

# REGIONAL SCALE MODELING OF EROSION RELATED TO LAND COVER EVOLUTION: A CASE STUDY IN BRAZILIAN SOUTHEASTERN REGION

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## ABSTRACT

Accelerated soil erosion is, at present, one of the most widespread environmental problems in the world. Geographic Information Systems (GIS) have become an essential tool in soil erosion studies and consequently in the development of appropriate soil conservation strategies. The objective of this paper was to assess the degree of soil erosion associated with land cover dynamics through GIS analysis and to validate the modeling with indicators of soil erosion. Universal Soil Loss Equation (USLE) model, GIS technology and ground-truth dataset (erosion indicators) were employed to elaborate the soil loss maps for four dates at Sorocaba Municipality (SP, Brazil). It was verified that, although the predicted soil loss rate is normally small along the study area, such rate is significantly greater than the soil formation rate. This shows a non-sustainable situation of soil and land cover management. Unplanned urban expansion seems to be the main driving force that acts in increasing the erosion risk/occurrence along the study area.

**Key words.** Environmental change, water erosion, USLE, GIS.

## MODELAGEM EM ESCALA REGIONAL DA EROSIÃO RELACIONADA COM A EVOLUÇÃO DA COBERTURA DO SOLO: UM ESTUDO DE CASO NO SUDESTE DO BRASIL

### RESUMO

A erosão acelerada é um dos maiores problemas ambientais ocorrentes em larga escala na atualidade. Por sua vez, Sistemas de Informação Geográfica (SIG) tornou-se uma ferramenta essencial em estudos de erosão e conseqüentemente no desenvolvimento de estratégias apropriadas para a conservação do solo. O objetivo deste trabalho foi avaliar o grau de erosão do solo associada com a dinâmica da cobertura do solo através de uma análise geoespacial e validar a modelagem com indicadores de erosão. Utilizou-se a Equação Universal de Perda de Solo (EUPS), recursos de SIG e dados de campo (indicadores de erosão) para elaborar os mapas de perda de solo para quatro datas para o município de Sorocaba (SP, Brasil). Verificou-se que, embora a taxa de perda de solo ao longo da área de estudo é normalmente baixa, esta taxa é expressivamente maior que as taxas de formação do solo. Isto mostra uma situação não sustentável de uso da terra. Expansão urbana não planejada parece ser o principal agente que proporciona o crescimento da ocorrência/risco de erosão ao longo da área de estudo.

**Palavras chave.** Alteração ambiental, erosão hídrica, EUPS, SIG.

### INTRODUCTION

Soil erosion is a geomorphic process that occurs under many circumstances worldwide. It can be caused by wind, snowmelt and/or raindrop/runoff actions. It is a natural phenomenon that is responsible for the modeling of the Earth's topography through soil loss, sediment transport and deposition. Conversely, the anthropogenic erosion is an accelerated form of the natural erosion process and the soil loss rates are much higher than the natural rates (Kirkby, 2001).

Land-use and land-cover change are the result of many interacting processes (Verburg *et al.*, 2002). Land cover change through time is closely driven by human population increase and distribution (L.R.R.B., 2003), rendering the soil more susceptible to erosion.

The erosion process can be observed and quantified under various methods (Boix-Fayos *et al.*, 2006). One of the most common is the mathematical approach, where many mathematical models have been developed. In general, the aim is to understand and predict the soil loss

according to environmental conditions, some of them integrated with GIS technology (Mati *et al.*, 2000).

In order to complement the GIS work and validate the results obtained from the modeling, ground-truth data is commonly used, both quantitative and/or qualitative. Quantitative data is usually obtained from experimental plots (Jimoh, 2001). On the other hand, qualitative data are obtained from erosion indicators (Okoba & Sterk, 2006) and can also be used to complement the GIS work and modeling.

In Brazil, the erosion processes occur in different forms and intensities due to the big territorial dimensions of the country. Rainfall is the main factor that initiates the soil erosion process (Silva, 2004). Conversely, the anthropogenic influence varies along the country and results in different forms of soil and land cover management.

