An information system to analyze and monitoring coastal areas for planning sustainable development.
Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina)

(Settore scientifico-disciplinare BIO/07)
“Only when the last tree has died and the last river has been poisoned and the last fish has been caught..... We will realize that we can not eat money”

Prophecy of the Cree Indians
I would like to thank all the people who in some way or another have helped me with the elaboration and research of this thesis. Those who either with logistic and technical support and mainly with their wise and valuable advises have guided me on the not easy path of carrying on this thesis and finally fulfilling my initial objective and my expectations when coming here to this country.

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Muchisimas Gracias
Coastal areas, are nowadays one of the most threatened zones all over the world, due to their attractiveness, convenience and availability of resources for urban and industrial development. Therefore, many of these areas worldwide have reached critical environmental conditions as a result of great anthropologic pressure and overexploitation of their resources. Coastal areas are among the most vulnerable of Earth's ecosystems, any activity carried out in these areas should be carefully planned since what happens to the coasts has effects that reach far beyond their local aquatic and human communities, thus, causing irreparable or long term consequences. The use of modern techniques as remote sensing and GIS have facilitated the study of environmental impacts on coastal zones and therefore the proposal of useful and reliable tools for local authorities to help them with the decision making process. The general aim of this research was to create a complete information system using GIS and remote sensing techniques as data sources for the analysis of local problems of Santos (Brazil) and Bahia Blanca (Argentina) which nowadays are under serious anthropogenic pressure as deforestation and intense agriculture respectively. These activities are causing serious soil loss in vulnerable areas of both sites and increasing the problem of urbanization specially in Santos. Furthermore, it was also part of this research the aim to estimate and compare rates of soil erosion obtained by two different erosion models stressing the importance of vegetation coverage as prevention of soil loss processes affecting these two study areas. The integration of landcover analysis making emphasis on multitemporal studies in the area of Santos to detect landcover change over a seven year period and the prediction of landcover change using specific software and modeling techniques was also included as an important source of information for the present and future studies. A Spatial Decision Support System (SDSS) was elaborated for Santos study area to tackle one of its most important problems, urbanization, therefore providing local authorities with a reliable tool for decision making processes.
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INTRODUCTION

Nowadays use of Geographical Information Systems (GIS) is almost a compulsory tool in every scientific field. Large amounts of information are handled worldwide by all the scientific community and the most efficient way to deal with this data is with GIS which significantly facilitate its storing, retrieval, manipulation, analysis, processing and display. GIS are compatible with most of the existing professional software which without doubts helps with the exchange, integration and storage of information on huge databases. GIS multisource databases are the basis for all type of analysis from the most simple to the most complex ones allowing in this way the possibility to have a complete overview of the situation, considering all possible components as socio-economic, natural, political, geographical, physical, etc which are all spatially related. An endless volume of data can also be generated by GIS like digital maps, graphs, tables and spatial models which according to the user’s necessities will be converted into final results or input to more complex models as Decision Support Systems (DSS) and Spatial Decision Support Systems (SDSS).

Decision support tools are interactive software-based systems intended to help decision-makers to compile useful information from raw data, documents and personal knowledge to identify and solve problems, evaluate alternatives and make decisions to achieve specific objectives. A DSS are numerical techniques based on various methods as Multi Criteria Analysis (MCA), for choosing the best among a number of alternatives. SDSS are DSS with spatial components i.e. for finding where to optimally locate the alternative chosen with DSS (Feoli et. al, 2006). DSS and SDSS are represented by different criteria and variables including factors (criterion that enhances or detracts from the suitability of a specific alternative) and constraints (serve to limit the alternatives under consideration). Environmental issues are always spatial orientated therefore SDSS are usually supported by GIS that are adequate to represent and work on spatial variability. GIS-based decision support systems allow considering different scenarios which can be easily modified by changing input data contained on the GIS.

Other technique as important as GIS, satellite remote sensing, was also applied on the development of this thesis. Remote sensing is a very useful tool often considered on environmental studies since it provides information concerning many natural phenomenon and events, anthropogenic activities, chemical and physical characteristics without even being physically present on the area of interest. Remote sensing is the most common tool at the moment for predicting and forecasting environmental changes not only at local scales but also at regional, national and global scales. Satellite images are an excellent source of information and thanks to continuous improvements on space satellites is possible to obtain high quality products, both concerning spatial and spectral resolution. Unfortunately, most of these high quality products are still quite expensive and inaccessible to everyone but nowadays it is possible to obtain reasonable quality sources free online. This is the specific case of Landsat satellite images used for this thesis (http://glcf.umiacs.umd.edu/index.shtml). Landsat images were the main source for elaboration of landuse, landcover and NDVI maps that were also complemented by field measurements to increase reliability of the images. Other sources as Digital Elevation Models (DEM) essential for soil erosion calculations were also downloaded from a free website (ftp://e0srp01u.ecs.nasa.gov/srtm/version2).

The obvious question that comes to everyone’s mind when using online information is: Is it reliable enough? Online information although being very convenient might also have
disadvantages as the reliability. In any case if there are any other sources available, preliminary results obtained by this mean can be considered as good examples of the possible products and results that could be obtained with high quality data. Scarcity or not existing information is usually overcome by substitution of required data, taking into consideration similarities and common characteristics (geographical, physical, biological) between the current study area and others areas on the world. Search of the most similar and suitable data is only possible having access to a vast and rich source of information which nowadays is mainly possible through internet sources. Sometimes it is not only a matter of not having availability and accessibility to data but people or authorities not knowing what could be expected and produced with the existing data. In these cases using final products (e.g. maps, GIS, databases, SDSS) is the best way to create awareness on authorities and decision-makers which might in the future realize the importance to invest on data acquisition for achieving high quality results.

GIS based systems allows integration of many sources of information coming from different ecosystems (e.g. aquatic and terrestrial). This thesis focus on two water-land coastal interaction areas located in South America, an estuary with mangroves (Santos-Brazil) and an estuary with wide intertidal areas (Bahia Blanca-Argentina). GIS is designed to carry out operations on the data stored in its database, according to a set of user specifications without the user needing to be knowledgeable about how the data is stored and what data handling and processing procedures are utilized to retrieve and present the information required (Rinos et. al, 2005). This consisted an enormous advantage for calculating soil erosion in both study areas since erosion models as RUSLE requires significant variety of data: lithology, type of soils, drainage, geomorphology, rainfall intensity, management methods, landcover, and steepness which can be easily stored in a GIS in various layers of mixed data types (resolution, scale, units) that are transformed to common coordinates before being processed together.

Two erosion models, RUSLE (Revised Universal Soil Loss Equation) and USPED (Unit Stream Power Erosion Deposition) were applied using GIS facilities. Final results consisted on erosion risk maps that put into evidence different degrees of erosion (low, medium, high) present in our study areas and also those areas where sediments are being deposited. These results and previous maps obtained by satellite processing and GIS analysis were the following input to create a GIS-based spatial decision support system for Santos Estuary, that focused on urbanization problems present in the Estuary and surroundings. The SDSS output consisted on suitability maps indicating the most “suitable” areas for urban development. The SDSS that takes into consideration a series of constraints (e.g. conservation areas, distance to rivers) and factors (e.g. slope, erosion) which were previously defined will facilitate local authorities with the decision of where to re-locate those people whom nowadays are living in protected areas (mangroves). The use of GIS also makes the models results accessible to a broad range of users.

In this way a series of modern technologies have been put into practice in order to solve common problems present in two different coastal areas by an integrated approach. A common factor identifying methodologies applied in this thesis, GIS, Remote Sensing and SDSS, is the considerable amount of data and information needed to produce reliable and acceptable results to be used as basis for problem solution and local authorities decision making processes. Data accessibility and availability were not always an easy task to overcome but were solved by the use of other sources of information, mainly bibliographical, related to other areas with similar characteristics to study areas mentioned above.
Chapter 1: Problem Statement, Aims of the thesis and Outline of the thesis

1.1. Problem statement

1.1.1. General state of coastal areas worldwide and coastal problems in study areas

1.1.2. Relevant regional information of landuse and landcover change associated with specific local problems of study areas and problem approach

- Landuse and landcover change
- Erosion
- Multitemporal Analysis

1.1.3. Relevant regional information about extraction and depletion of natural resources associated with specific ecosystems of study areas

- Forests
- Mangroves

1.1.4. Relevant regional information about production of wastes such as untreated wastewater associated with pollution problems in study areas

- Water

1.2. Objective and aim of the thesis

1.3. Outline of the thesis
Chapter 1

Problem Statement, Aims of the thesis and Outline of the thesis

1.1. Problem statement

1.1.1. General state of coastal areas worldwide and coastal problems in study areas

Coastal areas, broadly defined as near-coast waters and the adjacent land area, are nowadays one of the most threatened zones all over the world, due to their attractiveness, convenience and availability of resources for urban and industrial development. Therefore, many of these areas worldwide have reached critical environmental conditions as a result of great anthropologic pressure and overexploitation of their resources. Coastal areas are among the most vulnerable of Earth's ecosystems, any activity carried out in these areas should be carefully planned since what happens to the coasts has effects that reach far beyond their local aquatic and human communities, thus, causing irreparable or long term consequences.

The fact that more than 60% of the total world population tends to concentrate on these zones (Caffyn et al., 2002), living within 100 Km of the coastline put coasts on a hazardous position. Furthermore, by the year 2020, 75% of the population of the world will live within 60 Km of marine coasts and estuaries (Jedrzejczak, 2004). More than 3 billion people rely in some manner on coastal and marine habitats for food, building sites, transportation, space, recreation, and waste disposal. Around one third of the world's coastal regions are at high risk of degradation, particularly from land-based sources of pollution and infrastructure development (e.g. tourism industry). European coasts are most affected, with 80% at risk, followed by Asia and the Pacific with 70% and Latin America with 45%. In Latin America for example, some 50% of the mangroves are affected by forestry, aquaculture and agricultural activities (http://www-cger.nies.go.jp/geo1/exsum/ex3.htm). Other problems affecting coastal zones worldwide are oil spills, tourism industry and overexploitation of marine fisheries, i.e. globally more than 60% of marine fisheries are heavily exploited with declining stocks of commercial fish species.

Coasts house biological processes and diversity that are essential to the health and stability of the biosphere as a whole. They are approximately twice as productive as inland areas and suffer roughly nine times more damage because of the number of people living there. By concentrating its swelling population along the coasts, humanity is locating the ecological damage of its activities precisely where the world's most productive ecosystems are concentrated.

As Weber (1994) cited in his Worldwatch paper "...along the seams of the earth where land meets sea, biological productivity is much higher than for the rest of the planet's surface. If the coasts are to continue serving their essential ecological and economic functions, we will

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
have to begin altering our patterns of human settlement and development...” it is worth to think on the short and long term consequences of our actions and take a drastic change towards environmental strategies trying to reduce as much as possible the catastrophic impacts occurring at the present time.

Not all coastal habitat is highly productive: about 70% are lined with cliffs or ice, or are beaches with relatively low biological activity. However, wetlands and estuaries, where rivers turn brackish as they enter the sea, are among the most productive of all ecosystems. This is relevant to the two study areas discussed in this thesis: Santos Estuary and Bahia Blanca Estuary. Estuaries are particularly vulnerable because they are naturally sheltered harbors, and therefore tend to be heavily used and polluted. For example, wetlands (i.e. mangroves) have traditionally been considered wastelands and targets for city expansion thus, degraded by pollution and infrastructure services. Paradoxically, mangrove forest which cover only 0.4% of the world’s surface area, account for 2.3% of its plant productivity, making of them important nurseries for marine species i.e. two-thirds of all commercially caught fish spend their early life in estuaries and wetlands and many more species go to these coastal ecosystems to feed.

All over the world, there are coastal cities as Santos and Bahia Blanca that have degraded nearby estuaries and wetlands through the combined effects of direct habitat destruction and pollution. Santos, for example, has removed great part of its mangrove wetlands and Atlantic forests for urban settlements. However, it is agriculture not urbanization that causes the most extensive destruction of estuaries (Weber, 1994) due to misuse of pesticides-fertilizers and soil loss, which is expressly the case of Bahia Blanca characterized by high intensity agricultural activities.

Many of the cities in Latin America and the Caribbean (LAC) region were not conceived for the current demographic densities (UNDP, 1997). As a result, sprawling megacities as São Paulo with more than 10 million habitants have generated peripheral belts of fragile human settlements, usually located in environmentally unsuitable areas such as hill slopes, floodable grounds or in protected areas like in Santos, where poorest people have concentrated nearby mangrove or coastal forest (Mata Atlântica) reserve areas. This fact puts an increasing stress on urban planning that has also been tackle in this thesis by the elaboration of a SDSS to indicate most suitable areas for people relocation. It is important to mention that in the last decades, rural abandonment and poverty have accelerated the growth of urban areas, even more, the concern is that predictions for next decades will keep the same increasing tendency, as shown in Figure 1.1, by 2020 this figure is expected to increase to over 80%.

Figure 1.1: Percentage of population residing in urban areas in selected countries in LAC, 1985-2015 (UN, 1995a).
Although poverty and the growing global population are often targeted as responsible for much of the degradation of the world's resources, other factors such as the inefficient use of resources, waste generation, deforestation, pollution from industry, and wasteful consumption patterns are equally driving humanity towards an environmental precipice (UNEP, 1996). Tables 1.1 and 1.2 (UNEP, 1997) show the relative importance of environmental issues within and across regions and the trends for the same issues, respectively. Main interest should be put on LAC region which is the physical location of the two study areas mentioned above.

