

Proposal for selection of control, preventive and rehabilitation measures based on degradation land level and geoindicators in the fortaleza metropolitan region, State of Ceará, Brazil

Lázaro Valentin Zuquette · Jaime Quintas dos Santos Collares · Osni José Pejon

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Abstract Preventive, controlling, rehabilitative and corrective measures to improve the environmental quality of the hydrographic basins of the Fortaleza metropolitan region in the state of Ceará (Brazil) are presented based on geological and geotechnical data, land degradation rates and sources, and other geoindicators. The region is affected by coastal and stream erosion, gravitational mass movement, dunes, silting, and water pollution, sanitary landfills in inappropriate sites, decommissioned and abandoned aggregate mining, and swamp areas. Geoindicators were used to classify each of the 12 hydrographic basins as possessing low (4), intermediate (3), or high (5) degradation levels. A group of 59 environmental management measures related to ecological, bioengineering, mechanical, policy and administrative, agricultural and clean-up methods was selected. From this general group a set of 31 measures was chosen considering goals, efficacy for specific environmental problems, suitability for large or small areas, behavior under different annual climatic conditions, environmental problems of the region, geological and geotechnical limitations and degradation level of the basins. A set of the more suitable geoindicators was selected for monitoring efficiency of the measures for each basin.

Keywords Land use management · Regional planning · Brazil · Ceará

Introduction

The goal of regional environmental management is to improve the environment using preventive, controlling, corrective and rehabilitative measures in areas and sites degraded by intense natural processes (erosion, gravitational mass movements, flooding, etc.) and anthropic influences (pollution, excavation, mining, water exploitation, agriculture, etc.). According to the intrinsic characteristics the management measures can be classified into ecological, bioengineering, mechanical, policy and administrative, agricultural, and remedial types.

Barrow (1991) also states that “to establish the significance of land degradation, an assessment is necessary of the degree and extension of damage and whether it has been controlled or is reversible”. According to Blaike and Brookfield (1987), degraded land is one which has deteriorated in quality or suffered a decline in its capabilities. These changes are identified by geological, biological, and socio-economic processes, assessed by different magnitudes, severities, effects, and extension. Degraded land can be ranked by the scale of disturbance. In Brazil, anthropic interferences (agriculture, urban, industrial, and mining activity) and natural processes have created different types of land degradation of varying magnitudes.

Several ways exist to assess land degradation. Geoindicators are highly appropriate because they can identify a minimum set of parameters that describe short-term environmental dynamics. There are proxies

L. V. Zuquette (✉) · O. J. Pejon
Departamento de Geotecnia,
Escola de Engenharia de São Carlos,
Av. Trabalhador São-Carlense, 400,
13,566-590 São Carlos, Brazil
e-mail: lazarus1@sc.usp.br

J. Q. dos Santos Collares
CPRM-Brasil, 60,190-070 Fortaleza, Brazil

representing all parameters on which degradation processes depend (Berger 1997).

Geoindicators have been used for integrating environmental monitoring and identifying environmental changes, impacts, hazard damages, improvement, and rehabilitation degrees. Satisfactory results using these markers have been demonstrated by Berger (1996, 1997), Bush et al. (1999), Osterkamp and Schumm (1996), Gupta (2002), Osterkamp (2002), Morton (1996, 2002), and Zuquette et al. (2004b) due to the spatial and temporal aspects and inexpensive assessment methods.

The Fortaleza metropolitan region in the state of Ceará, northeastern region of Brazil, has registered several types of land degradation within the past 15 years. The population of this region has rapidly expanded and the environment has been strongly affected. Today, there are 4 million people living there, mainly in the coastal portion (within 15 km of the beach). Urbanization has caused environmental changes such as canalizations, man-made slopes, earthfills, sanitary landfills, aggregate exploitation, and land relief alternation. Environmental problems are evident throughout the region. Heavy investments have been made to rehabilitate degraded areas and to implement protection and control measures to avoid environmental problems, but results have been unsatisfactory. The greater part of the environmental management measures has been allocated for specific sites. Response has been inadequate for large areas such as hydrographic basins.

A study was performed to develop a system or matrix to select environmental management measures to improve the environmental quality in the Fortaleza metropolitan region as a whole.

Methodology

Previous data from an engineering geological mapping (Zuquette et al. 2004a) and environmental degradation levels of the basins (Zuquette et al. 2004b) based on the geoindicators were considered to select suitable environmental management measures.

Zuquette et al. (2004b) had delimited 12 drainage basins based on maps and charts elaborated by Zuquette et al. (2004a). The environmental problems and geoindicators defined the degradation as low, intermediate or high for each basin. Geoindicators were derived from basic engineering geological mapping carried out at regional and local scales by Zuquette et al. (2004a). A set of maps (lithological, unconsolidated

materials, pollution sources and drainage basins) and charts (slope, environmental problems, and water resources) was developed based on information from field and laboratory work. Nineteen environmental geoindicators (hydrological, geomorphological, climatological, and geological components, vegetation, water quality, and land-use patterns) were selected to assess land degradation and to choose adequate control, preventive, rehabilitative, and corrective measures.

The geoindicators were: shoreline position, soil and sediment erosion, relief changes, channel changes, surface water quality, stream sediment storage, dune changes, slope failures, stream channel changes, vegetation changes, ground water quality, pollution sources frequency, flooding frequency and intensity, urban and construction damages, depression of groundwater level, alteration of groundwater flow direction, alteration of surface water flow direction, organic material destruction and salt water intrusion into shallow groundwater aquifer.

Based on previous data (Zuquette et al. 2004a, b), general environmental management measures were selected to affect positively the next environmental aspects: minimize soil exposure, divert surface runoff, protect denuded surfaces, improve riparian vegetation, maintain low runoff velocities, minimize length and steepness of landforms, provide protection measures to pollution sources, control groundwater extraction, recover natural vegetation, insure adequate soil uses, implement adequate drainage system maintenance, and improve slope stability.

Fifty-nine environmental management measures (Tables 1, 2, 3) were selected based on the following points:

1. efficiency for specific environmental problems,
2. adaptability to large or small areas,
3. geological and geotechnical limitations,
4. adaptability and behavior under different annual climatic conditions,
5. efficiency for the environmental problems detected in the region (water erosion, accelerated coastal zone erosion, swamp area and sedimentation of lakes; water pollution, waste deposits, mining; dune movement, gravitational mass movements and flooding areas), and
6. capacity to give results in a short time.

A set of environmental management measures was then selected for each basin from the general list (Tables 1, 2, 3) based on the following aspects:

1. types of environmental problems found in each basin,

Table 1 General list of ecological and bioengineering measure types

Types/measures	Land degradation sources (a)	Targets (e)	Geological and geotechnical aspects (c)	Cost and efficiency (d)	Suitable geoindicators for monitoring (b)	Limitations for implanting the measure
Ecological						
Seeding	1,2,5,6,7	1,3,9,11,12	1	3	5,6,2,7,8,10,18	Large areas
Hydraulic mulches	1,6,7	1,3,9,11,12	1	1/2	5,6,2,7,8,10,18	Large areas
Windbreaks (shelterbelts)	7	1,3,9	3	1	2,7,14	High-cost maintenance
Turf	1,9	1,3,9,11,12	1	3	5,6,2,7,10,18	Turf sources
Grass lines	1,9	2,3,5,9	1	3	5,6,2,7,10	Temporal solution
Wood live barriers	1,9	2,3,5	1	3	5,6,2,7,10	Efficiency
Forest trees	1,7	2,3,5,9	1	3	5,6,2,1,7,8,14,17	Adequate sites
Vegetated riprap	1,6,7	12	2	3/4	5,6,2,1,7,8,14,17	Specific sites, e.g., (man-made slope)
Grassed water ways	1,7	5	1	1	5,6,2	High-cost maintenance
Bio-filters	1,6,5	7	2	2	5,6,2	Efficiency
Sediment trap	1	7	2	2	5,6,2,9,11	Efficiency
Riparian vegetation improvement	1,3,6,7,9	1,3,4,9,10,11,12	3	3	2,4,5,6,9,10,13	Existing environmental conditions
Revegetation (native species)	1,3,6,7,8	1,2,3,4,5,9,11,12	1	3	5,6,2,7,8,10,11,14,15,17,18	Adequate soil and climatic conditions
Bioengineering						
Soil conditioners	1,6,7	1,3	1	1	5,6,2,7,8	Expensive and soil types
Erosion control blankets	1,2,6,7	1,3	2	1/2	5,6,2	Very specific sites: vegetation dependency
In soil structural blankets	1,2,6,7	1,3	1	1/2	5,6,2	Vegetation dependency
Gabions with trees	1,2,3,5,6,7	1,3,12	2	1	5,6,2,1,3,8,9,14,18	Weather vulnerability
Geotextiles	4,5,6,7	11,12	1	1	5,6,2,1,7,11,18	Expensive