The State of São Paulo is the most developed Brazilian State and encompasses a great part of the Brazilian population and of the Gross National Product. In addition, Sorocaba is an important Brazilian municipality (Seade, 2006). Due to the high importance that the erosion process exerts, at equilibrium, of the ecological dynamics of a region, for Sorocaba Municipality it is considered a poorly investigated phenomenon both in urbanized and in rural areas.

Hence, the objective of this paper was to investigate the rate of soil loss that is associated with land use dynamics in Sorocaba Municipality and to validate the modeling with indicators of erosion.

## PROCEDURES

### Study Area

Our case study is Sorocaba, located in the Southeastern Brazilian region (São Paulo State) (Figure 1). It has an area of 456 km<sup>2</sup> and approximately 532,000 inhabitants, 98% of them living in urban settlements. It is an important socio-economic center, encompassing 1,078 industries (Seade, 2006) and showing an advanced urban expansion (Figure 1).

The annual average temperature is 21.4 °C and the annual average rainfall is 1,285 mm. The elevation ranges from 500 to 1,033 m above sea-level. Topography is highly variable: in the western area, where the land is intensively used for agriculture, the relief is flat or smoothly rolling. In the eastern area, topography is rolling to hilly. In the latter area the natural remnant vegetation occurs more frequently. There are two main soil classes: Yellow-red Alfisols and Red Oxisols, both dystrophic (Oliveira *et al.*, 1999).

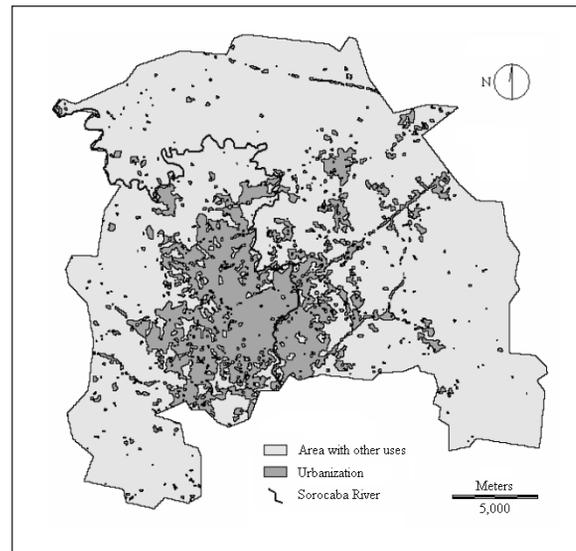


Figure 1. Localization of the study area (not scaled, left) and land use map for Sorocaba Municipality (2003).

Figura 1. Localização da área de estudo (sem escala, esquerda) e mapa de uso da terra para o município de Sorocaba (2003).

### Land cover maps

Four land cover maps of the study area were compiled by Silva (submitted) using three Landsat satellite images (1988, 1995 and 2003). The fourth land cover map was of 2011 and was compiled through Markov chain model (Aaviksoo, 1995; Eastman, 2004). The land cover classes and the percentage of occurrence of each land cover class according to the year are presented in Table 1. These land cover maps were used for determination of the C and P factors layers of the Universal Soil Loss Equation.

The Universal Soil Loss Equation (USLE) was the mathematical model used for predicting soil loss along the study site (Wischmeier & Smith, 1978). The USLE is:

$$A = R.K.L.S.C.P \quad (1)$$

Where: A - rate of soil loss ( $\text{Mg ha}^{-1} \text{y}^{-1}$ ), R - annual rainfall erosivity ( $\text{MegaJoule mm ha}^{-1} \text{hr}^{-1} \text{y}^{-1}$ ), K - soil erodibility ( $\text{Mg hr MegaJoule}^{-1} \text{mm}^{-1}$ ), L - slope length, S - slope steepness, C - cover management, and P - supporting practices. The last four factors are dimensionless.

All six parameters of the USLE were separately investigated and subsequently integrated through GIS techniques (Idrisi - Kilimanjaro version (Eastman, 2004)):

**R factor layer** – this layer was elaborated using the database and digital map of the rainfall erosivity for the Brazilian territory, extracted from the database elaborated and cited in Silva (2004).