**Table 1.1: Regional Concerns: Relative importance given to environmental issues by regions**

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<td>Lower priority</td>
<td>Negligible</td>
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An important quotation to be made in Table 1.2 is that in many instances, although trends are increasing, the rate of increase over the years has slowed down, this suggests that several countries are making the transition to a more sustainable environment at a lower level of economic development than industrial countries typically did over the last 50 years.

**Table 1.2: Regional Environmental Trends**

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<td>Africa</td>
<td>Increasing</td>
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An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
As nations develop, different sets of environmental concerns assume priority. Initially, prominence is given to issues associated with poverty alleviation and natural resource management to control land degradation, provide adequate water supply, and protect forests and coastal zones from overexploitation and irreversible degradation. Then, attention to issues associated with increasing industrialization and urbanization as well as energy, transport expansion and increasing use of chemicals follows. At last, more affluent societies focus on individual and global health and well-being issues like climate change and ozone destruction (UNEP, 1997). Figure 1.2 illustrates the observed progression on environmental priority issues.

Argentina and Brazil are a mix of groups 1 and 2, specially Brazil with its important agricultural activities of coffee, fruits and sugar cane and its rising aeronautical, automobile, textile and petroleum industries; in the other hand Argentina concentrates more on its agriculture and grazing activities than industrial ones, obviously neither of these two countries do belong to the affluent societies group.

The concentration of human activity affects the environment in three major ways (WRI/UNEP/UNDP, 1994):

1. landuse and landcover change,
2. the extraction and depletion of natural resources, and
3. the production of wastes such as untreated wastewater.

The infrastructure in urban areas in LAC is already stretched to the limit therefore, in the future it will be impossible to support further growth in population unless considerable investments in services are made. The population growth rate has had implication with regard to the expansion of agricultural frontiers and the associated deforestation (Winograd, 1994). For this reason is necessary to provide regional responsible authorities with the right tools as remote sensing and GIS and reliable planning sources like SDSS thus, helping them in the decision making process for efficiently face current problems avoiding a worsening of the present scenarios.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
According to some estimates, 26% of the LAC coastlines are under high potential threat of degradation (Figure 1.3), and a further 24% are under moderate potential threat due to coastal development (including tourism and infrastructure works); discharge of sediments, wastes, and contaminants from urban and industrial areas; sewage, industrial pollution, and oil spills (WRI/UNEP/UNDP/WB, 1996).

![Figure 1.3: Latin American and Caribbean coastal ecosystems threatened by development (Bryant et al., 1995). In circles, the two study areas.](image)

**Notes:**

a. Threat ranking depicts potential risk to coastal ecosystems from development-related activities.

b. Coastal areas falling within a city, major port or having a population density exceeding 150 persons per Km², a road network density exceeding 150 m of road per Km², or a pipeline density exceeding 10 m of pipeline per Km².

c. Coastal areas with a population density of between 75 and 150 persons per Km², a road network density of between 100 and 150 m of road per Km², or a pipeline density of between 0 and 10 m of pipeline per Km².

d. Coastal areas with a population of less than 75 persons per Km², a road network density of less than 100 m of road per Km², and no pipelines known to be present.

From Figure 1.3, it is possible to highlight that Santos study area has a more threaten coast with high and moderate levels, while Bahia Blanca, is represented by a coast with low threat potential.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
1.1.2. Relevant regional information of landuse and landcover change associated with specific local problems of study areas and problem approach

**Landuse and landcover change**

LAC region includes 23% of the world’s potential arable land, 12% of current cropland, and 17% of all pastures (Gallopin et al., 1991). In contrast with other regions, LAC still maintains a high percentage of natural ecosystems that have been little disturbed by human activities, particularly in the Amazon region and the southern tip of South America. However, these ecosystems are currently being degraded at a high rate still at their margins hence, it is crucial to keep these rates on their limits even more decrease them to reasonable and safe values for the benefit and prosperity of future generations.

Some 306 million hectares (72.7%) of the agriculturally used drylands (irrigated lands, rainfed cropland and range-lands) in South America (Figure 1.4) suffer from moderate to extreme degradation (UNEP, 1991) and about 47% of the soils in grazing lands have lost their fertility (LAC CDE, 1992). This land degradation includes erosion and soil degradation in hillsides and mountain areas like in Santos as well as in high intensity agricultural lands like Bahia Blanca, and in tropical pasturelands desertification brought by overgrazing, salinization and alkalization of irrigated soils.

![Figure 1.4: Desertification and land degradation in agriculturally used drylands of South America (Dregne, 1991).](image)

**Erosion**

Acceleration of erosion processes in South America is mainly due to expansion of the agricultural frontier and the overuse or unsustainable use of land for cultivation or grazing and deforestation due to mismanagement. Some of the best land is also being lost through urban expansion (Gligo, 1995).

Erosion problems affecting Santos and Bahia Blanca were also studied in this thesis. By the application of erosion models as RUSLE and USPED (also for sedimentation) the most sensitive areas affected by soil loss were identified and quantified in terms of mean erosion values (ton/ha.yr). Two types of erosion were calculated, real and potential, the first one takes

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
into consideration: landuse (vegetation coverage and support practices), climatic, topographic and soil characteristics while the second does not consider any type of landuse but just the inherent erodibility of the material and the magnitude of erosive forces as precipitation and slope. Potential erosion shows the worst scenario possible in terms of erosion, without considering any kind of soil protection and coverage i.e. vegetation or crops and without any support practice applied to the terrain. The considerable difference between these two types of erosion demonstrates the significant importance of appropriate support practices and preservation of a proper vegetation coverage to avoid land degradation in reference to soils loss either as erosion or sedimentation.

Erosion and sedimentation maps obtained through application of RUSLE and USPED models were associated to the landuse maps resulting from supervised classification applied to Landsat images of both study areas. Using ArcMap 9.0 zonal statistical analysis these correlations were clearly outlined, showing how each of the most important classes in the landuse maps (forest, mangroves, crops, bare soil, urban and industrial areas) are affected by soil loss processes. For example in Santos, forests represented by classes as Mata Atlântica of highlands and lowlands have the lowest erosion values together with mangroves, while bare soil has the highest erosion values. For a better correlation classes as water, shadow and clouds were masked for this analysis. Correlations between erosion maps and topographic aspects of the terrain, represented by DEM, were also elaborated, emphasizing in this way the importance and role of natural characteristics of the terrain.

Type of vegetation cover is one of the most important physical characteristics for soil loss stability and preventing land degradation. Other factor as important as vegetation cover is topography of the terrain. These characteristics and others as rainfall intensity, type of soils, management methods, and landuse are the main factors to be considered for soil erosion calculations. Factors can be divided into natural and not natural which means that some of them can not be changed or modified and are part of the intrinsic characteristics of the terrain (e.g. type of soils, elevation) meanwhile others are directly influenced by anthropogenic activities (management methods, land-use).

Geo-information and remote sensing tools in conjunction with erosion and sedimentation models are powerful tools for generating and supporting this understanding. Therefore, strong emphasis has been put on the use of geo-information techniques for geospatial data handling and processing, and remote sensing as data sources.

**Multitemporal Analysis**

To emphasize landcover and landuse changes, a multitemporal analysis was performed for Santos study area. Two Landsat satellite images from 1993 and 2000 were processed applying ArcMap 9.0 cross-tabulate tables, identifying in this way, the changes between each of the classes taken place during the 7 years period, in other words what have been transformed into what. Final maps put into evidence the areas were landcover changes have taken place, for example, where mangroves have been converted into low vegetation or instead where low vegetation was transformed into urban settlements. Four landcover changes—mangrove to urban settlements; mangrove to low vegetation; forest to urban settlements, and forest to low vegetation— do have significant environmental implications that must be considered for future urban planning and reinforcing laws for protection of fragile ecosystems.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Suitability analysis using Idrisi Andes software were applied to show where the best areas for
development or protection of areas as forest, mangrove, urban and low vegetation should take
place, based on a series of criteria and factors (usually physical) representing the most
important characteristics of the study area. This is possible through the Multi Criteria
Evaluation - MCE (Voogd, 1983; Carver, 1991), which combine the information from several
criteria, according to the objective of the decision, to form a single index of evaluation. The
overall procedure consist of two main concepts, the first involves a Boolean criteria
(constraints); and the second a series of weights assigned to each of the factors previously
defined.

Future predictions for landuse were also elaborated applying Marcov chains analysis, which
consists on the probability that one specific class will be transformed into another one. These
predictions are possible based on two principles, first the past transformations occurred
between 1993 and 2000, evident by a transition matrix performed to the two classified
images, and second by a transition probability matrix that express the likelihood that a pixel
of given class will change to any other class (or stay the same) in the next time period. These
predictions are crucial, thus giving an idea of what could be the future environmental
scenarios of Santos.

The operations and calculations needed for such analysis are based in GIS procedures. Details
of the methodology and results obtained by these series of analysis will be later discussed in
this thesis.

1.1.3. Relevant regional information about extraction and depletion of natural resources
associated with specific ecosystems of study areas

Forests

The impact of development activities and the advance of the agricultural frontier have put
forests in a threatening position. Latin America has both the world’s largest unfragmented
tropical forests (in Amazonia) and some of the most fragmented and most endangered tropical
forest, such as Mata Atlântica (present in the study area of Santos). About 28% of the world’s
total forested area and 52% of its tropical forest are in LAC (FAO, 1993). The accelerated
transformation of tropical and other forests into permanent pasture and other forms of land
use constitutes a critical environmental problem for Latin American countries that have lost
already more than 8% of its tropical forests including their savannah-grasslands also under
continuous threat (Winograd, 1995).

Forest cover in LAC declined from 992 million hectares in 1980 to about 900 million hectares
at the end of the 20th century, yielding and annual deforestation rate of 0.98% over this period
(Figure 1.5). Average annual deforestation rose from 5.4 million hectares in 1970 to almost 8
million hectares in the 90’s (FAO, 1995). Since forests ecosystems are the natural habitat for
many species, deforestation plays a decisive role on habitat loss. General estimates indicate
that at current rates, the conversion and deforestation of tropical and dry forests may wipe out
100,000 – 450,000 species within the next 40 years, if not less (Winograd, 1995).
Figure 1.5: Average annual change in the extent of forest in selected Latin American and Caribbean countries, 1981 – 1990 (FAO, 1995). Note: Forest consists of the sum of natural forest and plantation area categories for tropical and temperate developing countries.

A similar situation is affecting the Atlantic forest (Mata Atlântica) of Brazil, it remains only in 4% of its original 1 million square kilometers as pristine forests and an additional 6% as secondary forests (UNEP, 1995b). Most of these forests have been replaced by induced pastures, monocultures of exotic timber species or by urban and industrial settlements.

Mangroves

Mangroves that are also an important source of natural resources and effective protector of coastal zones are also under considerable stress. These unique forest ecosystems provide a number of additional environmental benefits for instance reducing and preventing coastal erosion, providing nearby communities with protection from winds, waves, and water currents.

Millions of people around the tropics and sub-tropics depend on mangrove forests as a source of fuelwood, charcoal, timber, and other non-timber products. Similar numbers rely on coastal fishery resources within or linked to mangrove ecosystems as one of most important source of livelihoods to coastal residents (http://www.fao.org/forestry/site/mangroveatlas/en).

Even if mangroves provide such valuable benefits, they are also being destroyed and polluted at alarming rates, specially due to urban and agricultural expansion and shrimp aquaculture. Around 20 percent of the world's mangrove forests have disappeared during the past 25 years as a result of over-exploitation and conversion to other uses, according to a new FAO study (http://www.fao.org/forestry/newsroom/en/news/2005/highlight_108389en.html). Mangroves, today cover around 15 million ha worldwide, down from 18.8 million ha in 1980, however, during the same time frame the annual rate of mangrove deforestation dropped from around 185 000 ha per year in the 1980s to 105 000 ha/yr during the 2000-2005 period.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Fortunately, over the last few years an increased awareness of the importance of mangrove ecosystems has led to new legislation, better protection and management of mangrove resources and in some countries even a re-expansion of mangrove areas (FAO, 2005). The conservation of mangroves is essential for the survival of the two other major tropical ecosystems: coral reefs and seagrass beds. Yet, the true value of mangroves and other wetlands is still underestimated and the loss of these ecosystems is significantly higher than for other forest types.

Mangroves are found in more than 120 countries and territories around the world, but close to half of the total mangrove area is found in just five countries: Indonesia, Australia, Brazil, Nigeria and Mexico, according to the UN agency. In the case of Brazil, this wakefulness related to importance of mangrove ecosystems, have also taken place. Nowadays, local authorities are looking forward for an improvement of environmental laws and protecting mangroves from urban development and overexploitation.

An efficient control of anthropogenic activities and urban planning play an important role in preservation of these fragile and unique ecosystems. For this reason the elaboration of a SDSS within this thesis, was intended to be a useful and reliable tool to help local authorities with the decision making process for solving Santos most critical threats affecting the city at the present time.

1.1.4. Relevant regional information about production of wastes such as untreated wastewater associated with pollution problems in study areas

Water

Water quality deterioration is an important matter affecting most countries in LAC. Main pollution sources common in most of this region are: industrial discharge, mining wastewater, waste disposal, agricultural runoff, manure runoff from feedlots, and domestic sewage and detergents (UNEP, 1991). The major consequences of these actions can be summarized in:

- toxic contamination caused by poorly or untreated industrial discharges;
- bacterial pollution of water supplies that causes adverse effects on human health;
- eutrophication due to an excess of nitrates and phosphates in water i.e. generally coming from animal wastes, agricultural runoff and sewage, that cause algal bloom and block of sunlight, and
- disappearance of aquatic life and food contamination that cause serious shortage of alimentary sources.