(a) 1 water erosion, 2 accelerated erosion of the coastal zone, 3 swamp area and sedimentation of lakes, 4 water pollution, 5 waste deposits, 6 mining, 7 dune movement, 8 gravitational mass movements, 9 flooding areas

(b) 1 shoreline position, 2 soil and sediment erosion, 3 relief changes, 4 channel changes, 5 surface water quality, 6 stream sediment storage, 7 dune changes, 8 slope failures, 9 stream channel changes, 10 vegetation changes, 11 ground water quality, 12 pollution source frequency, 13 flooding frequency and intensity, 14 urban and construction damages, 15 depression of groundwater level, 16 alteration of groundwater flow direction, 17 alteration of the flow direction of the surface water, 18 organic material destruction, 19 salt water intrusion into shallow groundwater aquifer

(c) 1 very important, 2 important, 3 moderately important

(d) 1 high cost and high efficiency, 2 high cost and low efficiency, 3 low cost and high efficiency, 4 low cost and low efficiency

(e) 1 minimize soil exposure, 2 divert surface runoff, 3 protect denuded surfaces, 4 improve riparian vegetation, 5 maintain low runoff velocities, 6 minimize length and steepness of landforms (slopes), 7 provide protection measures to the pollution sources, 8 control of the groundwater extraction, 9 recover natural vegetation, 10 adequacy of soil uses and occupations, 11 maintain adequate drainage systems, 12 slope stability improvement

Table 2 General list of mechanical measure types

Types/measures	Land degradation sources (a)*	Targets (e)	Geological and geotechnical aspects (c)*	Cost and efficiency (d)*	Suitable geoindicators for monitoring (b)*	Limitations for implanting the measure
Emulsion and binders	4,5,6	1,3	1	2	2,5,6,7	Temporal solution
Silt fences	1,2,4	7	2	2	2,4,5,6,9,11	Temporal solution and expensive
Sedimentation ponds	1,2,4	7	2	2	2,4,5,6,9,11	Temporal solution and high-cost maintenance
Gravel filters	4,6,8	11	1	3	2,4,5,6,8,14,15,16	Specific sites
Piper drains and inlets	4,6,8	11	1	1	2,4,5,6,8,15,16	Specific soil conditions
Riprap	2,5,6,7,8	3	2	3	1,7,9	Specific sites
Sand bags, bales, log-wood cribs	2,5,6,7	3	2	1/2	1,7,8,9	Preventive use
Hydraulic matrices	1,2,5,6,7	3	1	1/2	1,4,8	Expensive
Containment structures	1,2,5,6,7	3	2	1/2	1,4,8	Lifespan depends on material vulnerability
Formed concrete	1,2,5,6,7	1,3	2	1	1,7,8	Low durability
Concrete and masonry	1,2,5,6,7	1,3	2	1/2	1,7	Expensive
Check dams	1,2,3,4	7	2	1	2,4,5,6,9,11,13	Regular maintenance required
Drop structures	1,2,3,4	1,3	2	1	2,5,6	Expensive
Drop chutes and flumes	1,2,3,4	1,3	2	1	2,5,6	Expensive
Energy dissipaters	1,2,6,9	2,5,11	2	1	1,3,4,9,13	Expensive
Terraces	1,3,9	2,5,6,7,10,12	1	3	2,3,5,6,8,11,13,17,18	Steepness
Regulation dam	1,3,4,9	11	1	1	4,9,11,13	High-cost maintenance
Discharge regulation	1,3,4,9	11	2	1	4,6,9,11,13,14	Expensive
Streambank protection	1,4,9	4	1	1/3	2,4,5,6,9,14	Specific conditions
Drainage systems	1,2,3,8	11,12	1	1	2,3,5,6,8,9,13,14,15,16,17	Expensive
Canalization	9	7	1	1	2,4,5,6,10,13,14	Expensive
Longitudinal protection		11	1	1/3		
Contouring	1,9	2,5,6,10,11	1	3	2,3,5,6,13,17	Steep areas
Counter ditches	1,9	2,5,6,10,11	1	3	2,3,5,6,17	Steep areas and shallow soils
Contour bunds	1,9	2,5,6,7,10,11,12	1	3	1,2,5,6,11,13,17	Steep areas and shallow soils
Water ways	1,9	11	1	3	2,5,6,17	High-cost maintenance
Stabilization structures	8	11,12	1	1	3,4,8,14,16	Expensive
Increase resisting forces: structural systems, berms, anchors (external forces), reinforcement systems, subsurface drain, biotechnical stabilization (internal strength)	8	11,12	1	1/3	3,4,8,14,16	Geological and geomorphic characteristics
Reduce driving forces: change grade, subsurface and surface drain, reduce weight	8	11,12	1	1/3	3,4,8,14,16	Soil and site limitations

Footnotes as in Table 1

2. targets affected positively by measure,
3. geological materials and geotechnical conditions in the basin,
4. cost and benefit ratio,
5. suitable geoindicators for monitoring, and
6. limitations related to the measures.

General description of study area

Location and urban centers

The Fortaleza metropolitan region is in the state of Ceará, Brazil (Fig. 1), with an area of about 3,500 km² between longitudes 38°15' and 39°W, and latitudes 3°30' and 4°15'S. Several urban centers, with populations ranging from 1,000 to 180,000 inhabitants, and the city of Fortaleza, with 2 million inhabitants, are included in the region.

Geomorphologic and climatic characteristics

The region presents altitudes varying from 0 to 800 m, most of which are lower than 100 m. Geomorphologically it is divided into three units.

Coastal lands consisting of dunes, beaches, and fluvio-marine plains, with slopes lower than 3°, and some localized cliffs (active, stable, and dead) with slopes steeper than 45°. Annual average temperature ranges from 39 to 19°C, insolation averages 2,650 h/year, and rainfall is between 1,200 and 1,400 mm/year.

Interior plain characterized by altitudes of up to 100 m: u-shaped and rectilinear valleys presenting low inclinations (predominantly between 2 and 11° slope). There are fluvial plains comprised of sandy alluvium. Annual average temperature is between 33 and 23°C, insolation is 2,650 h/year, and rainfall is between 900 and 1,400 mm/year.

High residual massifs composed of granitic and migmatitic rocks with altitudes of up to 800 m. The slopes are predominantly higher than 11° with average values of around 45°. Annual average temperature is between 25 and 15°C, insolation is 2,650 h/year, and rainfall is between 1,400 and 1,600 mm/year.

The annual potential evapotranspiration varies from 1,500 mm in the coastal zone to 2,800 mm in the interior plain, with values exceeding 3,300 mm when a long dry period occurs. A total water deficit of around 800 mm is frequent throughout 8 months of the year.

Geological materials

The outcropping geological materials are shown in a simplified map (Fig. 2) elaborated by Zuquette et al. (2004a). Lithologically, the region is constituted of sandstones, siltstones, conglomerates, and claystones of the Barreiras Formation of the Tertiary age, and a large diversity of igneous and metamorphic lithologies such as granites, gneisses, migmatites, pyroxenites, phonolites, and trachytes.