**K factor layer** – it was generated by using the São Paulo state pedological map (Oliveira *et al.*, 1999) and erodibility values according to soil unity. The detailed

erodibility database for soil unities occurring along São Paulo State is presented in Silva & Álvares (2005). The classes Oxisol and Ultisol showed K values of 0.0162 and  $0.0425 \text{ Mg h MJ}^{-1} \text{ mm}^{-1}$ , respectively (Silva & Álvares, 2005).

The pedological map used in this study includes the class “urbanization”. According to De Kimpe & Morel (2000), within urban and suburban areas, soils are the support for diversified anthropocentric activities and needs: as infrastructure at the soil surface and underground, source and sink of raw materials; food production; recreational activities (*e.g.*, parks); and memory and cultural heritage (*e.g.*, cemeteries). As it is currently impossible to check the soil classes occurring along the urban area of Sorocaba, the average value for erodibility for this soil category was adopted ( $0.0293 \text{ Mg h MJ}^{-1} \text{ mm}^{-1}$ ).

**LS factor layer** – a 30-m resolution Digital Elevation Model (DEM) of the study area was used. The LS factor layer was generated using the DEM and the USLE-2D software (Van Oost & Govers, 2005). The value of each cell of this layer corresponds to the LS factor.

**C factor layer** – digital land cover maps (1988, 1995, 2003 and 2011) were used for checking the land cover classes (the land cover classes were the same). A specific “C” value was attributed to each land cover class, (Mitchell & Bubenzer, 1980). The land cover classes Pasture and Urban received C values = 0.01. The value for Remnant Natural Vegetation was 0.001; 0.1 for Cultures; 1.0 for Bare Soil; 0 for Water Bodies and 0.005 for Other.

**P factor layer** – similarly as the C factor, the same four land cover maps were used to elaborate the “P” factor layer and a dataset was also extracted from Mitchell & Bubenzer (1980) and Cerri *et al.* (2001). The value “0.5” was given to Pasture and Cultural classes since contour

Table 1. Percentage of occurrence of each land cover class for each analyzed year.

Tabela 1. Porcentagem de ocorrência da cada classe de cobertura do solo para cada ano analisado.

Classes	1988	1995	2003	2011
Pasture	54.6	56.1	36.2	28.7
Remnant Natural Vegetation	19.5	18.4	22.1	24.9
Cultures	2.7	2.8	11.3	12.7
Urban	10.7	14.6	18.7	22.1
Bare Soil	11.8	7.5	10.9	10.5
Water Bodies	0.6	0.4	0.8	0.9
Other	0.1	0.1	0.0	0.0

USLE dataset and modelling

farming is a common practice. For the remaining land cover classes support practices are not used. Hence, the P value was 1. Such information was obtained through many field surveys.

The same C and P values were assumed for each land cover class for all land cover maps (1988, 1995, 2003 and 2011).

Once the information for each USLE factor was determined, the respective layers were gathered in order to generate the Soil Loss Expectative map (SLE). The SLE map was reclassified into five interpretation classes.

(2006). These authors presented eleven erosion indicators that were identified according to their causes, and which were closely concordant with scientific knowledge. The occurrence of indicators (features) is briefly explained in Table 2, and was surveyed through field incursions. In 100 georeferenced observation points (randomly chosen, where each observation point had approximately 100 to 200 m<sup>2</sup>) the presence or nonappearance of erosion indicators was investigated along the study area and compared with the soil expectation map through GIS techniques.

### Validation of the USLE modelling

The validation of the USLE application and SLE map for the study area was carried out with soil erosion indicators, following descriptions made in Okoba & Sterk

### RESULTS AND DISCUSSION

Figure 2 shows the Soil Loss Expectation maps (SLE) for Sorocaba, expressed in six broad classes and ranging

Table 2. Description of the erosion indicators frequently found along the study area.

Tabela 2. Descrição dos indicadores de erosão encontrados com frequência ao longo da área de estudo.