Forest cutting also has a negative effect on water quality, besides causing serious erosion problems, this also increase the amount of suspended sediments, that in most of the cases have their final destination in rivers and/or estuaries, affecting the quality of this water resources and the functioning of dams and reservoirs.

Today, the region's water resources are chemically and biologically contaminated with evidence of elevated levels of phosphorous, nitrates, potassium, pesticides such as DDT, and highly organic effluents (LAC CDE, 1992), caused by the indiscriminate discharge of highly pollutant-loaded effluents. Unfortunately, just few Latin American cities have effective waste
and sewage treatment facilities or water treatment plants (Gligo, 1995). Industrial and hazardous wastes from the region as a whole flow straight into the ocean, while the river basins act as catchments areas for agricultural wastes, which then drain into the sea.

Santos and Bahia Blanca are affected by water quality problems, principally caused by industrial and urban discharges that have a poor or none previous treatment, and agricultural runoff carrying considerable concentrations of fertilizers, pesticides and nutrients. Estuaries of these two cities also suffer from solid waste discharges specially on wetlands and saltmarshes located on their coasts. Two main types of pollution characterize both of them, organic pollution originated mostly from urban and agro-industrial wastewater used for irrigation and chemical pollution result of using pesticides with a long residual life, as well as industrial wastewater. Urban and even more industrial discharges play a critical role on the weakening environmental conditions of Santos and Bahia Blanca since huge industries are located nearby these estuarine cities. Some of the most important industries in Santos and Bahia Blanca are:

<table>
<thead>
<tr>
<th>Santos</th>
<th>Bahia Blanca</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSIPA – steel industry</td>
<td>ESSO, Shell and PetroBras – oil refineries, petrochemical</td>
</tr>
<tr>
<td>PetroBras, Mobil – oil refineries</td>
<td>Electric Power Plant</td>
</tr>
<tr>
<td>CarboCloro – chemical industry</td>
<td>Oil Tanking - EBITEM</td>
</tr>
<tr>
<td>Copebras – Petrochemical industry</td>
<td>INDUPA- PVC, chemicals</td>
</tr>
<tr>
<td>Vopak Brasterminais, Stolthaven – bulk liquid terminals</td>
<td>Moreno – cereals processing industry</td>
</tr>
<tr>
<td>Dow Quimica – plastics, chemicals and agricultural products</td>
<td>Dow Quimica - Plastics, chemicals and agricultural products</td>
</tr>
</tbody>
</table>

In the case of Santos, a general analysis of pollution in sediments, water and marine organisms was elaborated using the fuzzy sets theory, so to get representative clusters of all these three groups and calculating an indicative pollution index of the current conditions of Santos Estuary. This analysis was based on past measurements of heavy metals, organchlorated pesticides, aromatic organchlorated, herbicides, dioxins among others, sampled between 1999 and 2000. Sampling sites were chosen according to vicinity of industrial areas.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
1.2. Objective and aim of the thesis

This thesis is developed within the ECOManage Project* which have the following strategic objectives:

1. Provide interdisciplinary framework to assist resolving conflicting uses of coastal resources;
2. Coupling of models (deterministic and conceptual) to describe the whole human-ecosystem interaction, including its physical, ecological and social parts;
3. To understand and quantify similarities and differences of estuarine system function in response to anthropogenic impacts in order to recommend restoration and/or sustainable development measures;
4. To provide scientific support to local environmental managers on best-practice policies.

on 3 different coastal zones, including an estuary with mangroves (Santos-Brazil), a large estuary with wide intertidal areas (Bahia Blanca-Argentina) and a fiord (Aysen-Chile).

This thesis focus mainly on two of these areas: Santos (Brazil) and Bahia Blanca (Argentina).

The general aim of this research is to create a complete information system using GIS and remote sensing techniques as data sources for the analysis of local problems of Santos and Bahia Blanca i.e. soil loss, urbanization. Furthermore, to estimate and compare rates of soil erosion obtained by two different erosion models stressing the importance of vegetation coverage as prevention of soil loss processes affecting these two study areas.

In this context the integration of landcover analysis making emphasis on multitemporal studies in the area of Santos to detect landcover change over a seven year period and the prediction of landcover change using specific software and modeling techniques (Idrisi 15.0 Andes Edition software) was also included as an important source of information for the present and future studies.

Also for Santos study area, the elaboration of a SDSS to tackle one of its most important problems, urbanization, therefore providing local authorities with a reliable tool for decision making processes. Summarizing the specific objectives of that this thesis address are:

• Application of remote sensing and GIS techniques as main source for producing reliable information to be used in future developing plans and integration on SDSSs;
• Outstanding importance of vegetation coverage in preventing soil loss in two different landscapes (Santos and Bahia Blanca) emphasizing their differences and identifying main reasons for soil degradation (application of erosion models RUSLE and USPED);
• Elaboration of a SDSS for Santos Estuary focusing on its urban planning problems proposing suitable solutions based on most important criteria and constrains of this study area which are mainly related to conservation of important vegetated areas.

* Project funded by the European Commission Sixth Framework Programme
1.3. Outline of the thesis

This thesis follows an environmental spatial analysis approach which consists on theories, methods and technologies associated with the proper handling and use of spatial data for the analysis and management of environmental problems and processes (e.g. erosion, landcover change).

The complexity of the environmental problems occurring nowadays requires understanding and fusion of spatial and other data from many sources, in many formats, and from multiple disciplinary perspectives. Thus, only by integration of technology and human resources and capabilities these problems can be solved. Remote Sensing and GIS were the main techniques applied in the development of this thesis since they integrate easily between each other, furthermore allowing easy processing of a huge volume of information and data collected during this research.

General principles of these techniques will be put into evidence emphasizing only their main characteristics in order to avoid useless repetition of these topics widely covered and explained in detail in thousands of books worldwide.

The content of this thesis is briefly summarized in the following way:

Chapter 1: A description of the worldwide coastal problems and their current situation focusing mainly on Latin American region. Includes also a general introduction of the research, making emphasis on those problems i.e. erosion – sedimentation, affecting the two study areas, Santos and Bahia Blanca.

Chapter 2: A general description of the main principles of the major tools applied in the elaboration of this thesis, focusing on GIS and remote sensing technologies. Basic concepts will be discussed within this chapter to help the understanding of the procedures and methodologies applied on the analysis performed in the following chapters.

Chapter 3: A description of the study areas, including a past and present review of their main characteristics. Relevant information has been included as a previous overview of these study areas to emphasize the importance of the problems analyzed in each one of them.

Chapter 4: A description of the methodology followed for processing Landsat satellite images and the application of supervised classification for obtaining landcover and landuse maps. It also includes post classification analysis applied for classification improvements using ArcGis facilities. Final landuse maps of Santos and Bahia Blanca are included in this chapter.

Chapter 5: A detailed description of the procedures applied for multitemporal analysis and predictions of landuse and landcover for Santos study area. Landcover changes based on cross calculations between the classification matrixes of the two Landsat images of Santos (1993 and 2000), suitability analysis for its main classes using MCE, and a future projection based on Markov Chain analysis will be discussed in this chapter.

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Chapter 6: A description of the two main models applied for soil loss calculations, RUSLE and USPED. Discussion and description of their main characteristics and data requirements is mentioned in this section. These included datasets on rainfall from local meteorological stations and retrievable from internet, soil properties from literature review, and topographical and landcover data from satellites. The techniques and advantages of using different remotely sensed data for obtaining the parameters needed to be modeled (i.e. cover vegetation and land practice factors) are also reviewed. A series of maps, and tables are presented and discussed in this chapter that gives a better explanation of the mentioned process taking place in these areas.

Chapter 7: A description of the methodology and criteria followed for the SDSS elaboration. The importance of the results obtained and the usefulness of this tool for local authorities and its application and relevance in the decision making processes regarding urban planning in Santos.

Chapter 8: A synthesis of the research is presented. The realization of the aim and objectives of the research are also discussed. Finally, some limitations encountered on the application of the methods is also presented, together with suggestions for future applications and improvement.

Chapter 9: Conclusions and final discussion of the thesis.
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Chapter 2

General Principles

2.1. Introduction to the main tools used in the development of this thesis: Geographical Information Systems (GIS) and Remote Sensing

The elaboration of this thesis was based on the application of two main tools: GIS and remote sensing techniques, which tremendously helped with the storage, elaboration, calculation and analysis of all the processes intended as part of the aims of this thesis.

Since this thesis deals with huge amounts of information coming from different sources and formats, besides the fact of dealing with two different study areas, the application of GIS was a compulsory tool to efficiently deal with this load of data in an organized and systematic way, helping like this with all the processing and storage of results frequently requested as part of the input data of the following process.

Other technique as important as GIS, satellite remote sensing, was also applied on the development of this thesis. Remote sensing is a very useful tool often considered on environmental studies since it provides information concerning many natural phenomenon and events, anthropogenic activities, and physical characteristics without even being physically present on the area of interest.

Remote sensing is the most common tool at the moment for predicting and forecasting environmental changes not only at local scales but also at regional, national and global scales. Satellite images are an excellent source of information and thanks to continuous improvements on space satellites is possible to obtain high quality products, both concerning spatial and spectral resolution.

2.2. Geographical Information Systems (GIS)

2.2.1. Definition

GIS is a powerful computer system tool to help record, analyze, manage and map spatial data. The word geographic implies that location of the data items are known in terms of coordinate systems like geographic (latitude, longitude), UTM (North, South) coordinates. The word information implies that the data in a GIS are organized to yield useful knowledge, often as maps and images, but also as statistical graphics, tables, and various on-screen responses to interactive queries. The word system implies that a GIS is made up from several interrelated and linked components with different functions. All these attributes gave GIS functional...
capabilities for data capture, storage, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output (Burrough and McDonnell, 1998). GIS bring together huge volumes of spatial data from diverse sources into a unified database.

Information is stored as data layers (e.g. land-cover, DEM, NDVI, satellite images, rivers, etc) which can be at different resolution, scale, units but all are spatially registered, that facilitates their correct overlap at all locations (Burrough and McDonnell, 1998). All data is correlated to its own attributes table which contains useful information (e.g. names, depth, population, species) about the represented objects.

A richer database consent a wider overview of an object or situation which imply a completer analysis of a specific problem. GIS provides tools for analyzing and modeling interrelationships between these attributes and individual layers of spatial data. Figure 2.6, provides a schematic view of the most important characteristics of GIS and its spatial integration between each other.

Figure 2.6: Combining and overlapping different spatially related data and their attribute tables. (Modified from Schlüter et al., 2000)

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2.2.2. Representation of spatial features

GIS data represents real world objects like rivers, landcover, elevation, slope and others with digital data. All objects on Earth can be divided into two abstractions: discrete objects (a station) and continuous fields (rainfall or elevation). There are two methods used to store data and represent spatial features on a GIS: vector and raster.

GIS can also convert existing digital information as satellite images generated through remote sensing into forms it can recognize and use and at the same time be combined with other data already existing on the GIS database. This property of GIS make it possible to integrate Landsat satellite images and results obtained by their analysis (landuse, NDVI) into a whole and unique system which enormously simplified the elaboration of erosion risk maps and GIS-based SDSS.

a. Vector

Vector data use points, lines (arcs) and polygons to represent objects which are encoded and stored as a collection of x, y coordinates (Figure 2.7). The vector model stores the boundaries of objects and uses topological attributes such as connectivity and adjacency (what is next to what), containment (what is enclosed by what), proximity (how close something is to something else) and relative position to analyze the spatial relationships among mapped phenomena independent of their exact position (Bolstad, 2005).

Points can represent location of field observations, main cities, meteorological stations which are directly linked to attribute tables containing categorical or descriptive data of these objects like geographical coordinates, names, physical characteristics, rainfall, temperature, etc.

Lines can represent coastlines, rivers, roads, bathymetric contours which are also linked to attribute tables containing numerical values as depth, caudal, length or descriptive data as names, dates, etc.

Polygons can represent provinces, sub-basins, specific vegetation groups as mangroves, forest, crops fields, etc. containing their own attributes.

![Figure 2.7: Vector data in three different formats (points as cities and flow stations; lines as rivers and roads and polygons as sub-basins and limits of study area).](image)

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b. Raster

Raster format is represented by a grid-cell data structure where each cell stores a single value and represents a spatial variable. This format is best suited to represent continuous spatial data (e.g. bathymetry, elevation). While vector models are stored as a series of x,y coordinates and topological relationships, grid cells are stored as rows and columns. In the raster format, each location is represented as a cell. Each row contains a group of cells with values representing a geographic phenomenon. The raster data model is a regular grid where spatial relationships are implicit, therefore explicitly storing spatial relationships is not required as it is for the vector data model (Bolstad, 2005).

Most often, raster data are images (e.g. DEM) where the value recorded for each cell may be a discrete value, such as elevation, a continuous value, such as rainfall, or a null value if no data is available (Chang, 2005). The resolution of the raster dataset is referred to the cell’s dimensions in ground units. Landsat raster images used in this thesis are represented by a 30 x 30 m cell and DEM by a 90 x 90 m cell (Figure 2.8).

Figure 2.8: Raster data represented by a DEM with 90 x 90 m cell size.