The main unconsolidated material units defined and delimited are:

1. Residual from the Barreiras Formation unit: constituted of unconsolidated materials from siltstones and claystones, and secondarily by sandstones. The weathered profiles are very heterogeneous due to spatial distribution of lithotypes and position in relief.
2. Residual unconsolidated materials from Igneous and Metamorphic lithologies as gneiss, granites, and migmatites. These present thicknesses of less than 2 m and the weathered profiles are little developed, thus retaining some intrinsic characteristics of the rocks. Due to relief evolution, small colluvial deposits overlying the residual materials are very common.
3. Residual unconsolidated materials from granites/migmatites with weathered profiles showing different materials and depth, normally controlled by fractured zones.
4. Alluvial deposits occur in the flood zones of main rivers in the region. They present varied textures and thicknesses, poor drainability; and a high percentage of organic materials. In the fluvio-marine plains, they are classified as swamp and have high saline concentration.
5. Colluvial deposits constituted of rock blocks and sandy particles are found at the foot of the highlands.
6. Dunes and palaeodunes are located in the coastal zone and present sandy texture (>95% of fine and medium sand), without cohesion, thicknesses varying from 2 to 50 m, and hydraulic conductivity higher than 10⁻⁵ m/s.
7. Low-depth Palaeodunes less than 5 m in depth overlie other geological material. However, the palaeodunes present more stability than dunes because they are characterized by an outcropping layer rich in organic materials due to vegetation.

Table 3 General list of policy and administrative, agricultural practice, and clean-up and remedial measure types

Types/measures	Land degradation sources (a)*	Targets (c)	Geological and geotechnical aspects (c)*	Cost and efficiency (d)*	Suitable geointicators for monitoring (b)*	Limitations for implanting the measure
Policy and administrative						
Regulation of groundwater pumping	4	7,8,11	1	3	19,15,16	Control rules
Increase of infiltration rate	1,7	7,8,11	1	3	15,19	Soil characteristics
Avoid problems: relocate facility	8,9	7,8,11,12	1	3	11,18	Control and regulation
Avoid problems: remove unstable materials	8,9,5,7	7,8,11,12	1	3	3,7,12	Site limitations
Avoid pollution sources	4,5	7,8,11	1	3	19,15,16	Adequate legislation
Territorial planning rules and legislation	1,2,3,4,5,6,7,8,9	1,2,3,4,5,6,7,8,9,10,11,12	1	3	2,7,10,11,13,15,18,19	
Agricultural practices						
Forest trees (commercial species)	1,3,6,7,8	1,2,3,4,5,9,11,12	1	3	5,6,2,7,8,10,11,14,15,17,18	Adequate soil and weather
Mulching	1	1,3,5,9	2	3	2,5,10,17,18	Soil conditions
Strip-cropping	1	1,3,5,9	2	3	2,5,10,17,18	Soil conditions
Clean-up and remedial techniques						
Pumping wells	4,5	7	1	1/2/3	6,11,12,19	Geological and geotechnical conditions
Barriers	4,5	7	1	1/2/3	6,11,12,19	Geological and geotechnical conditions
Top capping	4,5	7	1	1/2	6,11,12,19	Adequate site and material conditions
Waste removal	4,5	7	1	1/2	6,11,12,19	Waste and polluted geological material volume

Footnotes as in Table 1

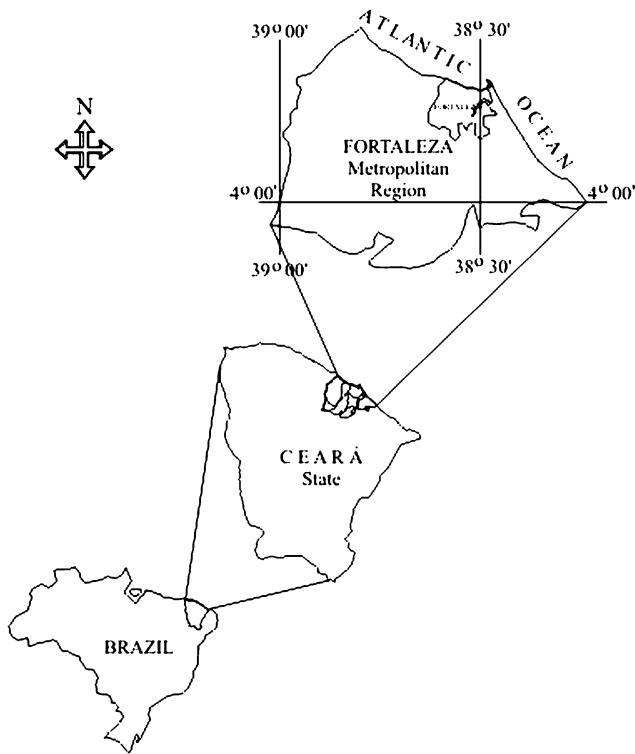


Fig. 1 The Fortaleza metropolitan region location map

Surface and groundwater

A chart elaborated by Zuquette et al. (2004b) shows 4 aquifers and 12 drainage basins (Fig. 3). The Cocó, Maranguapinho, Ceará, Jua, and Cauípe rivers and the coastal basins are entirely within in this region. Parts of São Gonçalo, Gereraú, and Curu basins are also included, and only the upstream Cponga Funda, Catu, and Pacoti basins are outside the region.

Among the basins, the Ceará and Pacoti basins are responsible for about 50% of the total regional stream discharge. There are 23 reservoirs in one-third of the Ceará Basin and 25 in the upstream half of the Pacoti basin. Considering the stream discharge/km² rates, the Juá, Pacoti, Cponga Funda, and Gereraú basins stand out because of their contribution to the total regional stream discharge. The Juá and Cponga Funda basins present special characteristics because they are basically constituted of lithologies pertaining to Barreiras Formation, dunes, and palaeodunes. Urban occupation of these basins has intensively affected the infiltration rate and annual discharges. The main groundwater sources are: dunes and palaeodunes formed of sands spread along the coastal zone; alluvial deposits predominantly overlying all the regional lithologies, and which are intensely exploited when they cover igneous and metamorphic rocks in the

interior plain zone; and the Barreiras Formation presents high heterogeneity with permeable and non-permeable layers. When a permeable layer occurs, hydrogeological parameters are very favorable for water supply and the fractured aquifer presents high heterogeneity. As the rivers are associated with fractures, the success of the wells depends on the recharge by rivers and alluvial deposits in open fractures. Waters from fractured aquifers present high saline concentration when associated with saline unconsolidated materials.

Analysis

Natural processes (water and coastal erosion, silting, dune movement, gravitational mass movement, and flooding) and human interferences (mining, water pollution, waste disposal) have been identified as land degradation factors in several areas (Fig. 4). These factors are described in Zuquette et al. (2004b). Despite measures implanted at some sites, results have not been satisfactory and problems have continued. Figure 4 indicates locations of sites shown in Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18

A brief description of land degradation sources follows.

Water erosion

During the past 50 years, deforestation caused by agriculture, raising cattle, urbanization, and other land uses has occurred in the region. Deforestation combined with geological materials and agricultural activities has triggered intense water erosion predominantly of the sheet and rill types, which have changed drainage channels, siltation of rivers, lakes and reservoirs, and stripped organic material.

Accelerated erosion of the coastal zone

The coastal line of the Fortaleza metropolitan region is 35 km long. Heavy urban occupation occurs mainly in the downstream parts of the Cocó, Ceará, Maranguapinho, and Pacoti basins. Rates of wind erosion from dunes to the beaches and sediment retention in the small dam reservoirs and changes in marine wave orientation due to the moles built in the past 30 years (Figs. 5, 6, 7, 8) all contribute to coastal erosion.