Number	Erosion indicator	Brief description
1	Splash pedestals	Describes the created craters by raindrop and protected soil column by stone, root or crop residues. Commonly found under and outside tree canopies.
2	Sheetwash	Marked by runoff flow path leaving smoothed surface that shows direction of the flow.
3	Rills	Continuous or discontinuous channels. Developed after intensive rainfall events, beginning from a short distance from the ridge-crest or base of a plant; due to the leaf structure that concentrates canopy-intercepted rainfall.
4	Root exposure	Exposure of aerial roots after topsoil is stripped off by runoff and splash effect of raindrop. Indicates that topsoil has been removed thus weakening crop stability.
5	Sedimentation	Identified by the burying of crops/grass or deposition of "new soil". Marked by a fertile or infertile area in a field. Soil material could be dark nutrient-rich or coarse sandy/stony deposit.
6	Broken SWC	Marked by gaps in formally continuous strips/bands of conservation structure. Reveals excessive runoff that could not be contained by the existing structures.
7	Stoniness	Small loose stones lying on the soil surface. Overlaying topsoil and subsoil layers have been removed by water erosion.
8	Rock outcrops	Partly exposed rocks. Indicates that soils are shallow and have been washed off by runoff flow, exposing tips of underlying parent rock.
9	Gullies	Larger than rills and locally distinguished from rills when a 7 year-old child cannot jump across.
10	Red soils	Top-dark soils have been removed by runoff. Strong indicator of severely eroded and unproductive soils.
11	Loose soils	Soils prone to wind erosion and easily scoured by runoff water. They are neither dark nor red but have poor water-holding capacity. They do not occupy large areas since they are interspersed between red and darker soils.

Source: Okoba & Sterk (2006).

from “null - very low” risk areas ( $< 10 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ) to “very high” risk areas ( $> 200 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ). As Figure 2, Table 3 also indicates that the predominant class is “null – very

low” for the four erosion maps. This class occurred in 79.9% of the 1988 SLE map, in 82.3% of the 1995 SLE map, in 76.8% of the 2003 map and in 76.8% of the 2011 map.

