Press, USA, 399 p.

[29] Castillo, M.E., Baldwin, E.M., Casarin, R.F., Vanegas, G.P., Juaréz, M.A. 2012. Characterization of Risks in Coastal Zones: A Review Clean – Soil, Air, Water. 40(9), 894–905.

[30] Silva, R., Martínez, M.L., Hesp, P., Catalan, P., Osorio, A.F., Martell, R., Fossati, M., Miot da Silva, G., Mariño-Tapia, I., Pereira, P., Cienfuegos, R., Klein, A., and Govaere, G. 2014. Present and future challenges of coastal erosion in Latin America. In: Silva, R. and Strusińska-Correia, A. (eds.), Coastal Erosion and Management along Developing Coasts: Selected Cases. *J Coastal Res*, Special Issue, 71, 1–16. Coconut Creek (Florida), ISSN 0749-0208.

[31] Muehe, D. 2010. Brazilian coastal vulnerability to climate change. *Pan-Am J Aquatic Sci–Electron Peer-Rev Sci J*. 5(2), 173-183.

[32] Martínez, R., Silva, R., and Mendoza, E. 2014. Identification of coastal erosion causes in Matanchén Bay, San Blas, Nayarit, Mexico. In: Silva, R., and Strusińska-Correia, A.

(eds.), Coastal Erosion and Management along Developing Coasts: Selected Cases. *J Coast Res*, Special Issue, 71, 93–99. Coconut Creek (Florida), ISSN 0749-0208.

[33] Dominguez, J.M.L. 2009. The coastal zone of Brazil. In: Dillenburg, S., Hesp, P.A. (eds). 2009. *Geology and Geomorphology of Holocene Coastal Barriers in Brazil*. Springer-Verlag Lecture Notes in Earth Sciences. 107, 17-51.

[34] Mallmann, D.L.B., Pereira, P.S. 2014. Coastal erosion at Maria Farinha Beach, Pernambuco, Brazil: Possible causes and alternatives for shoreline protection. In: Silva, R. and Strusińska-Correia, A. (eds.), Coastal Erosion and Management along Developing Coasts: Selected Cases. *J Coast Res*, Special Issue, No. 71, 24–29. Coconut Creek (Florida), ISSN 0749-0208.

[35] Gomes, G., Silva, A.C. 2014. Coastal erosion case at Candeias Beach (NE-Brazil). In: Silva, R. and Strusińska-Correia, A. (eds.), Coastal Erosion and Management along Developing Coasts: Selected Cases. *J Coast Res*, Special Issue, 71, 30-40. Coconut Creek (Florida), ISSN 0749-0208.

[36] Wang, H., Saito, Y., Zhang, Y., Bi, N., Sun, X., Yang, Z. 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. *Earth-Sci Rev*. 108, 80–100.

[37] SUDENE, 1990. Dados pluviométricos mensais do Nordeste. Estação de Pernambuco: Recife, 363 p.

[38] USGS – United States Geological Survey. 2005. Techniques of Water Resources Investigation. Washington, book 9, chaps. A1-A9, available online at http://pubs.water.usgs.gov/twri9A.

[39] Wilde, F.D., Radke, D.B. 1998. Field Measurements. In: *National Field Manual for Collection of Water – Quality Data*. U.S. Geological Survey. Techniques of Water Resources Investigations, Book 9, chap A4, 7–99.

[40] USGS – United States Geological Survey. 1973. Techniques of Water Resources Investigations. Washington. 20 p.

[41] Merten, G.H., Poleto, C. 2006. Qualidade dos Sedimentos. Associação Brasileira de Recursos Hídricos – ABRH. Porto Alegre, RS. 397 p.

[42] Horowitz, A.J. 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. *Hydrol Process*, 17, 3387–3409.

[43] Gray, J.R. 2005. Sediment data collection techniques. U.S. Geological Survey Training Course. CD-ROM.

[44] Souza, W.L.S. 2011. Produção de Sedimento da Bacia Hidrográfica do Rio Capibaribe para Zona Costeira da Região Metopolitana do Recife. Dissertação, Programa de Pós-

Graduação em Ciência do Solo da Universidade Federal Rural de Pernambuco, 137 p.

[45] Saeidi, P., Tabatabaei, J., Saedi, T. 2011. Effective discharge for suspended sediment transportation in Ghohruod watershed. *Afri J Agric Res*. 6(23), 5360-5366.

[46] Horowitz, A.J., Elrick, K.A., Smith, J.J. 2008. Monitoring urban impacts on suspended sediment, trace element, and nutrient fluxes within the City of Atlanta, Georgia, U.S.A.: program design, methodological considerations and initial results. *Hydrol Process*. 22, 1473–1496.

[47] Colby, B.R.. 1963. Fluvial sediments-a summary of source, transportation, deposition and measurement of sediment discharge: *US Geol Survey Bull*. 118l–A, 47 p.

[48] Lima, J.E.F.W., Santos, P.M.C., Carvalho, N.O., Vieira, N.O., Silva, E.M. 2005. Suspended sediment fluxes in the large river basins of Brazil. In: VII Congresso Científico da IAHS. Foz do Iguaçu, RS. 291. pp. 355-364.

[49] Guyot, J.L., Filizola, N.P., Laraque, A. 2005. Régime et bilan du flux sédimentaire de l'Amazone à Óbidos (Pará, Brésil) de 1995 à 2003. In: *Sediment Budgets 1.* Walling, D.E., Chorowitz, A.J. IAHS Publication. 291. pp. 347-354.

[50] Meade, R. H., Moody, J. A. 2008. Changes in the discharge of sediment through the Missouri- Mississippi river system, 1940–2007. In: VIII Encontro Nacional de Engenharia de Sedimentos. Campo Grande, Brazil, 2-8 November 2008, Proceedings, 27 p.

[51] WMO – World Meteorological Organization. 2003. Manual on sediment management and measurement. Operational Hydrology Report, n. 47. Ed. Xiaoquing, Yang. Geneva, Switzerland. 176 p.

[52] Medeiros, P.R.P., Knoppers, B.A., Santos Júnior, R.C. 2007. Aporte fluvial e dispersão de matéria particulada em suspensão na zona costeira do Rio São Francisco (SE/AL). *Geochimica Brasiliensis*. 21(2), 212–231.

[53] Jiao, J., Wang W., Li, J. 2003. Silting land and sediment blocking benefit of check-dams in hilly and gully region on the Loess Plateau. In: Transact Chinese Soc Agric Engin. 19(6), 302–306.