For nearly 60 years, several civil engineering works have been built in this region. The loss of sandy beaches and buffer zones from these projects has caused serious changes in erosion and sediment transport

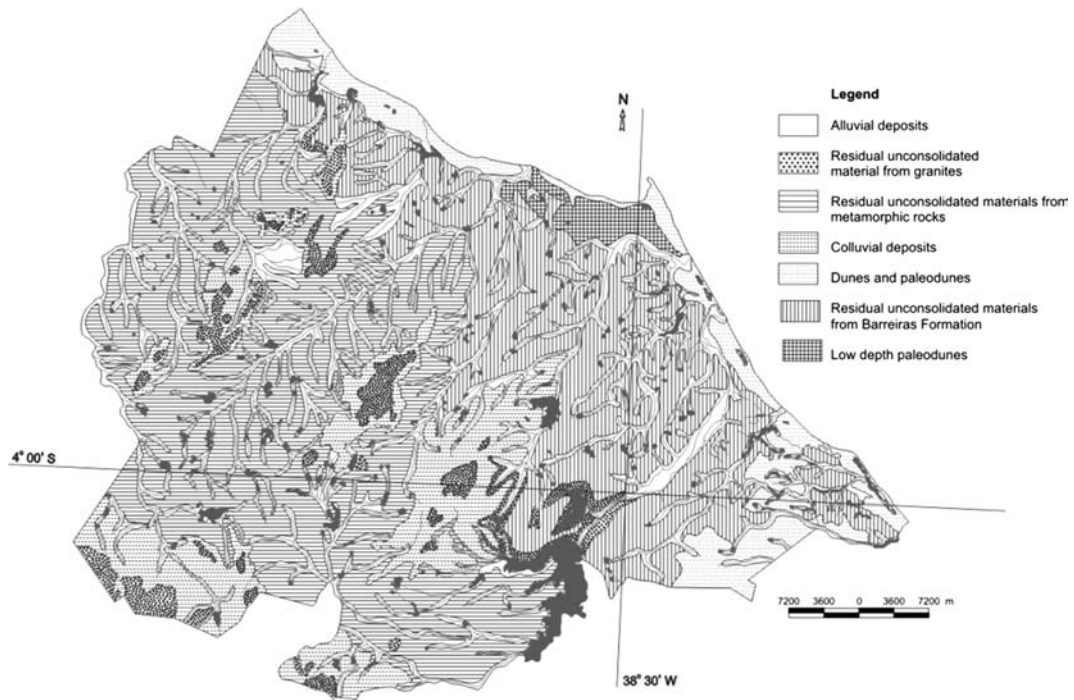


Fig. 2 Map of the outcropping geological materials (after Zuquette et al. 2004a)

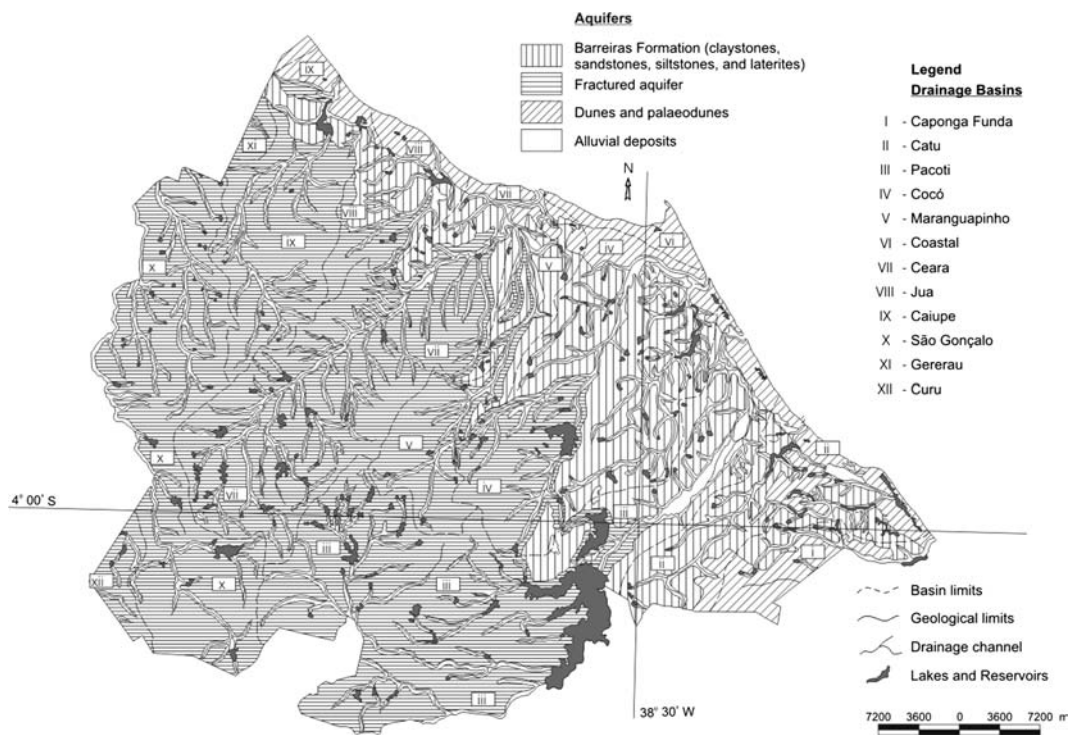


Fig. 3 Surface and groundwater chart (after Zuquette et al. 2004b)

behavior by rivers, wind, and longshore currents. Intense coastal erosion has resulted. The changes in erosion/sedimentation of the coastal zone have produced economic and environmental losses.

Swamp area and sedimentation of lakes

Swamps and lakes are mainly located in the alluvial plains and cover large areas (Figs. 9, 10). The lakes are sources of potable water, and the swamps are the important economic resources for salt extraction and fishing. The main anthropic activities that accelerate land degradation here are: earthfill for implementing civil works, deforestation near lakes and swamps for urban activities, salt exploitations, small earth dams, changes in the drainage channels, and canalization of the rivers in the urban zones.

Water pollution

The aquifer constituted of the sandstones of the Barreiras Formation and reservoirs and lakes are the main water sources for the regional population and industries. All sources have been affected by pollutants. There are point sources (cemeteries and sanitary landfills) and non-point sources (urban areas, agriculture zones) located in aquifer recharge areas. Surface

water has shown contamination by coliformes, nitrates, chorines, and ions from urban, agricultural, and industrial activities. Most contaminants are transported by surface runoff (Fig. 11). Domestic and industrial liquid wastes are disposed of in cesspools or directly into a surface water body. The Barreiras aquifer shows contamination by nitrates and inorganic ions from cesspools and agricultural usages (Fig. 12).

Almost all waters used to supply human and industrial needs are from shallow aquifers or surface waters which can easily be contaminated by anthropic interferences.

Sanitary landfills

Improper sanitary landfills can cause water, soil, and air pollution. Solid and liquid wastes and other garbage from urban residences, industries, and hospitals were disposed at a site called Jangurussu located on the Coco' River flood plain on alluvial material and sandstones of the Barreiras Formation about 20 km from coastal line (Figs. 13, 14, 15). The Aquiraz landfills are located in the Pacoti river basin (Fig. 4). The Jangurussu uncontrolled sanitary landfill reached 30 m high and covered 1.0 km² area. It received 1,500 tons/day, about 75% of regional solid wastes. Two new sanitary landfills (Fig. 4) are located on the metamor-