2.2.3. Advantages and Disadvantages of Raster and Vector formats

There exist advantages and disadvantages for both formats when representing reality. Raster format stores data in every point of the image which may occupy lots of space instead vector format do store data only where it is specify.

Raster data allows easy overlay operations but vector data is much more simpler to combine when coming from different sources. Raster data allows very fast and simple analysis related with mathematics calculations which is just a matter of cell to cell value computation (map algebra). This characteristic was an asset when applying erosion model formulas which require tremendous amount of data and complicated algorithms for soil loss calculations.

All these characteristics might be taken into consideration when using one format or the other to avoid spread of time and resources.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
2.3. Remote Sensing

2.3.1. Definition

There exist several definitions for this term, however in the broadest sense, remote sensing is the measurement or acquisition of information of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object. In practice, remote sensing is the utilization at a distance (as from aircraft, spacecraft, satellite, or ship) of any device for gathering information about the environment (Campbell, 2002).

Even if remote sensing technology has been around for decades, is only in the last decade that its products, specially satellite images are available to almost everybody. This is possible due to recent technological advances and legislative changes which have given access to many types of imagery recorded and stored in the past. This new “open” approach and share of information has been a gigantic step forward for worldwide scientific cooperation.

One of the most significant examples of this recent open approach was the repeal of the Landsat Commercialization Act, these data can now be obtained at lower costs than before and even obtain data for free by simply downloading information from the web (Figure 2.9). Another important advantage of these series of records is the existence of a rich background of Landsat satellite images that allow study of temporal changes on the land surface (landuse, vegetation, urban planning) of almost every part of the world in the last 25 years approximately.

Data may be acquired through a variety of devices depending upon the object or phenomena being observed. Every object in nature (plants, houses, water, soil) emits a specific radiation in different wavelengths according to their current condition that can be measured by special sensors. This unique characteristic which represents each object and make possible its identification and classification from the rest is called “spectral signature”.

Most remote sensing techniques make use of emitted or reflected electromagnetic radiation of the object of interest in a certain frequency (infrared, visible light, microwaves), while other remote sensing systems use sound waves and variations in gravitational or magnetic fields (Lillesand and Kiefer, 1994).

Imaging systems are not restricted only to "visible" part (0.4 to 0.7 μm) of the electromagnetic spectrum (what human eye can see), it can also measure energy at wavelengths invisible to the eye, such as near-infrared (useful for vegetation categorization), thermal infrared and radio wavelengths. Most remote sensing instruments record these different wavelengths at the same time, yielding to numerous images of the same location on the ground, each corresponding to a different range of wavelengths (band). During image analysis of these data, each band is treated as a layer in a raster GIS.
2.3.2. Data Processing

In order to have comprehensible and reliable data coming from remote sensing techniques, particularly talking about satellite images is necessary to follow a series of steps to increase the quality of these products previous to their processing and analysis. Summarizing the most important steps are (Lillesand and Kiefer, 1994):

**Georeferencing:** involves matching up points in the image with points in a precise map (100% reliable points) or in a previously georeferenced image and finally warp the image to reduce distortions.

**Radiometric correction:** gives a scale to the pixel values, i.e. the scale of 0 to 255 will be converted to actual radiance values.

**Atmospheric correction:** eliminates atmospheric haze by rescaling each frequency band so that its minimum value (usually in water bodies) corresponds to a pixel value of 0.

Nowadays, almost all commercial satellite images are already georeferenced and corrected when delivered to the public. After these corrections have been applied, interpretation can take place, which consists on the critical process of making sense of the data.

Besides the mentioned corrections there are other intrinsic properties of satellite images which also determines the quality of data. These properties are:

**Spatial resolution:** refers to the size of a pixel that is recorded in a raster image. Typically, pixels may correspond to square areas ranging from 1 to 1000 m. Spatial resolution is very important specially at local scales since higher the spatial resolution better, clearer and more
information is obtained from the image which significantly facilities image analysis. Unfortunately, better spatial resolution possible by some satellites as IKONOS (1 m, 4 m) or Quickbird (0.6 m) is still quite expensive to acquire by the average users worldwide.

**Spectral resolution**: refers to the number of different frequency bands recorded by the sensor. Landsat 5-7 images have between seven and eight bands, including several in the infra-red and visible spectrum and one in the thermal spectrum. Depending on how many and which part of the spectrum are these bands located will define the most suitable applications for the different kind of satellites. MODIS and EO-1 (Hyperion) have the highest spectral resolution with 36 and 220 bands respectively.

**Temporal resolution**: refers to the frequency of flyovers performed by the satellite or plane, and is only relevant in time-series studies or those requiring an averaged or mosaic image. Shorter the temporal resolution more probabilities to avoid cloud cover. In order to have frequent temporal coverage, the sensor must cover a wide swath of ground beneath the satellite. Unfortunately, this also means that spatial resolution must be coarse in order to image such a large area at once (Richards and Jia, 2006).

The length of time between imaging can be short (daily) or long (once per month or even longer), depending on the satellites design.

**Radiometric resolution**: refers to the number of different intensities of radiation the sensor is able to distinguish. Typically, this ranges from 8 to 16 bits, corresponding to 256 to 65,536 intensities or "shades" of color in each band.

Some people also refer to the "economic resolution", that is, how much data you get or are able to process per unit money.

Since applications vary in their interest as well as in spatial, temporal and spectral resolution requirements, a variety of sensors and satellites (e.g. Landsat, SPOT, IKONOS, Quickbird, MODIS, ASTER, ENVISAT, ERS, IRS, GOES, NOAA, SeaWiFs, RADARSAT) exist to meet these needs.

2.3.3. Types of remote sensing

There are two types of remote sensing technologies: passive and active (Lillesand and Kiefer, 1994).

**Passive**: relies on naturally reflected or emitted energy of the imaged surface. Sun is the most common source of natural energy for passive remote sensing. Most remote sensing instruments fall into this category, obtaining pictures of visible, near-infrared and thermal infrared energy.

**Active**: means that the sensor provides its own illumination and measures what comes back. Some examples of active remote sensing are Lidar (laser) and radar. Radars are sensitive to very different surface properties than visible/near-infrared imagery. For example, rather than vegetation "color," radar images are sensitive to the moisture content in leaves and their shape, orientation and size.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
2.3.4. Integration of GIS and Remote Sensing

Landsat satellite images and aerial photographs were the main source coming from remote sensing techniques used for this thesis. Remotely sensed imagery from aircraft (aerial photographs) and satellites represent one of the fastest-growing sources for raster GIS data. Often satellite imagery is preferred for environmental studies since it covers larger regions at economical costs besides integrating perfectly with GIS. Passive visible and near-infrared data are used in a variety of GIS applications, for example, classification of vegetation and land-use is particularly common, and may be performed at a variety of temporal and spatial scales.

Digital imagery can greatly enhance a GIS since imagery is a powerful visual aid and serves as a source of derivative information such as planimetrics and classification schemes to derive in land use or vegetation information (http://www.gislounge.com).

Both, remote sensing and GIS were necessary to fulfill the aims of this thesis since the first technique makes it possible to measure parameters on spatial scales while the second integrates the spatial analytical functionality for spatially distributed data.

Remote sensing represented by satellite images was used for elaboration of landuse maps which were obtained applying classification techniques. These maps were the base of future analysis like the SDSS for solving urbanization coastal problems (Santos) and derivate maps required by RUSLE and USPED equations like C and P factors maps. NDVI maps were also obtained by application of band mathematics which then led to final maps containing NDVI values representing the photosynthetic output (amount of green stuff) in a pixel in a satellite image. All the treatment and process followed for satellite images used in this thesis and products and maps obtained will be discussed in detail in the following chapters.

GIS was the main tool used to integrate all maps and databases obtained at each step. In this way all data was arranged and stored in only one source of information which tremendously facilitated the different calculations performed for erosion and SDSS models. These models require huge amounts of information present in different forms (spatially, temporally, thematic, format, etc) like landcover maps, erosion factors, water bodies, communication means, type of soils, rainfall data among others, and the only way to integrate and be able to use this data in an easy way was through GIS. Also all the calculations required by SDSS and erosion models which are characterized by its complicated algorithms and mathematics expressions, were performed using GIS facilities present in the software like raster calculator, spatial statistical analysis, spatial modeling, etc. These attributes significantly saved time and space for processing all this data.

Without these two techniques treatment and process of all the information available and necessary to achieve the expected results of this thesis would have been almost impossible to accomplish and it would have required much more time consumption.

Image processing software designed for analysis of remotely sensed data is really a specialized form of raster GIS. Softwares used in this research were: for GIS ArcGIS/ArcMap (Version 9.0 from ESRI Co.) and GRASS 6 (Geographic Resources Analysis Support System - Open Source GIS) and for remote sensing analysis ENVI (Version 4.0, Research Systems Inc) and Idrisi Andes (Clark Labs).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
2.4. Main source of information: satellite images

2.4.1. Generalities

Satellite images, specifically Landsat images (ETM+ and TM) played a major role for vegetation and landuse classification, being the main source of information for the elaboration of vegetation cover maps, NDVI maps and DEM for both study areas, Santos (Brazil) and Bahia Blanco (Argentina). Landsat images were used for this purpose principally due to its temporal (i.e. frequent, making possible that a considerable number of images were available) and spectral resolution (i.e. a variety of bands covering almost all electromagnetic spectrum: visible, infrared-useful for vegetation classification, and thermal), although its spatial resolution is not the best for elaborating precise and detailed vegetation analysis, it is quite acceptable and reliable if no other sources are available. Another important aspect taken into consideration and very much significant to support this choice was economical, since these images can be downloaded directly from the free website: http://glcf.umiacs.umd.edu/index.shtml. DEM images were also downloaded from the free website: ftp://eOsrp01u.ecs.nasa.gov/srtm/version2. Some adjustments were done in order to meet the specific requirements of this thesis, particularly referring to delimitation of study areas, since in both cases the images covered more than the area required which implicates more space and time consumption. This disadvantage was easily solved by a basic image process: subsetting, which consists on “cutting” the image with specific delimitation of geographical coordinates.

The images were chosen according to their quality (few cloud coverage) and date in which they were taken, trying to fulfill two main aspects: the most recent image in order to have an idea of current conditions of both areas and to compare this image with training areas collected during in-situ fieldwork in March 2005 (Santos) and 2006 (Santos and Bahia Blanco); and an past image (1996) to elaborate multitemporal analysis identifying the main changes in landuse over a specific period of time. Unfortunately, recent images of the same date of fieldwork were not available on this free site neither for Santos nor for Bahia Blanco, specially for Santos where the latest image was from year 2000. The main characteristics of Landsat images selected are described in Table 2.3.

<table>
<thead>
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<th>Date</th>
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<th>Path/Row</th>
<th>Sensor</th>
<th>Producer</th>
<th>Attributes</th>
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<td>Brazil</td>
<td>22 June 1993</td>
<td>23°30'S - 46°05'W</td>
<td>219/077</td>
<td>TM</td>
<td>EarthSat</td>
<td>Ortho-GeoCover</td>
<td>GeoTIFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24°00'S - 46°30'W</td>
<td></td>
<td>7 bands Landsat 5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Brazil</td>
<td>30 April 2000</td>
<td>23°30' S - 46°05' W</td>
<td>219/077</td>
<td>ETM+</td>
<td>EarthSat</td>
<td>Ortho-GeoCover</td>
<td>GeoTIFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24°00' S - 46°30' W</td>
<td></td>
<td>8 bands Landsat 7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Argentina</td>
<td>18 April 2004</td>
<td>38°15' S - 61°45' W</td>
<td>226/087</td>
<td>ETM +</td>
<td>EarthSat</td>
<td>Ortho-GeoCover</td>
<td>GeoTIFF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39°40' S - 62°30' W</td>
<td></td>
<td>8 bands Landsat 7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanco (Argentina).
2.4.2. Description of Landsat satellite

Because Landsat satellite images were broadly used in this thesis, the most significant characteristics of this satellite and its products will be described in the following paragraphs.

The Landsat Program is one of the longest running programs for image acquisition from space, first launched in 1972, it has been managed between the U.S. Geological Survey (USGS) and NASA. Seven satellites have so far been launched, the most recent being Landsat 7. All the images are transmitted through Landsat receiving stations around the world, and archived at central locations within the United States.

Landsat satellite imagery offers a unique resource for global change research and applications in agriculture, geology, forestry, regional planning, education, and national security.

Satellite images from Landsat 5 and 7 were used for vegetation analysis and landuse classification.