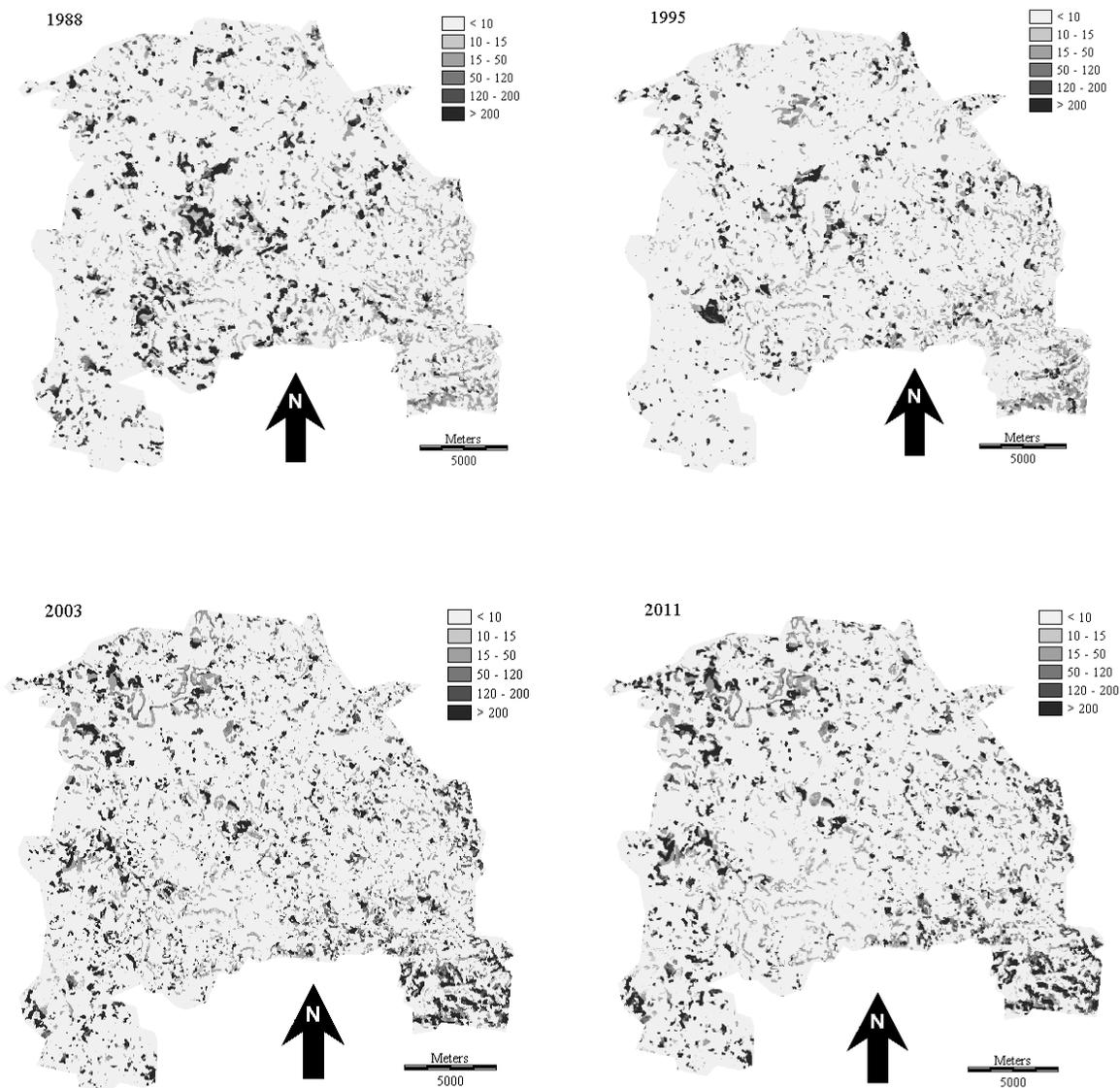


Figure 2. Soil loss expectation maps for Sorocaba (values in  $\text{Mg ha}^{-1} \text{ y}^{-1}$ ). In the legend, class “ $< 10$ ” means null/very low soil loss expectation, “ $10 - 15$ ” means low, “ $15 - 50$ ” means medium, “ $50 - 120$ ” means medium / high, “ $120 - 200$ ” means high and “ $> 200$ ” means very high.

Figura 2. Mapas de expectativa de perda de solo para Sorocaba (valores em  $\text{Mg ha}^{-1} \text{ a}^{-1}$ ). Na legenda, a classe “ $< 10$ ” significa expectativa nula / muito baixa, “ $10 - 15$ ” baixa, “ $15 - 50$ ” média, “ $50 - 120$ ” média / alta, “ $120 - 200$ ” alta e “ $> 200$ ” muito alta.

Table 3. Percentages of occurrence of each SLE class according to the studied years.

Tabela 3. Porcentagens de ocorrência de cada classe de expectativa de perda de solo conforme os anos estudados.

Range of values	1988	1995	2003	2011
< 10	79.0	82.3	76.8	76.8
10 to 15	5.3	5.1	4.5	4.2
15 to 50	7.0	6.6	7.5	7.7
50 to 120	1.6	1.2	2.7	2.9
120 to 200	0.8	0.6	1.4	1.4
> 200	6.3	4.2	7.1	7.0

Table 4 indicates that small alterations in the percentage of occurrence of each class have occurred in the investigated period. In general, the two classes that indicate smaller soil loss rates decreased between 1988 and 2011 and the four classes that indicate major soil loss rates increased. This situation is closely linked to areas where bare soils/suburban settlements occurred. These areas were slowly substituted by the “urban settlement” class through the years, causing a decrease in the erosion risk.

Similarly as observed by Sparovek & Schnug (2001) in Piracicaba City (Brazil – 100 km from the study area) and Mati *et al.* (2000), large and uninterrupted areas of low soil loss values were observed for the land cover classes “pasture” and “forest”. On the other hand, highest erosion risk areas were scattered throughout the study area, with some concentrations occurring in the central

part of the municipality, as also reported by Cerri *et al.* (2001) for the Piracicaba River Basin.

Sparovek & Schnug (2001) also mention the average rate of soil formation ( $-0.0002 \text{ m y}^{-1}$ ) and the constant value adopted for soil density ( $1,200 \text{ kg m}^{-3}$ ). Taking into account these values and comparing with soil loss rates observed in this study, we could suppose that the soil loss rate in Sorocaba is higher than the average rate of soil formation in 94.2% of the area for the 1988 SLE map, 93.9% of the area for 1995, 92.7% of the area for 2003, and will be 91.8% of the area for 2011. Considering these set of values as an indicator of environmental sustainability (Van der Werf & Petit, 2002), we may conclude that, although the soil loss is predominantly low along the study area, the land cover and use of Sorocaba is far from being sustainable.