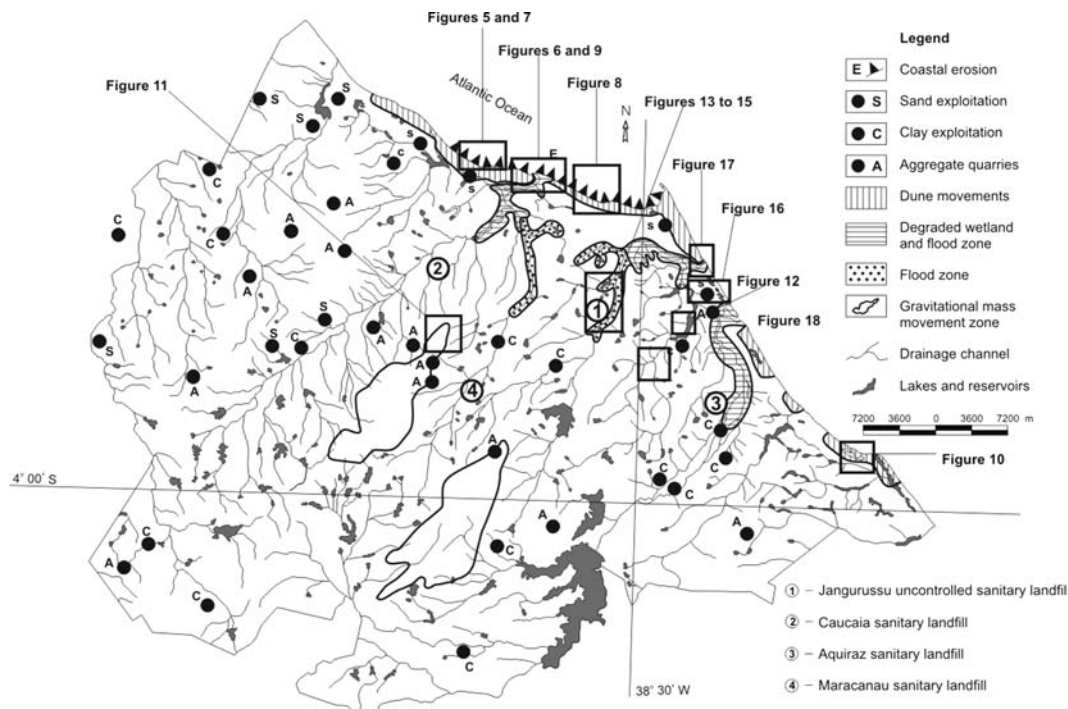


Fig. 4 Distribution of some problems responsible for land degradation in the Fortaleza metropolitan region (modified from Zuquette et al. 2004b)

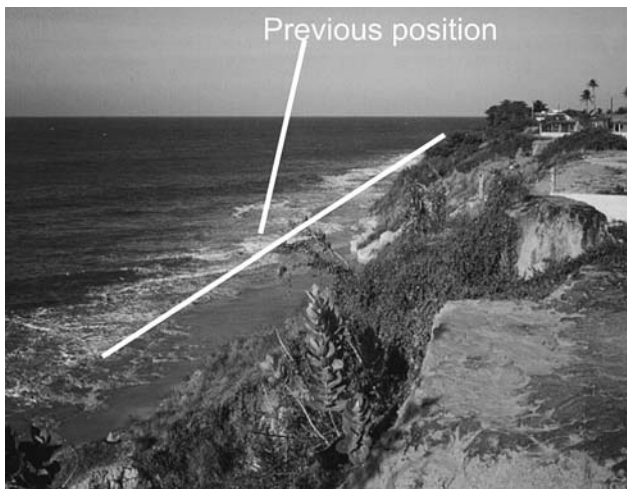


Fig. 5 Intense coastal erosion processes which destroyed and damaged houses and urban infrastructures



Fig. 7 Riprap to protect cliff. But the erosion process has continued in the upper portion



Fig. 6 General view of the estuary of the Ceará River: 1 dikes built (moles) to control erosion/sedimentation processes, 2 dune movements toward the road and residences, and 3 sediment load transported by Ceará River

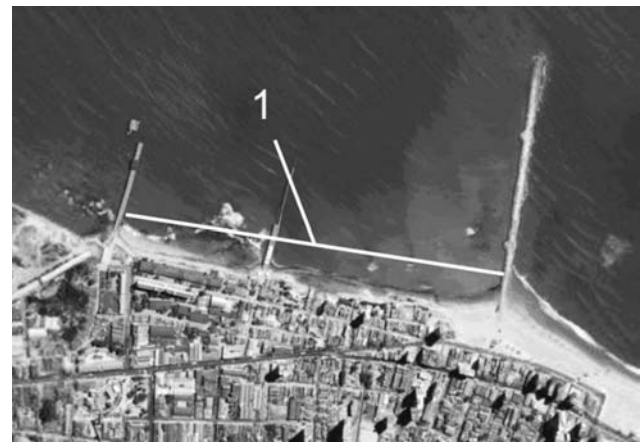


Fig. 8 Very intense coastal erosion in Fortaleza city, despite the protection dikes (1 zone affected by coastal erosion where streets and buildings were destroyed)

phic rocks in the city of Maracanau, the second on the Barreiras Formation on the left side of the Pacoti River, in Aquiraz.

Surface mining

In the quarries, several procedures are used, e.g., removal of sterile materials (soil and rock blocks), deforestation, and blasting with explosives. Sand from dunes, palaeodunes, and sandy soils have been mined for the past 20 years, mainly in coastal zones (Fig. 16). This mining has produced deep excavation, intense erosion processes, silting of rivers and lakes, forest destruction, damage of houses and other buildings by explosions, scars on the land, inadequate disposal of sterile materials, powder, landslides, rock fall and rolling.



Fig. 9 Example of swamp and flood zone associated to Ceará River

Dune movement

Dunes and palaeodunes in the coastal zone have been deeply affected by the rates of wind erosion during the past 25 years due to deforestation and increasing urban occupation.



Fig. 10 Detail of the swamp zone showing natural condition very degraded by anthropic interferences



Fig. 11 Example of lake with high sediment load (arrow) due to water erosion and wastes transported by surface water flow

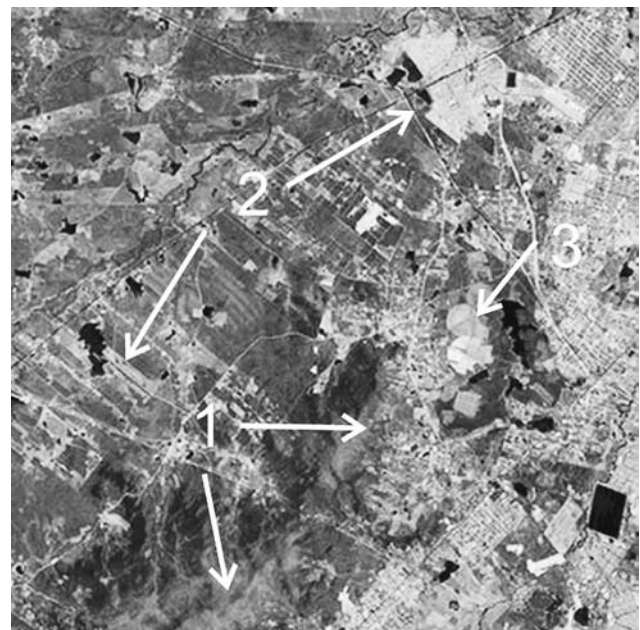


Fig. 12 Satellite image shows the high residual massif (1) and interior plain (2) units with different uses and occupations. Circles (3) are irrigation areas, an important pollutant source due to fertilizer load used



Fig. 13 Location (1) of the Jangurussu uncontrolled sanitary landfill near the (2) Cocó river—environmental conditions in 2002



Fig. 14 Lateral view of the Jangurussu uncontrolled sanitary landfill (1) near the Cocó river (2002)

Dunes have been displaced up to 250 m/year in the dry period and 0.1 m/year in the rainy period. The main damages resulted from dune movements are sedimentation on roads and buildings, lake and river



Fig. 15 Current conditions (vertical view) of the Jangurussu uncontrolled sanitary landfill. Control measures (surface drainage and covering system) implanted after 2004 are visible

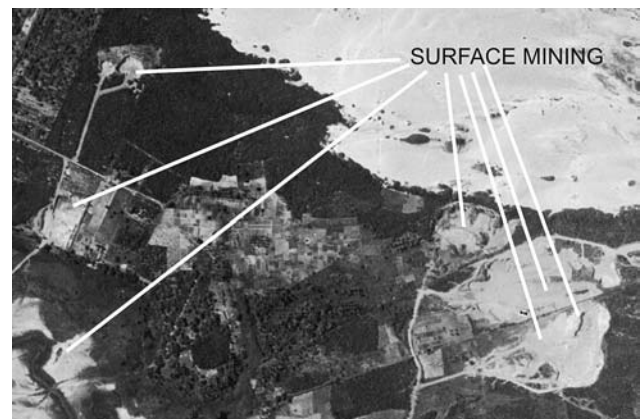


Fig. 16 Abandoned and decommissioned surface mining

impairments (physical effects), and costs of repairing roads, houses, public properties, and production losses (economic effects).