2.4.3. Landsat sensors and spatial and spectral resolution

The sensors and their most important characteristics onboard the different Landsat missions are (http://www.geoimage.com.au):

a. MSS

The Multispectral Scanner (MSS) was the main sensor on LANDSAT 1-3. The MSS sensor had a spatial resolution of 56m x 79m and collected imagery in 4 spectral bands (i.e. from visible green to near infrared specially selected for agricultural purposes) with a range of 128 intensity levels. The MSS sensor became subsidiary to the Thematic Mapper (TM) sensor on LANDSAT 4 and 5 and there was no MSS instrument planned for LANDSAT 6 and 7 since it was ceased in Landsat 5 and turned off in August 1995. (http://landsat.gsfc.nasa.gov/about/landsat5.html).

b. TM

The TM sensor is an advanced, multispectral scanning, Earth resources instrument designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity, and greater radiometric accuracy and resolution than the previous MSS. TM collected imagery in 7 spectral bands (i.e. from the visible, through the mid-IR, into the thermal-IR portion of the electromagnetic spectrum with an additional sensor for geological information) with a spatial resolution of 30 m x 30 m (except for band 6 which has an IFOV of 120 m by 120 m) and a data range of 256 intensity levels.

c. ETM+

The Enhanced Thematic Mapper Plus (ETM+) sensor replicates the capabilities of the TM and is present on Landsat 7. ETM+ has an IFOV of 60 m by 60 m in band 6 and it adds an extra panchromatic band of 15 m resolution.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
2.4.4. Landsat 7

Most of the images analyzed in this research refer to those obtained from satellite Landsat 7. Only one image (June 22, 1993) collected by Landsat TM-5 (launched on March 1, 1984) was used in this thesis, specifically for the multitemporal analysis elaborated in Santos. An instrument malfunction occurred on this satellite resulted in various problems with image registration. One of the effects caused by this failure is a shift in some of the satellite tracks, that gives a "shifted" appearance in some stripes of the image. This inconvenient was solved by masking the shifted stripe on this image for all the processes and analysis concerning this particular image. Methodology followed for satellite processing will be discussed in detail in Chapters 4 and 5.

Landsat 7 was launched on April 15, 1999. This satellite as mentioned before is equipped with an ETM+ instrument. The satellite orbits the Earth at an altitude of approximately 705 km (438 miles) with a sun-synchronous 98-degree inclination and a descending equatorial crossing time of 10 a.m. These satellites were also designed and operated to collect data over a 185-km swath (http://glcf.umiacs.umd.edu/data/landsat/). The most significant characteristics of Landsat 7 are summarized in Table 2.4.

Table 2.4: Sensitivity and resolution used on Landsat-7/ETM+ Mission (http://glcf.umiacs.umd.edu/index.shtml).

<table>
<thead>
<tr>
<th>Sensor ETM+ Landsat 7</th>
<th>Spectral Sensitivity (μm)</th>
<th>Nominal Spectral Location</th>
<th>Ground Resolution (m)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>0.45-0.52</td>
<td>Blue</td>
<td>30x30</td>
<td>Bathymetry, soil-vegetation, forest types, support analysis of landuse</td>
</tr>
<tr>
<td>Band 2</td>
<td>0.52-0.6</td>
<td>Green</td>
<td>30x30</td>
<td>Quality and healthiness of vegetation</td>
</tr>
<tr>
<td>Band 3</td>
<td>0.63-0.69</td>
<td>Red</td>
<td>30x30</td>
<td>Chlorophyll absorption, vegetation discrimination, soil boundary, geological-boundary delineations</td>
</tr>
<tr>
<td>Band 4</td>
<td>0.76-0.9</td>
<td>Near-IR</td>
<td>30x30</td>
<td>Responsive to the amount of vegetation biomass present, used for crop ID, emphasizes soil/crop and land/water contrasts</td>
</tr>
<tr>
<td>Band 5</td>
<td>1.55-1.75</td>
<td>Mid-IR</td>
<td>30x30</td>
<td>Sensitive to the turgidity of water in plants, crop drought studies/plant health, discriminates between ice, snow, clouds, rock and mineral types</td>
</tr>
<tr>
<td>Band 6</td>
<td>10.4-12.5</td>
<td>Thermal-IR</td>
<td>60x60</td>
<td>Thermal, measures amount of infrared radiant flux emitted from surfaces, useful for locating geothermal activity, vegetation classification, vegetation stress analysis and soil moisture studies</td>
</tr>
<tr>
<td>Band 7</td>
<td>2.08-2.35</td>
<td>Mid-IR</td>
<td>30x30</td>
<td>discriminates geologic rock formations</td>
</tr>
<tr>
<td>Band 8</td>
<td>0.52-0.90</td>
<td>False color</td>
<td>15x15</td>
<td>Panchromatic</td>
</tr>
</tbody>
</table>

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### Chapter 3

#### Study areas

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Chapter 3

Study areas

3.1. Study area of Santos (Brazil)

3.1.1. General Description of Santos and surroundings

The study area, Santos, is located in South America in the southeastern part of Brazil as illustrated in Figure 3.10. Santos is a municipality of São Paulo State which is one of the biggest states of Brazil with a total area of 248,176.7 Km², a population of 40'404,010 inh. (estimated for May 2006), representing 21.5% of Brazil’s population with a density of 149.2 inh/Km². These facts make of São Paulo State the most populous country subdivision in the Western Hemisphere (i.e. geopolitical term for the Americas and associated islands). Santos is located approximately at 70 Km distant from the city of São Paulo. Since Santos is part of São Paulo State, it is very much affected and influenced by the State’s activities, economy, physical conditions, climate, and development, for this reason a brief and general information of São Paulo State is useful for a better understanding of Santos current situation.

Figure 3.10: Location of Brazil and study area of Santos (red square).

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Economy

São Paulo is the richest state in Brazil. It has the second highest per-capita income (lower only than the Federal District), and together with the states of Rio Grande do Sul and Santa Catarina, the highest standard of living in Brazil, despite the poverty in some peripheral parts of the largest cities.

São Paulo state is responsible for approximately one-third of the Brazilian GDP (Gross Domestic Product). The state's GDP (Purchasing Power Parity-PPP) consists of 550 billion dollars, making it also one of the biggest economies in Latin America. Its economy is based on machinery, automobile and aviation industries, services, financial companies, commerce, textiles, orange cultivation, sugar cane and coffee production, among the most important ones. Unfortunately, wealth is unequally distributed in this state. The richest municipalities are centered around Greater São Paulo (such as Campinas, Jundiaí, Paulínia, Americana, Santos, Indaíatuba, São José dos Campos, etc.), as well as a few other more distant around Ribeirão Preto, situated at 313 Km from the capital city, São Paulo. On the other hand, some regions, such as Registro and Bananal, in the border with Rio de Janeiro, are very poor, nearly as poor as municipalities in the Northeast of Brazil (http://en.wikipedia.org/wiki/S%C3%A3o_Paulo).

Climate

There are five climatic regions in Brazil: equatorial, tropical, semi-arid, highland tropical and subtropical. Cities such as São Paulo and Brasilia, on the plateau, have a mild climate with temperatures averaging 19°C. The climate of São Paulo is tropical to subtropical and altitude is the most significant contributor for climatic variations. The capital, São Paulo, barely outside the tropics in the south of the state and about 800 m above sea level, has a daily minima and maxima average temperature about 19°C - 29°C respectively at the warmest time of year and about 12°C - 22°C respectively at the coolest time of year. Temperatures, however, can reach around 40°C on the hottest days and 5°C on the coldest nights.

The region has essentially two seasons: summer (from November to April) or wet season, and winter (from May to October) or dry season (http://www.sonesta.com/saopaulo/). In the dry season there is no rain (Figure 3.11) at all and in the wet season it can vary from a good cleansing rainstorm for an hour each day to a few days of rain.

Figure 3.11: Monthly rainfall for Santos (1984 – 2005) represented by Caete meteorological station.

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3.1.2. Main characteristics of the study area - Santos

Santos is partially located on the island of São Vicente, and partially on the mainland, it also includes the Santos Bay (Figure 3.12). Summarizing the main characteristics of Santos are:

**State:** São Paulo

**Area:**
City: 281 Km$^2$
Metropolitan area: 2373 Km$^2$

**Population at Metropolitan area:**
418,375 hab (Estimated in 2006)

**Height:** 2 m above sea level

**Geographical location:**
23°57.28’ S
46°18.57’ W

Santos is located on the coast of São Paulo, it is the main city in the metropolitan region of Baixada Santista which has a total area of 2373 Km$^2$. The Baixada Santista although, covering less than 1% of the state’s total area (248,176 Km$^2$) as seen in Figure 3.13, it is one of the most populated areas in the state.

The main municipalities of Baixada Santista (http://en.wikipedia.org/wiki/Santos) are: Santos, São Vicente, Praia Grande, Mongaguá, Cubatão, Guarujá, Itanhaém, Bertioga, and Peruibe (Figure 3.12).

The area of Santos is formed by two islands (São Vicente and Santo Amaro) very close to the continent, thus delimiting three channels: Santos, São Vicente and Bertioga. This area is located in the southern limit of the tropical zone with mean temperatures of 22°C, and an average rainfall index of 2500 mm/year. Due to Santos vicinity to São Paulo city it shares practically the same climatic characteristics described before.

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About 39 Km$^2$ of Santos municipality is located in São Vicente Island which is very plain and near the coast, and is here where most of the population is concentrated. Then, more than 230 Km$^2$ are located on the continent, here it is very low populated and is where the ecological reserves of *Mata Atlântica* are found.

Another important characteristic of this area is the mountainous range surrounding it, Serra do Mar (Figure 3.14), that will be better described in the following section of this chapter due to its ecological importance. Serra do Mar constitutes a very important ecosystem since it is partially covered by the Atlantic Forest.

![Santos, part of its estuary and mountainous range (Serra do Mar) surrounding the city.](image)

**Figure 3.14:** Santos, part of its estuary and mountainous range (Serra do Mar) surrounding the city.

Regarding coastal plains, they were originally covered by extensive mangroves forests, that have been gradually occupied by the industrial complex of Cubatão (established since 1940), by urban settlements, and by the harbor of Santos, consequently few pristine areas do remain. Currently, the Brazilian legislation considers mangroves as permanent preservation areas, as a result much more control and attention is given to these natural ecosystems, protecting them from urban and industrial development.

Santos lives from its port, tourism, some important industries (i.e. copper, chemical), commerce, banks and other services. Santos has the most important seaport in Brazil (Figures 3.15 and 3.16) which is at the same time the biggest one in Latin America: it traded over 72 millions tons in 2006. Santos is also a significant tourist centre, housing hundreds of local and international tourist, has large industrial complexes and shipping centers that handle a large portion of the world’s coffee exports; as well as a number of other Brazilian exports including oranges, bananas and cotton.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
3.1.3. Serra do Mar – *Mata Atlântica* Ecosystem

Santos study area is surrounded by one of the main and extensive mountainous range in Brazil, Serra do Mar. Serra do Mar is a 1500 Km long mountainous system (Figure 3.17 and 3.18) which runs parallel to the Atlantic Ocean coast and extends from the state of Espírito Santo to Santa Catarina State in the south. The main escarpment forms the boundary between the sea level “littoral” and the inland “plateau” (*planalto*), which has a mean altitude of 400 to 500 m. The mountain ranges are discontinuous and receive individual names, such as Serra...
da Mantiqueira, Serra de Bocaina, Serra de Paranapiacaba, Serra Negra, etc. The highest point of Serra do Mar is the Pico das Agulhas Negras with a height of 2878 m, located between the states of Rio de Janeiro and Sao Paulo at the National Park of Itatiaia.

The Serra do Mar coastal forests is an eco-region of tropical moist forest (Figure 3.17) that runs along the southern coast of Brazil for about 100 Km. It has a subtropical climate with high levels of annual rainfall ranging from 1400 to 4000 mm without a dry period. This area of Brazil is characterized by slopes and high summits of the Serra do Mar formed by pre-Cambrian rocks. Geologically, the Serra do Mar belongs to the massive crystalline rock platform that form Eastern South America and tectonically is very stable. More of the elevations of Serra do Mar were formed about 60 million years ago (Mantovani, 1993). Tropical nutrient-impoverished soils (e.g. yellow-red latosol, podsols and lithosols) characterize this mountainous region (Radambrasil, 1983).

![Figure 3.17: Tropical moist forest, part of Serra do Mar ecosystem.](image)

The Serra do Mar mountain range defines this ecoregion with mountain forest of Bromeliaceae, Myrtaceae, Melastomataceae and Lauraceae species (Leme, 1998, Lima et al., 1997). This region contains outstanding biodiversity in endemism and species richness of flora, mammal, birds and herpetofauna. It comprises one of the more remarkable centers of endemism in South America, unfortunately, more than half of the original forest has been altered; urban development and tourism constitute the main threats for this eco-region (Silva et al., 1982).
Forests range from coastal plains located at 20 m elevation up to the highest mountains at 1200 to 1500 m, creating a remarkable vegetation gradient from shrubs to well-developed mountain forests. The main type of vegetation is the Atlantic moist forest (lowland to upper mountain), a four-strata vegetation with emergent trees taller than 30 m (Veloso et al., 1991). Emergent and canopy layers are rich in species of Leguminosae (*Copaifera trapezifolia*), Sapotaceae (*Pouteria, Chrysophyllum*), and several species of Lauraceae (SILVA et al., 1982). Vegetation cover has been divided into four types of dense Atlantic ombrophilous forest (lowland, sumountainous, mountainous, and secondary forest) and agricultural activity.

The Serra do Mar forests have been reduced in 53% of its original area (SOS Mata Atlântica, 1998). Serra do Mar contains the main remaining of Mata Atlântica, which has been condensed to less than 5% of its original area. Habitat loss occurs preferentially in lowland forests, which are replaced quickly by urban areas.