Table 4. Percentage increase or decrease for each SLE class according to the considered time interval.

Tabela 4. Percentual de aumento ou diminuição de cada classe de EPS conforme o intervalo de tempo considerado.

Range of values	1988 - 1995	1995 - 2003	2003 - 2011	1988 - 2011
< 10	3.3	-5.5	0.0	-2.2
10 to 15	-0.2	-0.6	-0.3	-1.1
15 to 50	-0.4	0.9	0.2	0.7
50 to 120	-0.4	1.5	0.2	1.3
120 to 200	-0.2	0.8	0.0	0.6
> 200	-2.1	2.9	-0.1	0.7

Table 5 presents the occurrence of erosion indicators in relation to each SLE map class. Almost all observed erosion indicator categories appear predominantly in the SLE class “< 10”. This shows the inevitable uncertainties that exist in the erosion mapping, as also reported by Lu *et al.* (2003) and Oliveira *et al.* (2007). In the study carried out by Oliveira *et al.* (2007), the authors did not find high soil loss expectative values in the mapping (also executed using USLE and GIS). However, in many places they registered, photographically, the occurrence of erosion features. They registered the occurrence of rills and sedimentation, two of the most common erosion indicators found in the present study. Here, the occurrence of erosion indicator number 5 (sedimentation) mainly in class “< 10” was not considered a surprise because in areas with plane relief, USLE frequently outputs low values of soil loss, mainly due to LS factor (most markedly the S factor – slope) (Desmet & Govers, 1996).

Gullies occurred in three occasions and two of them are directly associated with the mismanagement of the runoff generated in the adjacent highway.

Such apparent inconsistency between erosion mapping and occurrence of erosion indicators along the study area is probably due to the resolution of the digital material used in this study (30 meters) and, on the other hand, the majority of the erosion indicators occurred in a relatively small area.

Two erosion indicators that successfully showed a relationship with erosion mapping were sediment delivery ratio in the rivers (Silva, 1999; Lu *et al.*, 2003) and

evaluation of loss of soil fertility, the latter especially for sheet erosion that is normally present in rural areas.

As detailed in LRRB (2003), the basic steps to control erosion and sediment loss are the following: 1. Minimize both the area and time that soil is exposed. 2. Manage storm water moving across a site by reducing its speed and volume. 3. Install erosion and sediment control measures early in construction (keep them well maintained). 4. Keep sediment on site. 5. The seeding activity can reduce erosion by 90% in areas under human interventions (urban or agricultural). 6. Maximize vegetation establishment by knowledgeable selecting the appropriate seed, preparing the seedbed, and planting at the right time. Hence, these the first procedures that should be considered to avoid problems of sediment accumulation in streams and also avoid flooding and other related hydrological problems.

## CONCLUSIONS

Taking into account the wide spatial diversity and some limitation in the data (especially for erodibility) it was found that in general the USLE successfully predicted the soil loss expectation in the study area. Un-planned urban intensification was considered the most important driving force that accelerated soil loss. The GIS-USLE simulations for 1988, 1995 and 2003 revealed similar general trends - that the erosion risk in most of the city is low and that areas at high erosion risk are localized.

Table 5. Number of observed erosion indicators in relation to SLE map classes.

Tabela 5. Número de indicadores de erosão observados em relação às classes do mapa de expectativa de perda de solo.

E. I.	< 10	10 – 15	15 - 50	50 - 120	120 - 200	> 200	Totals
1	6	-	1	1	-	4	12
2		17	1	8	-	-	5
31	3	33		3	4	-	-
6	46	4	3	-		-	-
-	-	3	5	10	3	4	
1	-	2	20	6	-	-	-
-		-	-	0	7	21	3
6	1	-		8	39	8	1
-	-	-	-	-		1	9
-	1	-	-	1	1	3	
10	1	1	-	-	-	1	3
11	3	1	1	-	-	1	6
No E. I.	14	5	2	-	-	2	23

Although these latter areas are scarce compared to the study area, they have a significant negative impact on the soil and water quality of the area, and programs to reduce the erosion risk need to be implemented.

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