Gravitational mass movements

In high residual massif zones (Fig. 12) landslides, rock fall, and earth flows have occurred causing loss of lives and properties as well as river and reservoir silting. These movements are associated with the following environmental factors: (1) rock blocks controlled by geological structures located in the high altitudes during high intensity rainfalls fall towards drainage channels, (2) accelerated deforestation of highest part of the highlands to allow agriculture development, and (3) residential occupation of inadequate areas located near drainage channels, steep slopes, and scarps.



Fig. 17 Dune movements (*ellipses*) toward vegetation, streets, and building areas in the estuary area of the Cocó River

Flooding areas

Flooding occurs every year during the rainy period. Deforestation, geometric changes, and silting of water channels are the main causes. From February to May rainfall can reach 80% of the annual total. All drainage channels can be affected by flooding in varying intensities due to the low gradients (Fig. 18).

Suggested environmental management measures

A set of the environmental management measures (Tables 4, 5, 6, 7, 8) was selected for each basin. The Coastal, Pocoti, Ceará, Coco, and Maranguapinho basins have been seriously affected and present the highest degradation levels due primarily to anthropogenic causes and, secondarily by natural processes. The Jua, Cauipe, and Catu basins present intermediate



Fig. 18 Example of flood areas where urban infrastructures are frequently affected

degradation levels, while São Gonçalo, Caponga Funda, Gererau, and Curu basins were classified as having low degradation levels.

Water erosion predominates in the upstream portion of the Maranguapinho, Ceará, Pacoti, and Cocó basins, while water pollution is found mainly in the Coastal basin. Urbanization is the main problem affecting 100, 60, 50, and 25% of the Coastal, Maranguapinho (in the downstream portion), Cocó, and Ceará basins, respectively. Floods have affected areas mainly located in the flood plains of the Cocó, Maranguapinho, and Ceará Rivers (Fig. 4).

The Coastal basin contains many small degraded areas. Ecological, bioengineering, and mechanical measures are recommended to control and rehabilitate areas, while policy and administrative measures should be adopted to improve the groundwater quality degraded due overpumping and urbanization.

The Ceará, Coastal, Maranguapinho, Cocó, and Pacoti basins have been affected by coastal erosion more than the other basins.

For the Maranguapinho, Ceará, Cocó, and Coastal basins, six types of management measures were proposed (Tables 4, 5, 6, 7, 8). Ecological, mechanical, policy and administrative, and agricultural measures are predominantly indicated to control water erosion, flood, and groundwater and surface water contamination.

The Pacoti basin, the largest in the region, is very important because dozens of lakes and reservoirs are within its limits and it has the largest swamp area, which has been heavily affected by deforestation and agricultural usage. The downstream half is constituted

Table 4 Preventive, control, corrective, clean-up, and rehabilitation measures proposed for the Caponga Funda and Catu drainage basins and geoindicators for monitoring

Drainage basins/area (km ²)	Environmental management measures																										
	Land degradation sources	Degraded environmental components	Degradation level (Zuquette et al. 2004b)	Geoindicators for monitoring																							
Caponga Funda 75.47	Mining Agriculture Urbanization	Swamp area Water pollution	Low	Dune changes																							
				Stream channel changes																							
Catu 247.30	Mining Agriculture Urbanization	Swamp area Water pollution	Intermediate	Shoreline position																							
				Soil and sediment erosion																							
<table border="1"> <thead> <tr> <th colspan="5">Environmental management measures</th> </tr> <tr> <th>Ecological</th> <th>Bioengineering</th> <th>Mechanical</th> <th>Policy and administrative</th> <th>Agricultural</th> <th>Clean-up techniques</th> </tr> </thead> <tbody> <tr> <td>Revegetation Seeding Hydraulic mulches Wood live barriers</td> <td>Gabions with trees</td> <td>Contouring</td> <td>Regularization of groundwater pumping Avoid pollution sources Improve infiltration rate</td> <td>Strip-cropping Mulching</td> <td></td> </tr> <tr> <td>Revegetation Seeding Hydraulic mulches Wood live barriers</td> <td>Gabions with trees</td> <td>Contouring Check dams Stream-bank protection</td> <td>Avoid pollution sources Regularization of groundwater pumping Rules related to territorial planning</td> <td>Strip-cropping Mulching</td> <td></td> </tr> </tbody> </table>					Environmental management measures					Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques	Revegetation Seeding Hydraulic mulches Wood live barriers	Gabions with trees	Contouring	Regularization of groundwater pumping Avoid pollution sources Improve infiltration rate	Strip-cropping Mulching		Revegetation Seeding Hydraulic mulches Wood live barriers	Gabions with trees	Contouring Check dams Stream-bank protection	Avoid pollution sources Regularization of groundwater pumping Rules related to territorial planning	Strip-cropping Mulching	
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Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques																						
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Revegetation Seeding Hydraulic mulches Wood live barriers	Gabions with trees	Contouring Check dams Stream-bank protection	Avoid pollution sources Regularization of groundwater pumping Rules related to territorial planning	Strip-cropping Mulching																							

Table 5 Preventive, control, corrective, clean-up, and rehabilitation measures proposed for the Pacoti and Cocó drainage basins and geoindicators for monitoring

Drainage basins/area (km ²)	Land degradation sources	Degraded environmental components	Degradation level (Zuquette et al. 2004b)	Environmental management measures						
				Geoindicators for monitoring	Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques
Pacoti 747.06	Mining Agriculture Urbanization Deforestation	Dune movement Sedimentation Swamp area Gravitational mass movement Flooding Water pollution Waste disposal Water erosion	High	Shoreline position Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Dune changes Slope failures Stream channel changes Vegetation changes Ground water quality Pollution sources frequency Flooding frequency and intensities Organic material destruction	Revegetation Seeding Hydraulic mulches Improve riparian vegetation	Geotextiles Gabions with trees	Contouring Rip rap Streambank protection Increase resisting forces Drainage systems Terraces	Regularization of groundwater pumping Increase of infiltration rate Avoid pollution sources Rules related to territorial planning	Strip-cropping Mulching Forest trees	Clean-up techniques

Table 5 continued

Drainage basins/area (km ²)	Land degradation sources	Degraded environmental components	Degradation level (Zuquette et al. 2004b)	Geoindicators for monitoring	Environmental management measures					
					Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques
Cocó 483.96	Mining Urbanization Agriculture Deforestation	Coastal erosion Dune movement Sedimentation Swamp area Gravitational mass movement Flooding Water pollution Waste disposal Water erosion	High	Shoreline position Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Dune changes Slope failures Stream channel changes Vegetation changes Ground water quality Pollution sources frequency Flooding frequency and intensities Urban and construction damages Depression of groundwater level Alteration of surface water flow direction Organic material destruction	Revegetation Vegetated riprap Improve riparian vegetation Windbreaks	Gabions with trees Geotextiles	Streambank protection Check dams Rip rap Increase resisting forces Drainage systems Regularization dam Terraces	Remove instable materials Relocate facilities Avoid pollution sources	Forest trees Mulching	Clean-up techniques

Table 6 Preventive, control, corrective, clean-up, and rehabilitation measures proposed for the Maranguapinho and coastal drainage basins and geindicators for monitoring