Serra do Mar forests are spread over the more industrialized region of Brazil in which human population sometimes reaches 1000 individuals per Km² (Monteiro et al., 1999). In addition, traditional human activities like palm-heart extraction represent a severe threat to plants and frugivorous vertebrates, in some localities more than 10,000 Kg of palm-heart is extracted per year (Galetti et al., 1998). Most of the forest cover has been destroyed and now it remains almost exclusively in the steep escarpments facing the sea. Remaining natural vegetation is represented by 45,928 Km² of moist forest, while protected areas encompass 1403 Km² of these moist forests, including large blocks of mountainous forest which are currently protected by national parks and ecological stations (SILVA et al., 1999).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Chapter 3

Study Areas

3.1.4. Santos Estuary

Santos Estuary is referred as a very polluted estuary, years ago it used to receive raw sewage coming from São Paulo and discharges from industrial and hydroelectric plants from Cubatão. Currently high levels of oxygen-demanding substances, phenols, heavy metals (e.g. copper and zinc) and pesticides have been detected in the water, while heavy metals and pesticides have been found in sediments. Santos Estuary after 500 years of urban, industrial and port use is nowadays a highly changed ecosystem. It has extensive areas of mangrove partially depredated but still with some well preserved areas (EcoManage, 2003).

To increase environmental quality in the Estuary, the Brazilian Company of Environmental Sanitation Technology (Companhia de Tecnologia de Saneamento Ambiental - CETESB), established in 1983 the Program for Environmental Pollution Control. CETESB is the institution linked to the government of São Paulo State responsible for the evaluation, prevention and control of environmental pollution, as well as the execution of scientific and technological services direct or indirectly related to its field of action (http://www.cetesb.sp.gov.br/). The Company also acts as the technical institution of the State's Environmental System (Sisema) and of the National Environmental Council (Conama).

The program is particularly noteworthy for its development and use of epidemiological studies, biological methods, criteria for assessing toxicity, and models for evaluating environmental risks (Ecomanage, 2003). Santos estuary has been subject of intensive field campaigns as part of this program. The main aims of the program regarding Santos estuary are:

- surveying pollution sources,
- inventorying emissions to the estuary,
- developing environmental control plans for each industrial source in Cubatão.

The industrial activity on the area is characterized by a high pollution potential, making of Santos and São Vicente estuaries the main receptors of toxic residuals, liquid polluted effluents, and sewage coming from Santos Port and main cities of the region (Procop, 2001). As a result, all these activities have contributed to the serious environmental degradation of the area. After the creation of this program significant improvements on the environmental quality of these estuaries have been recorded, specially on water, nevertheless, there are still serious pollution problems affecting the estuaries nowadays.

3.1.5. Marine pollution in Santos Estuary

Due to the availability of relevant and reliable data, coming from sediments, water and marine organisms sampling campaigns in Santos Estuary, it was consider appropriate the elaboration of a general pollution analysis of these three groups. The analysis were performed using fuzzy sets theory, to get representative clusters of each of the samples collected in these three groups, and calculating an indicative pollution index of the current environmental conditions of this estuary.

The analysis was based on past measurements (heavy metals, PCBs, PAHs, dioxins and furans) elaborated by CETESB on water, sediments and local aquatic organisms in Santos

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Bay. The measurements took place between February and June 1999 (due to some technical problems some samples were also collected in January 2000) and consisted on 26 sampling points (water: 22 samples; sediments: 63 samples, and aquatic organisms as fish, crustaceans and molluscs: 161 samples) distributed around the Bay. Sampling sites were chosen according to vicinity of industrial areas (Figure 3.19).

![Figure 3.19: Location of the main industries in Baixada Santista and sampling points (Procop, 2001).](image)

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Regarding the industries of this area, Baixada Santista, Table 3.5 summarize the most important industries and their activities.

**Table 3.5: Main industries of Baixada Santista**

<table>
<thead>
<tr>
<th>Industry</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSIPA</td>
<td>Steel industry</td>
</tr>
<tr>
<td>PetroBras, Mobil</td>
<td>Oil refinery, bulk liquid terminal, Petrochemical</td>
</tr>
<tr>
<td>CarboCloro, Rhodia, Alba, Liquid Quimica, Columbia</td>
<td>Chemical industries</td>
</tr>
<tr>
<td>CopeBrás</td>
<td>Agricultural chemicals</td>
</tr>
<tr>
<td>Brasterminais, Stolhaven</td>
<td>Bulk liquid terminals</td>
</tr>
<tr>
<td>Dow Quimica</td>
<td>Plastics, chemicals and agricultural products</td>
</tr>
<tr>
<td>IFC, Ciel</td>
<td>Agricultural products</td>
</tr>
<tr>
<td>Manah, Ultrafértil, Solorrico</td>
<td>Fertilizers manufacturers</td>
</tr>
<tr>
<td>Serrana</td>
<td>Shoe factory</td>
</tr>
<tr>
<td>Union Carbide</td>
<td>Carbon, chemicals</td>
</tr>
<tr>
<td>Petrocoque</td>
<td>Carbon industry</td>
</tr>
<tr>
<td>Cia. Santista de Papel</td>
<td>Paper, celluloid</td>
</tr>
<tr>
<td>Citrosuco, Cargill Citrus</td>
<td>Citrics</td>
</tr>
<tr>
<td>Dibal, Hamilton Fox, Granel, Argemil</td>
<td>Bulk liquid terminal</td>
</tr>
</tbody>
</table>

Photos of some of the main industries terminals located on the port of Santos can be seen in Appendix 1.

3.1.6. **Methodology followed on sampling and analysis (CETESB and Petrobrás)**

Almost 120 parameters were previously determined and analyzed by CETESB and Petrobrás, including heavy metals and arsenic, organoclorated pesticides, aromatic organoclorated, herbicides and other pesticides, also phenol compounds, poli-aromatic hydrocarbons (PAHs), aromatic solvents and halogens, polioarcomerated biphenyl (PCBs), dioxins and furans. Five zones were delimited according to their ecological characteristics (Figure 3.19): I. River Cubatão, II. Santos Estuary, III. São Vicente Estuary, IV. Santos Bay, and V. Open sea (Procop, 2001).

Physical and chemical parameters as well as heavy metal measurements on water were determined by CETESB (CETESB, 1979), while the rest of chemical analysis were determined by Petrobrás laboratories (CEGEC/CENPES) located in Rio de Janeiro.

A brief description of the methodology followed by these two institutions regarding water, sediments and organisms sampling and analysis will be provided in the next paragraphs.

**Water**

Water samples were collected on low tide using glass containers. Water samples for physical-chemical, microbiological and ecotoxicological analysis were collected according to Agudo, (1989) and APHA (1985).
Sediments

Sediment samples were collected in three replicates with a Van Veen drag. These samples were then transferred to plastic trays, homogenized and then separated according to its composition in different containers.

Aquatic organisms

Samples were selected according to the most representative organisms of the area taking into consideration their feeding habits, ecological habitats and frequency on the region. The species selected were: common snooks (*Centropomus undecimalis* and *parellus*), caitipa mojarra (*Diapterus rhombeus*), mullets (*Mugil curema, Mugel liza*), Nile tilapia (*Oreochromis niloticus*), blue crabs (*Callinectes sapidus*), shrimbs (*Penaeus sp*), crab (*Ucides cordatus*), ostriches (*Crassostrea sp*), mussel (*Perna perna*), and tagelus (*Tagelus sp*). Analysis were performed only on eatable parts of these species. Fish sampling was done together with local fishermen; mollusks were directly collected from mud, mangrove roots and rocks, and blue crabs and crabs using special traps. All samples were measured, weighted and classified according to their size (Procop, 2001).

Sediments, organisms and PCBs samples were analyzed according to the United States Environmental Protection Agency-USEPA (1994) and ASTM (1996), dioxins and furans compounds according to Bonn (1997). Heavy metals as Al, Cd, Pb, Cu, Fe, Mn and Zn were analyzed using spectrometry and atomic absorption-flame according to APHA (1995) proceedings. Mercury (Hg) was determined by spectrometry atomic absorption cold vapor using APHA (1995) methodology.

Results were then interpreted according to the Brazilian legislation and for those parameters not included in this legislation, criteria from the Canadian Environmental Agency (Environment Canada, 1999) and Florida Department of Environmental Protection (FDEP,1994) were applied, specifically using the TEL (Threshold Effect Level) and PEL (Probable Effect Level) classifications. For organisms were used TEFs proposed by Van den Berg *et al.* (1998).

3.1.7. Methodology followed using Fuzzy sets theory

An example of the results obtained by CETESB and Petrobrás can be seen on Appendix 3. A next step towards the calculation of an indicative pollution index for each one of the analyzed groups and a general quality index for all the estuary was performed using fuzzy sets theory. This will be briefly described since it was not a main objective of this thesis, but just to show a measurable and easy understandable indicator of the current pollution in Santos Estuary.

Fuzzy sets theory

Fuzzy set theory are sets (or classes) without well-defined boundaries between those objects that belong to the class and those that do not. It allows objects to belong partly to multiple sets. Fuzzy logic is useful for describing the vagueness of entities in the real world, where belonging to a set is really a matter of degree (Zadeh, 1965; Klir and Yuan, 1995). A fuzzy set is characterized by a fuzzy membership grade or degree to which it belongs to a set (also

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called possibility) that ranges from 0.00 to 1.0, indicating a continuous increase from nonmembership to complete membership. Specifically, a fuzzy set on a classical set \( X \) is defined as follows:

\[
\tilde{A} = \{(x, \mu_A(x)) \mid x \in X\}
\]

The grade of membership is described by the function \( \mu_A(x) \) that quantifies the grade of membership of the elements \( x \) to the fundamental set \( X \) (Schmucker, 1982). For example, an element \( x \) clearly belong to \( A \) if \( \mu_A(x) = 1 \) and clearly does not belong to \( A \) if \( \mu_A(x) = 0 \). Values strictly between 0 and 1 characterize the fuzzy members.

This concept was applied for obtaining the most representative clusters, as seen in the dendrogram on Figure 3.20, that represents the integration of data (water, sediments and organisms samples) in seven groups according to their similar range of pollution (degree of membership in vaguely defined sets-fuzzy sets).

![Dendrogram of the samples obtained by fuzzy set analysis, identifying 7 clusters.](image)

**Figure 3.20:** Dendrogram of the samples obtained by fuzzy set analysis, identifying 7 clusters.

Afterwards, these sets (clusters) were established and for a better understanding of pollution conditions of the estuary regarding water, sediments and organisms, a quality index was obtained for each group according to a correlation between these groups and their distance to the worst and best situation. First, the Euclidean distance between the fuzzy sets and the best and worst situation was calculated in a matrix (Table 3.6).

**Table 3.6:** Euclidean distance (normalized) between the fuzzy sets and the best and worst situation.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>worst</th>
<th>best</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.340</td>
<td>0.146</td>
<td>0.314</td>
<td>0.293</td>
<td>0.779</td>
<td>1.496</td>
<td>0.340</td>
<td>1.496</td>
</tr>
<tr>
<td>2</td>
<td>0.340</td>
<td>0</td>
<td>0.283</td>
<td>0.536</td>
<td>0.566</td>
<td>1.048</td>
<td>1.708</td>
<td>0.043</td>
<td>1.708</td>
</tr>
<tr>
<td>3</td>
<td>0.146</td>
<td>0.283</td>
<td>0</td>
<td>0.301</td>
<td>0.377</td>
<td>0.831</td>
<td>1.510</td>
<td>0.280</td>
<td>1.510</td>
</tr>
<tr>
<td>4</td>
<td>0.314</td>
<td>0.536</td>
<td>0.301</td>
<td>0</td>
<td>0.233</td>
<td>0.551</td>
<td>1.210</td>
<td>0.550</td>
<td>1.210</td>
</tr>
<tr>
<td>5</td>
<td>0.293</td>
<td>0.566</td>
<td>0.377</td>
<td>0.233</td>
<td>0</td>
<td>0.504</td>
<td>1.234</td>
<td>0.580</td>
<td>1.234</td>
</tr>
<tr>
<td>6</td>
<td>0.779</td>
<td>1.048</td>
<td>0.831</td>
<td>0.551</td>
<td>0.504</td>
<td>0</td>
<td>0.764</td>
<td>1.065</td>
<td>0.764</td>
</tr>
<tr>
<td>7</td>
<td>1.496</td>
<td>1.708</td>
<td>1.510</td>
<td>1.210</td>
<td>1.234</td>
<td>0.764</td>
<td>0</td>
<td>1.732</td>
<td>0</td>
</tr>
<tr>
<td>worst</td>
<td>0.337</td>
<td>0.043</td>
<td>0.280</td>
<td>0.550</td>
<td>0.580</td>
<td>1.065</td>
<td>1.732</td>
<td>0</td>
<td>1.732</td>
</tr>
<tr>
<td>best</td>
<td>1.496</td>
<td>1.708</td>
<td>1.510</td>
<td>1.210</td>
<td>1.234</td>
<td>0.764</td>
<td>0</td>
<td>1.732</td>
<td>0</td>
</tr>
</tbody>
</table>

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Second, the worst and best distances were used to calculate the quality index $C$ for each of the seven clusters (Table 3.7). Index $C$ was obtained using Hwang and Yoon (1981) technique for order preference by similarity to the ideal solution (TOPSIS), synthesised for this case in the following expression:

$$C = \frac{\text{distance}_\text{worst}}{\text{distance}_\text{best} + \text{distance}_\text{worst}}$$

<table>
<thead>
<tr>
<th>Cluster</th>
<th>$D_{\text{worst}}$</th>
<th>$D_{\text{best}}$</th>
<th>$\text{Index } C$</th>
<th>Normalized index $C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.734413</td>
<td>1.00746</td>
<td>0.421623</td>
<td>0.185212</td>
</tr>
<tr>
<td>2</td>
<td>0.658809</td>
<td>1.089352</td>
<td>0.376858</td>
<td>0.024641</td>
</tr>
<tr>
<td>3</td>
<td>0.736316</td>
<td>0.99743</td>
<td>0.424696</td>
<td>0.156359</td>
</tr>
<tr>
<td>4</td>
<td>0.843679</td>
<td>0.888424</td>
<td>0.487084</td>
<td>0.312473</td>
</tr>
<tr>
<td>5</td>
<td>0.820529</td>
<td>0.924177</td>
<td>0.470297</td>
<td>0.319991</td>
</tr>
<tr>
<td>6</td>
<td>0.999442</td>
<td>0.735611</td>
<td>0.576029</td>
<td>0.582273</td>
</tr>
<tr>
<td>7</td>
<td>1.277578</td>
<td>0.474052</td>
<td>0.729365</td>
<td>1</td>
</tr>
</tbody>
</table>

Distance of each cluster to the best and worst situation, indicates the degree of pollution. The shortest the distance to the worst indicates a more polluted condition. For example, from the table above, cluster 2, is the most polluted, since the distance to the worst situation (0.658809) is the shortest among all the clusters, followed by clusters 1, 3, 5, 4, 6 and 7. Then, by calculating index $C$, the quality condition of each cluster is more evident, higher the index, better the condition. For example, cluster 7, is the least polluted one, since the quality index $C$ has the highest value (0.729365). Location of the samples and their belonging to each of the seven clusters with their respective quality index $C$ can be seen in Figure 3.21.