Drainage basins/area (km ²)	Land degradation sources	Degraded environmental components	Degradation level (Zuquette et al. 2004b)	Environmental management measures						
				Geoidicators for monitoring	Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural Clean-up techniques	
Maranguapinho 265.05	Mining Urbanization Agriculture Deforestation	Coastal erosion Dune movement Sedimentation Swamp area Gravitational mass movement Flooding Water pollution Waste disposal Water erosion	High	Shoreline position Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Dune changes Slope failures Stream channel changes Vegetation changes Ground water quality Pollution sources frequency Flooding frequency and intensities Urban and construction damages Alteration of surface water flow direction Organic material destruction	Revegetation Improve riparian vegetation Turf Seeding Windbreaks	Soil conditioners Geotextiles Gabions with trees	Contouring Check dams Streambank protection Regularization dam Terraces	Remove unstable materials Relocate facilities Rules related to territorial planning	Strip-cropping Forest trees Mulching	Clean-up techniques

Table 6 continued

Drainage basins/area (km ²)	Land degradation sources	Degraded environmental components	Degradation level (Zuquette et al. 2004b)	Geoindicators for monitoring	Environmental management measures					
					Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques
Coastal basins 31.04	Urbanization	Coastal erosion Dune movement Water pollution	High	Shoreline position Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Dune changes Stream channel changes Ground water quality Pollution sources frequency Urban and construction damages Depression of groundwater level Alteration of groundwater flow direction Alteration of surface water flow direction	Vegetated rip rap Wood live barriers Revegetation Seeding Hydraulic mulches Turf Windbreaks	Soil conditioners Gabions with trees Geotextiles	Rip rap Check dams	Regularization of ground-water pumping Relocate facilities Avoid pollution sources		Clean-up techniques

Table 7 Preventive, control, corrective, clean-up, and rehabilitation measures proposed for the Ceará and Juá drainage basins and geoidicators for monitoring

Drainage basins/ area (km ²)	Land degradation sources	Degraded environmental components	Degradation level (Zuquette et al. 2004b)	Environmental management measures						
				Geoidicators for monitoring	Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques
Ceará 598.73	Mining Agriculture Urbanization Deforestation	Coastal erosion Dune movement Sedimentation Swamp area Gravitational mass movement Flooding Water pollution Waste disposal Water erosion	High	Shoreline position Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Dune changes Slope failures Stream channel changes Vegetation changes Ground water quality Pollution sources Flooding frequency and intensities Urban and construction damages Alteration of surface water flow direction Organic material destruction	Revegetation Improve riparian vegetation Seeding Turf Hydraulic mulches Wood live barriers Vegetated rip rap Windbreaks	Geotextiles Gabions with trees	Contouring Check dams Streambank protection Rip rap Regularization dam Terraces	Remove unstable materials Relocate facilities Increase resisting forces Reduce driving forces Rules related to territorial planning	Strip-cropping Mulching Forest trees	Clean-up techniques
Juá 132.67	Mining Agriculture Deforestation Urbanization	Coastal erosion Dune movement Water pollution	Intermediate/ low	Shoreline position Soil and sediment erosion Surface water quality Dune changes Vegetation changes Pollution sources Alteration of surface water flow direction	Revegetation Seeding Wood live barriers Windbreaks	Geotextiles Gabions with trees	Rip rap Contouring	Avoid pollution sources Remove unstable materials Relocate facilities Regularization of groundwater pumping Improve infiltration rate	Strip-cropping Mulching	

Table 8 Preventive, control, corrective, clean-up and rehabilitation measures proposed for the Cauipe, São Gonçalo, Gereraú, and Curú drainage basins and Geoindicators for monitoring

Drainage basins/area (km ²)	Land degradation sources Types	Environmental problems Types	Degradation level (Zuquette et al. 2004b)	Geoindicators for monitoring	Environmental management measures					
					Ecological	Bioengineering	Mechanical	Policy and administrative	Agricultural	Clean-up techniques
Cauipe 326.99	Mining Deforestation Urbanization Agriculture	Water pollution Dune movement Water erosion	Intermediate	Shoreline position Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Dune changes Stream channel changes Vegetation changes Alteration of surface water flow direction Organic material destruction	Revegetation Seeding Wood live barriers Windbreaks	Geotextile Gabions with trees	Contouring Mulching	Regularization of groundwater pumping Avoid pollution sources	Strip-croppings Mulching	
São Gonçalo 494.59	Mining Deforestation Agriculture Urbanization	Water pollution Water erosion	Low	Soil and sediment erosion Relief changes Channel changes Surface water quality Stream sediment storage Stream channel storage Vegetation changes Pollution sources frequency Alteration of surface water flow direction Organic material destruction	Revegetation Seeding Wood live barriers	Geotextiles Gabions with trees	Contouring Mulching	Regularization of groundwater pumping Avoid pollution sources	Strip-cropping Mulching	

Table 8 continued

Drainage basins/area (km ²)	Land degradation sources	Environmental problems	Degradation level (Zuquette et al. 2004b)	Geoindicators for Environmental management measures						
				Types	Types	Relief changes	Ecological	Bioengineering	Mechanical	Policy and administrative
Gereraú 52.67	Mining	Water pollution	Low	Water pollution	Relief changes	Revegetation	Geotextiles	Contouring	Regularization of groundwater pumping	Strip-cropping
	Agriculture	Water erosion		Water erosion	Channel changes Surface water quality Stream sediment storage Stream channel changes Alteration of surface water flow direction	Seeding Wood live barriers	Gabions with trees	Mulching		
Curú 38.45	Mining	Water pollution	Low	Water pollution	Relief changes	Revegetation	Geotextiles	Contouring	Regularization of groundwater pumping	Strip-cropping
	Agriculture	Water erosion		Water erosion	Channel changes Surface water quality Stream sediment storage Stream channel changes Alteration of surface water flow direction	Seeding Wood live barriers	Gabions with trees	Mulching		

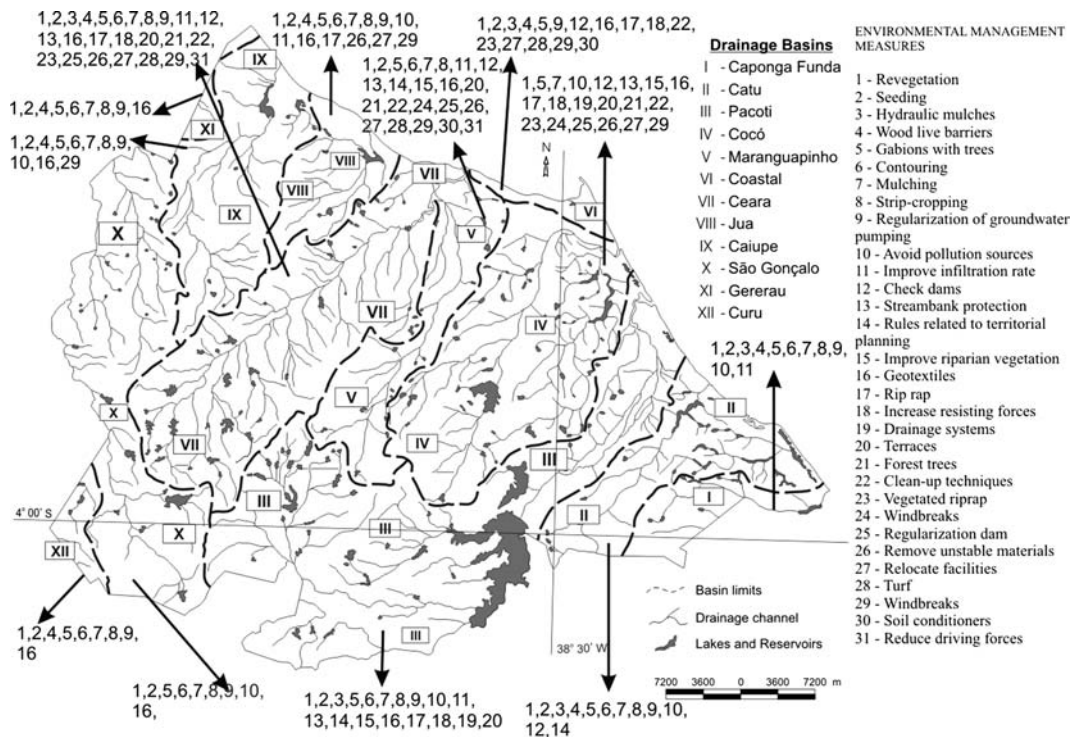


Fig. 19 Spatial distribution of environmental management measures for implanting in the drainage basin

of geological materials with good groundwater characteristics, but agriculture and urbanization have affected groundwater quality. The floodplain of the Pacoti River is very large and flooding has affected agriculture and pasture areas.