Figure 3.21: Samples and clusters obtained with their respective quality index (descending order, from the worst to the best).
Third, this quality index C was correlated to the water, sediments and organisms matrixes then normalized, so to get a membership grade (Table 3.8) of the polluted samples of these three groups to each one of the clusters, taking into consideration that they have been already classified according to their environmental conditions (Figure 3.21). A membership grade closer to one indicates a higher membership to a specific cluster.

**Table 3.8:** Pollution condition according to the membership degree (normalized) of water, sediments and organisms matrixes to each cluster.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.875</td>
<td>1</td>
<td>0.795</td>
<td>0.629</td>
<td>0.809</td>
<td>0.504</td>
<td>0</td>
</tr>
<tr>
<td>Sediments</td>
<td>1</td>
<td>0.957</td>
<td>0.996</td>
<td>0.810</td>
<td>0.790</td>
<td>0.548</td>
<td>0</td>
</tr>
<tr>
<td>Organisms</td>
<td>0.687</td>
<td>1</td>
<td>0.810</td>
<td>0.641</td>
<td>0.494</td>
<td>0.173</td>
<td>0</td>
</tr>
</tbody>
</table>

Cluster 2, which is the most polluted one, shows that water and organisms have the highest degree of membership (1) and mostly belong to this cluster, so they are quite polluted, while sediments fits (belong) better into cluster 1, which is on the second place of pollution. Therefore, none of the samples belong to cluster 7 which is the best cluster according to its environmental conditions. This can be synthesized into: the higher the membership degree the worse environmental condition.

Figures 3.22, 3.23 and 3.24 shows distribution of sampling points for each of the water, sediments and organisms groups and their respective pollution condition according to their membership degrees to the clusters. To facilitate the classification of the samples according to this membership concept, three classes were defined concerning their pollution conditions:

- **Bad:** $>0.80$
- **Moderate:** $0.50 - 0.80$
- **Acceptable:** $0 - 0.50$

![Figure 3.22: Water samples classified according to their pollution condition, taking into consideration membership degree to the clusters.](image)

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Figure 3.23: Sediment samples classified according to their pollution condition, taking into consideration membership degree to the clusters.

Figure 3.24: Organism samples classified according to their pollution condition, taking into consideration membership degree to the clusters.

From these graphs it is possible to say that sediments are the most contaminated samples of all, since most of their samples belong to the worst classification with values higher than 0.8, followed by water samples and finally organisms with the less number of samples belonging to bad classification. Most of the organisms samples belong to the acceptable class, which indicate that pollution values on the analyzed species seem to be low.

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Finally, to have a general overview of the environmental quality of Santos Estuary (Figure 3.25), an integration of all fuzzy indexes was performed, which summarize all the three previous individual scenarios. In this case the quality index C previously calculated (normalized) was taken as a reference for determining the environmental conditions of the Estuary. Here a new classification was adopted, since higher values of index C indicate better conditions:

Bad: 0 – 0.50  
Moderate: 0.51 – 0.60  
Acceptable: > 0.60

Figure 3.25: Quality index C of the samples associated to their respective clusters. Index values from 0 – 0.50 indicate most polluted sites, from 0.50 – 0.60 moderate polluted sites and index values higher than 0.60 indicate the least polluted sites.

As a conclusion from this analysis and taken as a reference Figure 3.25, it is possible to say that the general environmental conditions of Santos Estuary seem to be worrying, since most of the samples indicate a low quality index, specially those located on the interior parts of the estuary, while those with a higher environmental index (better conditions) are located close or in the open sea according to Figure 3.19. This can be considered a normal situation since closer to the open sea there are more probabilities of water exchange, recirculation and dispersion of pollutants due to currents and waves action.
3.2. Study area of Bahia Blanca (Argentina)

3.2.1. General Description of Bahia Blanca (BA) and surroundings

Bahia Blanca is located in the eastern side of Argentina, in Buenos Aires Province (Figure 3.26). Buenos Aires Province has an important seaport at the head of Bahia Blanca, which is the second largest seaport in Argentina (Figure 3.28). Bahia Blanca is an important transhipping and commercial center, handling the large export trade of Buenos Aires and other provinces.

It is almost a plain region with just few soft contours through the coastal area, however there exist a significant mountainous formation, Sierra de la Ventana, on the north-eastern part of Bahia Blanca. These mountains have average heights between 500 – 800 m, but it can also reach more than 1000 m. The coastal area is characterized by the presence of two streams, Napostá Grande and Maldonado, with very fertile soils and abundant pastures.

![Figure 3.26: Argentina and location of the study area, Bahia Blanca.](image)

Economy

The advantageous location of Bahia Blanca is determined first by its well implemented and prosperous port, that canalizes the economic fluxes from the south-eastern part of Buenos Aires and the Rio Negro Valley, therefore, establishing flourishing and crucial relations at a regional, national and international level. Second, because Bahia Blanca is located in a transitional area between the important regions of the “Pampas” and “Patagonia”, this place the city at a vital convergent nucleus regarding circulation and communication networks, including a well served railway network, the third one in Argentina after Buenos Aires and Rosario.

Also, Bahia Blanca is an important administrative, commercial, financial and cultural center, fulfilling a crucial and essential function on the agricultural, commercial, industrial and

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educative activities of the whole region. Bahia Blanca manages the export activities of grains and wool from southern Buenos Aires Province, oil from the Province of Neuquén and fruit from the Río Negro Valley (http://es.wikipedia.org/wiki/Bahía_Blanca_(ciudad)).

Its economy is mainly based on the intense agricultural and cattle activities taking place in the region. Followed by important industrial activities also present in the area, like oil refineries (ESSO, Shell, Petrobrás), chemical (INDUPA, Dow Quimica) and oil tanking activites.

The harbor area is located nearby the coastal area between 3.4 m and 2.7 m above sea level, and 7 Km from the city, that is well connected by several routes of easy access. The sea port has an average natural depth of 10 m, although the depth of the main channel is kept at 12.19 m by regular maintenance and dredging.

**Climate**

Bahia Blanca is located on the south-western part of Buenos Aires Province, on the Atlantic Coast. Due to its position, Bahia Blanca belongs to a Temperate Climatic Zone, with average yearly temperatures between 14°C and 20°C and thermal seasons very well differentiated. Bahia Blanca is characterized by rigorous and intense summers and winters, while spring and autumn seasons are mildly and pleasant. Winds are, generally, moderated with an average of 25 Km/h, however during spring and summer (December, January and February) wind speed can increase up to 60 Km/h and more, coming from the north and north-west in summer and from the south and south-east in winter.

The yearly rainfall range fluctuate between 500 mm and 600 mm, with a high monthly index variability. Rains are more frequent and abundant at the end of spring and beginning of summer (March, October, February and November) (Figure 3.27). Summarizing, Bahia Blanca is characterized by rainy summers, specially at the beginning and at the end, and quite high temperatures, sometimes reaching 36°C - 38°C; while winters are very dry with low temperature, sometimes lower than 0°C. Thus, is possible to say that Bahia Blanca does not strictly belong to a well defined climatic sub-class, but that it is a consequence of the variability of its climatic cycles.

![Figure 3.27: Climatic characteristics of Bahia Blanca](http://es.wikipedia.org/wiki/BAhía_Blanca).

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3.2.2. Main characteristics of the study area – Bahia Blanca

**Province:** Buenos Aires

**Area:**
Metropolitan area: 2300 Km²

**Population:**
323,152 hab (Estimated in 2006)

**Height:** 20 m above sea level

**Geographical location:**
38° 43’ 0” S
62° 16’ 60” W

---

Bahia Blanca is located on the final boundary of the Pampas, where it is already possible to see the first irregularities of the terrain, represented by dunes and elevations between 200 m and 500 m, except by Sierra de la Ventana, that reaches up to 1200 m.

According to INDEC (Instituto Nacional de Estadística y Censos) Bahia Blanca is also formed by the districts of Villa Harding Green and Villa Stella Maris, General Daniel Cerri; and the localities of Ingeniero White, Grünbein, Cabildo, Villa Espora and Villa Bordeau (Figure 3.29).

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Bahia Blanca is characterized by a significant and dynamic growth, due to the important economical and commercial activities taking place in the city and surroundings. This has been greatly favored by the presence of different ports located nearby the city and along its estuary. Urbanization level of this district is quite high, about 98.5% of the population, which indicates that most of the population tends to concentrate within urban areas (http://www.world66.com/southamerica/argentina/bahiablanca/). An aerial view of Bahia Blanca and its port can be seen in Figure 3.30.

![Figure 3.30: Bahia Blanca and its main port on the horizon.](image)

Bahia Blanca concentrates a huge industrial nucleus (Cámara Regional de la Industria – CRI) and a strong artisan fishery. The industrial nucleus lodges several and different types of industries from chemical to petrochemical, also cereal processing plants and the largest fertilizers factories of the country (Ecomanage, 2003). One of the largest urea industrial producers in the world, PROFERTIL, is located here. Table 3.8 summarizes the main industries located in this area.

**Table 3.8: Main industries of Bahia Blanca**

<table>
<thead>
<tr>
<th>Industry</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSO, Shell and Petrobrás</td>
<td>Oil refineries, petrochemicals</td>
</tr>
<tr>
<td>Electric Power Plant</td>
<td>Energy</td>
</tr>
<tr>
<td>EBITEM</td>
<td>Oil tanking</td>
</tr>
<tr>
<td>INDUPA, POLISUR, PBB</td>
<td>Chemicals</td>
</tr>
<tr>
<td>CARGILL, Moreno</td>
<td>Cereal processing plant</td>
</tr>
<tr>
<td>PROFERTIL, Moreno</td>
<td>Fertilizers factory</td>
</tr>
<tr>
<td>Dow Quimica</td>
<td>Plastics, chemicals and agricultural products</td>
</tr>
</tbody>
</table>

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Bahia Blanca groups several sea ports specially on the nort-eastern shore of the bay, two are
the most important ones: Puerto Ingeniero White and Puerto Galván (Figure 3.29). Puerto
Ingeniero White is mainly used for grains and containers, it concentrates a large percentage
of Argentina’s exportation of cereal and oil (Figure 3.31). Puerto Galván, is a smaller port
specializing in sunflower and soy oil, and chemicals such as urea (http://www.world66.com/southamericalargentinalbahiablanca).

Between these two main ports, several industrial and chemical plants operate their own piers.
The petrochemical pole of the region made the port a very convenient one. The competition
between the ports of Bahía Blanca and those located in the shores of Patagonia (on the south
of the country), puts a great pressure on Bahia Blanca, consequently maintaining a high
standard of its ports by continuous improvement and keeping them very well organized. In
order to keep the ports of Bahia Blanca well functioning and efficiently, they continuously
receive investments from the private sector like CARGILL.

The combination of a rail-road network for grains and cereal transportation, its trade potential,
the availability of energy (natural gas and electricity) and human resources make the area of
Bahia Blanca very interesting from the industrial and commercial perspectives. An important
remark to mention is that the construction of the railway was of great importance for the
commercial development and prosperity of the city, thus to transport all the goods and
products manufactured and produced in the city to the rest of the country.

Bahia Blanca also allocates at 29 Km of its southwestern coast, Puerto Belgrano, the navy
base most important of Argentina and South America.

Figure 3.31: Puerto Ingeniero White during loading activities of grain containers.

An information system to analyze and monitoring coastal areas for planning sustainable development.
Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
3.2.3. Bahia Blanca Estuary

The Bahia Blanca Estuary is a mesotidal coastal plain estuary. It is a less modified coastal system than Santos Estuary (Ecomanage, 2003). The estuary is characterized by the presence of various canals, fine sand and silt-clay sediments and saltmarshes on the estuary boundaries (Isaach et al., 2006). The tidal oscillations of 4 m and predominant northwesterly winds create strong tidal currents, which facilitates water mixture, leading to uniform vertical distribution of the main oceanographic parameters (Ecomanage, 2003).

Bahia Blanca estuary includes a large tidal plain with an area of approximately 1150 Km², a relatively small input of inland water, and several marginal areas that seasonally function as hypersaline ecosystems (Figure 3.32). The middle-littoral is characterized by beaches with scarce slopes, and broad surface abundantly covered by halophyle vegetation or “espantillar” (Spartina sp. Salicornia sp.) (Figures 3.33) and crab caves or “cangrejales” basically from Chasmagnathus gramulata crab populatios (Ecomanage, 2003).