Revegetation, reforestation, improvement of the riparian vegetation, terrace, check dam, and policy and administrative measures are highly recommended to recover part of the original environmental characteristics.

The Cocó, Jua, Caiupe, and São Gonçalo basins have portions supported by high residual massif, but gravitational mass movements have damaged neither the residences nor the infrastructure system here, as has occurred in the Maranguapinho basin. Both require a territorial planning program to designate land uses and environmental protection zones.

The Caponga Funda, Gereraú, and Curu basins have been affected by anthropogenic and natural processes. Water pollution and water erosion are most frequent, mainly due to deforestation (>75%). Gereraú and Curu basins contain some urbanized sites. Agriculture and urbanization in the Caponga Funda basin pollute surficial and groundwater. For the Caponga Funda, Gereraú, and Curu basins, revegetation, strip-cropping, contouring, and policy and administrative measures are needed to maintain current environmental quality and low degradation level. For abandoned or decommis-

sioned excavations from sand exploitation, seeding, geotextiles, and gabions with trees are recommended.

Agriculture has been very intensive close to the drainage channels, lakes, and reservoirs of the Caponga Funda, Catu, and Pacoti basins, and the intermediate portion of the Cocó, upstream part of the Maranguapinho and Jua basins. These basins require ecological (revegetation, improve riparian vegetation), agricultural (mulching, strip-cropping) and territorial planning measures.

The Jua basin is less affected by anthropogenic and natural processes. More than 50% is covered by natural vegetation in the upstream portion. Most of the geoindicators are mainly related to urbanization and agriculture and were detected in 30% of the downstream portion. Good aquifers occur in the downstream portion, but the water quality will probably be affected within the next few years unless policy and administrative measures (avoid pollution sources, remove unstable material, relocate facilities, regularize groundwater pumping, improve infiltration rate) are introduced.

The Caiupe and São Gonçalo basins are more than 75% deforested. Agriculture and urbanization occupy less than 10% of land surface. Agriculture predominates close to drainage channels, lakes, and reservoirs, while urbanization occupies the coastal portion in dunes and palaeodunes, and the Barreiras Formation.

Revegetation of dune and palaeodune zones and areas close to the drainage channels are priority measures. Mulching and strip-cropping are better for the agricultural zones. In the Barreiras Formation, regulation of groundwater exploitation and pollutant source control is recommended.

The Catu basin is very special because it is constituted of geological materials, which provide good aquifer conditions. Deforestation is mainly for agricultural usages, while urbanization is close to lakes and the sea. Management of agricultural practices is necessary to protect the waters. Groundwater and surface water pollution has resulted from a combination of agriculture usages and aquifer characteristics. Policy and administrative measures (regulation of pumping, avoid pollution sources, territorial water use planning) are fundamental to avoid increased degradation.

The Pacoti, Catu, Jua, and Caiupe basins present natural dune movements due to urbanization on the dunes and palaeodunes. In these basins, revegetation and other ecological measures, as well as policy and administrative controls should be adopted.

The four sanitary landfills of the region are located in the Cocó, Pacoti, Ceará, and Maranguapinho basins. The leachate produced can reach surface and groundwater, affecting social and economical activities.

The Jangurussu and Aquiraz sanitary landfills present high potential for polluting the Barreiras Formation and dune/palaeodune groundwater because these geological materials have high permeability and are considered good shallow aquifers. The leachate, wastes, and garbage can reach the Coco and Pacoti rivers and can be carried into the ocean during the rainy periods. Wastes can spread to the Futuro and Goiabeiras beaches due to ocean currents flowing toward the northwest. The new sanitary landfill in the city of Maracanau is located on metamorphic rocks, and a second is on Barreiras Formation on the left side of the Pacoti River in Aquiraz. These four sites demand an intensive monitoring program and adoption of protection, rehabilitation, and clean-up measures. Among the 59 environmental management measures selected, a set of 31 was suggested for implementation. Figure 19 shows the spatial distribution of the 31 environmental management measures for each basin.

Conclusions

Engineering geological mapping is a very efficient tool for geological and geotechnical characterization. Geoindicators to assess degradation land levels and to

propose measures to improve environmental quality can be selected from the result.

The geoindicators and land degradation levels associated with the geological and geotechnical characteristics of the drainage basins give adequate information to select appropriate environmental management measures. The geoindicators suggested for monitoring are adequate to detect the results generated by the recommended measures within a relatively short period for both large and small areas.

Environmental problems have been responsible for regional economic losses. Municipal administrations have spent heavily to rehabilitate some affected sites, but the results have not been satisfactory.

Ecological, policy and administrative, and agricultural measures are strongly recommended for the whole region.

Reforestation of the riparian zones of the São Gonçalo, Pacoti, Maranguapinho, Caiupe, Gereraú, and Cocó basins should be introduced to improve water quality, avoiding stream–bank erosion, and protect the swamp areas.

The Jua, Cocó, and Catu basins require intensive protection measures because they have better groundwater reserves than other areas, and also they have intermediate and high degradation levels.

Some portion of the aquifers presents intermediate contamination levels from biological and chemical pollutants. Clean-up measures should be implemented for pollution sources, e.g., sanitary landfills and cess-pools and septic tanks.

References

- Barrow CJ (1991) Land degradation. Cambridge University Press, London, 295 pp
- Berger AR (1996) The geoindicator concept and its application: an introduction. In: Berger AR, Iams WJ (eds) Assessing rapid environmental geoindicators: changes in earth systems, Balkema, Rotterdam, pp 1–14
- Berger AR (1997) Assessing rapid environmental change using geoindicators. *Environ Geol* 32(1):36–44
- Blaikie P, Brookfield H (1987) Land degradation and society. Methuen, London
- Bush DM, Neal WJ, Young RS, Pilkey OH (1999) Utilization of geoindicators for rapid assessment of coastal-hazard risk and mitigation. *Ocean Coastal Manage* 42:647–670
- Gupta A (2002) Geoindicators for tropical urbanization. *Environ Geol* 42:736–742
- Morton RA (1996) Geoindicators of coastal wet land and shorelines. In: Berger AR, Iams WJ (eds) Assessing rapid environmental geoindicators: changes in earth systems. Balkema, Rotterdam, pp 207–232
- Morton RA (2002) Coastal geoindicators of environmental change in the humid tropics. *Environ Geol* 42:711–724

- Osterkamp WR (2002) Geoindicators for river and river-valley monitoring in the humid tropics. *Environ Geol* 42:725–735
- Osterkamp WR, Schumm SA (1996) Geoindicators for river and river-valley monitoring. In: Berger AR, Iams WJ (eds) *Assessing rapid environmental geoindicators: changes in earth systems*. Balkema, Rotterdam, pp 97–114
- Zuquette LV, Pejon OJ, Collares JQ (2004a) Engineering geological mapping developed in Fortaleza metropolitan region, State of Ceará, Brazil. *Eng Geol* 71:227–253
- Zuquette LV, Pejon OJ, Collares JQ (2004b) Land degradation assessment based on environmental geoindicators in the Fortaleza metropolitan region, State of Ceará, Brazil. *Environ Geol* 45(3):408–425