![Figure 3.32: Marginal areas functioning as hypersaline ecosystems.](image)

At the northern boundaries of the estuary various ports (mentioned in the previous section), towns (with populations exceeding 350,000 inhabitants) and industries are located, and several streams discharge within the area. Oil refineries and terminals, petrochemical industries, meat factories, leather plants, fish factories, textile plants, wood washing plants, silos and ceral mills discharge their effluents into the estuary with or without treatment. Moreover, this area is extensively used by fishing boats, oil tankers and cargo vessels, therefore requiring regular dredging even if its natural depth of 10 m is quite convenient.

All these activities and urbanization puts the estuary under increasing stress and pressure. For this reason, several campaigns and measurements have been organized in the estuary during the last years with the aim of keeping it monitored and under surveillance regarding its environmental conditions. Nevertheless, the estuary nowadays suffer from water pollution due
to industrial and urban discharges, as well as being used as a public dumping site. One of the main consequences is that this estuary is severely affected by solid waste disposals, for example, old tires, old refrigerators, old furniture, plastic recipients and containers, etc., that are thrown in the estuary and uncovered during low tides (Figures 3.34 and 3.35).

For a better visualization of the estuary, its main characteristics, and the activities taking place in the surroundings, Appendix 3, contains several photos that give a clear image of all them.

![Figure 3.33: Saltmarshes present on the estuary boundaries of Bahia Blanca Estuary.](image)

![Figure 3.34: Dumping sites, old tires and solid waste throw into the estuary.](image)

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3.2.4. Agricultural activities in the area

The region of Bahia Blanca is characterized by sandy and clay-sandy soils, light and permeable, with impermeable and hard calcareous soils. It has also abundant underground hydrological resources about 650 and 1000 m depth (http://www.fao.org/ag/AGP/AGPC/doc). Soil characteristics and its template climate, with enough rains, facilitates the development of herbaceous vegetation and pastures that characterize this productive zone.

The main activities taking place in Bahia Blanca are related to cattle and agriculture (Figures 3.36 and 3.37). The main types of crops are (http://www.agro.uba.ar/lart):

- Wheat (the most important)
- Sunflower (2nd most important, 2001-2002 plantations were about: 35,322 ha, 32,214 ton)
- Soy
- Corn
- Maize
- Sorghum
- Barley

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In this region it is very normal to have few years of agriculture (short or mid term seasons) characterized by a rotation of crops and long seasons of pastures (forage, specially barley) specially for cattling activities. The average sowing dates and main seasons for agricultural activities in the area are summarized in Table 3.9 (www.inta.gov.ar/pro/radar).

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Table 3.9: Sowing seasons for agricultural activities in Bahia Blanca

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Beginning</th>
<th>Sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season 1</td>
<td>Mid of June</td>
<td>Early sowing 25/5 to 25/6</td>
</tr>
<tr>
<td>Season 2</td>
<td>End of June</td>
<td>Intermediate sowing 26/6 to 15/7</td>
</tr>
<tr>
<td>Season 3</td>
<td>Mid of July</td>
<td>Intermediate sowing 26/6 to 15/7</td>
</tr>
<tr>
<td>Season 4</td>
<td>End of July</td>
<td>Late sowing 16/7 to 10/8</td>
</tr>
</tbody>
</table>

Regarding crops the main tendencies in the area are summarized in Table 3.10. Types of crops sowed vary according to the season and time of the year (http://www.agro.uba.ar/lart), for example:

**Winter:** wheat, oat, barley, rye

**Summer:** maize, sorghum, sunflowers, mijo, moha

Table 3.10: Main harvests and sowing times.

<table>
<thead>
<tr>
<th>Winter harvest</th>
<th>Optimal sowing</th>
<th>Optimal sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>½ May end of June</td>
<td>End of December – ½ January</td>
</tr>
<tr>
<td>Oat</td>
<td>½ May end of June</td>
<td>December</td>
</tr>
<tr>
<td>Barley (forage)</td>
<td>½ May end of June</td>
<td>December – January</td>
</tr>
<tr>
<td>Barley (brewing)</td>
<td>June</td>
<td>Beginning – end of December</td>
</tr>
<tr>
<td>Rye</td>
<td>June</td>
<td>December - January</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summer harvest</th>
<th>Optimal sowing</th>
<th>Optimal sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>½ October - November</td>
<td>March – April until May</td>
</tr>
<tr>
<td>Sorghum (grain)</td>
<td>November – December</td>
<td>March – April - May</td>
</tr>
<tr>
<td>Sunflowers</td>
<td>½ October – November</td>
<td>Beginning March - April</td>
</tr>
<tr>
<td>Soy</td>
<td>End of October – November, December</td>
<td>March – April – May</td>
</tr>
</tbody>
</table>

**Forage for animals**

<table>
<thead>
<tr>
<th>Winter pastures</th>
<th>Optimal sowing</th>
<th>Optimal sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oat, barley (forage), rye</td>
<td>½ February – March</td>
<td>From March until October</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summer pastures</th>
<th>Optimal sowing</th>
<th>Optimal sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize (forage), mijo/moja</td>
<td>October – November</td>
<td>December until May</td>
</tr>
</tbody>
</table>

Summarizing:

- The suitable time for crops sowing activities are between November and December,
- In October the crops are already growth and in December sowed (Bahia Blanca),
- In October 2004 wheat was mainly cultivated (AgroRadar, 2003),
- In October 2005 soy was mainly cultivated,
- In June-July usually wheat seeding and in September (short cycle) the sowing of the plant,
- For sunflower, the best sowing time is in March and seeding of sunflowers is in July,
- Usually they do one crop annually (rotation of crops).
Chapter 4: Processing of Landsat images: Supervised Classification

4.1. Processing of Landsat satellite images

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4.1.2. Subset of satellite images

4.1.3. Methodology for classification of Landsat images

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4.2.1. Landcover and vegetation classification of Santos

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4.4.1. NDVI

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Chapter 4

Processing of Landsat images: Supervised Classification

4.1. Processing of Landsat satellite images

4.1.1. Introduction for general processing of satellite images

Satellite images as described in Chapter 2, were the main source of information for the development of this thesis, specially for the elaboration of vegetation cover and landuse maps of both study areas. Landuse maps were then the base for a series of processes and analysis part of this study, like erosion, SDSS and landcover changes. This chapter makes emphasis on the description of the methodology applied for satellite image processing and the final maps obtained.

As mentioned in Chapter 2, there are a series of steps that must be applied to satellite images in order to have a comprehensible and reliable output as: georeferencing, radiometric and atmospheric correction among the most important ones, in this case these steps were not necessary since Landsat images downloaded from http://glcf.umiacs.umd.edu/index.shtml were already corrected.

The most important process applied to the three Landsat images used in this thesis, refers to classification of the images, specifically referring to supervised classification that will be described in detail in the next sections.

4.1.2. Subset of satellite images

Landsat images usually cover a bigger area than that of real interest and needed for the study. In this case, so to save valuable time in processing and space for storage, a simple process, called subset, is applied. This basically consists in "cutting" the image, taking into consideration only the area of interest.

All Landsat images were subset in order to focus only on the study areas of Santos and Bahia Blanca. This process is based on a selection of coordinates that limits the area that will be cut.

ENVI software and its processing tools were used to subset Landsat images of Brazil and Argentina.

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 Subset of Santos

In the case of Santos, two images were analyzed, one of April 2000 and the other one of June 1993. The same steps and classification process were followed for both images. Figure 4.38 shows the original Landsat-7 ETM image of Brazil and the subset of the study area, Santos. This subset area was used for the following supervised classifications of these two images.

![Figure 4.38: Landsat satellite image and subset of the study area, Santos (Brasil-SP).](image)

 Subset of Bahia Blanca

The same procedure used for subsetting the Landsat image of Brazil was followed for Argentina to subset Bahia Blanca study area. For Bahia Blanca only one image was analysed and processed, April 18-2004, given by IADO partners in Bahia Blanca. This image was selected since it is more recent than the ones available on the free site http://glcf.umiacs.umd.edu.data. Figure 4.39, shows the original Landsat-7 ETM image of Argentina and the subset of the study area, Bahia Blanca.

![Figure 4.39: Landsat satellite image and subset of the study area, Bahia Blanca (Argentina-BA).](image)
4.1.3. Methodology for classification of Landsat images

Selection of bands

The right selection of bands is very important for good classification results, it generally depends on the main purpose and objective of the study. There are several ways to combine bands depending on the number and type of bands present in each satellite. The combination of bands based on their specific characteristics are able to differentiate and emphasize particular properties of the objects represented in the satellite image.

Classification of vegetation, was very important for the aim of this thesis, for this reason and based on the bands present on Landsat satellite (Chapter 2), bands 3, 4, 5 were selected. This band combination is useful and the most convenient for highlighting and studying vegetation. Bands 3, 4, 5 represent the red, near IR and mid IR part of the electromagnetic spectrum respectively, that are the best ones for identification and differentiation of vegetation (Figure 4.40). These bands consent a good classification of vegetation based on its spectral signatures and its chlorophyll content, allowing also a good distinction of it among other features as not vegetated, urban and water areas (water –land interfaces).

The same bands were used for all classifications of the Landsat images as the emphasis of these classifications was to differentiate the different types of vegetation of Santos and Bahia Blanca.

![Figure 4.40: Landsat images of Santos and Bahia Blanca with band selection: 3,4,5.](image)
Supervised Classification

The type of classification applied to satellite images for the two study areas was supervised classification, since it is more reliable comparing to unsupervised classification, and as it can be controlled and guided by the operator.

Supervised classification uses specific training areas that are represented either by data collected in-situ (in the field), maps, aerial photographs, existing files, or any other reliable source of information that will help to classify what is on the image. For each study area specific classes were selected according to the most representative characteristics of each one of them (e.g. forest, plantations, mangroves, urban areas, crops, pastures, saltmarshes, etc.), then for these classes the appropriate training areas (groups of pixels) were placed in the image (Figure 4.41).

Supervised classification based on the selected training areas, which contains specific spectral signatures (pixel values) of the represented classes, and by the application of an algorithm (i.e. Parallelepiped, Minimum Distance, Mahalanobis Distance, Maximum Likelihood, Spectral Angle Mapper (SAM), Binary Encoding, and Neural Net) compares these training areas with the rest of the image. Afterwards, based on spectral associations and taking into consideration the specific characteristics of the selected algorithm the image is completely classified according to the training classes. In this case, the algorithm selected for all supervised classifications was the Maximum Likelihood, that assumes that the statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class, each pixel is assigned to the class that has the highest probability (Richards, 1999).

Training classes used for the classification representing the most important characteristics of the area: mangroves, urban, forests, water, etc.

![Figure 4.41: Supervised classification process, selection of training areas and location on the map](image)

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Chapter 4 Processing of Landsat images: Supervised Classification

The training areas for Santos and Bahia Blanca were mainly collected during field campaigns organized in these two areas. For Santos two campaigns were organized, one in April 2004 and another one in March 2006, for Bahia Blanca only one in March 2006. These field campaigns were prepared in cooperation with local partners since they have a better knowledge of the area and their features. Maps of the zones, bibliographical data, aerial photographs (Santos), and other information provided by the different partners were also used for the classifications, as much information available better and more reliable the output of the supervised classifications.

The tracks followed on the field campaigns were previously studied and planned, so to have a clear idea of which areas will be covered and what is present in each one of them. Once in the field, the training areas are defined with the help of a GPS, trying as much as possible to select them homogeneously all over the region of interest and representing the areas or materials wanted to be mapped in the output i.e. main characteristics of the site. Training classes must be defined prior to performing supervised classification (ENVI, 2003), this to facilitate (guide) the classification, putting emphasis on the recognition of these patterns. A good selection of the training areas is crucial for the overall success of the supervised classification.

In general, to facilitate supervised classifications, it is important to plan fieldwork campaigns, closer in date (month) to that of the satellite images available, specially the most recent one. In this way, the classification is easier thanks to the similarity of characteristics between natural ones and those registered on the image, having also a lower occurrence probability of significant landscape changes, that will condition the efficiency of the training areas.

Since training areas are collected with a GPS, the exact coordinates are registered in each case, furthermore, observations of the surroundings are also necessary for a reliable image classification. Thus, once back to the laboratory and provided by specialized software, ENVI Version 4.0 (RSI), these annotations (coordinates and description) are used for the supervised classification. Training areas are located in the satellite images referring to their geographical coordinates, finally using a specific module of ENVI the whole image is classified according to likelihood of spectral signatures of the training areas and the rest of the images.

The same procedure was applied for supervised classifications of the two Landsat images (TM and ETM+) of Santos and one Landsat image (ETM+) of Bahia Blanca.

4.2. Landcover and description of vegetation for Santos study area (Brazil)

4.2.1. Landcover and vegetation classification of Santos

As mentioned before, two Landsat images were used for Santos, specifically to perform multitemporal analysis and landcover change in this area. The images were selected according to their quality (less cloudiness), spatial coverage and availability. The images used for elaborating landuse maps of Santos study area were: 1) Landsat 5-TM from June 22, 1993 (winter – dry season) and 2) Landsat 7-ETM from April 30, 2000 (summer – rainy season).

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Unfortunately, there were not two images of the same date (season), this would have been the optimal situation for multitemporal analysis, yet the images available represent a good source of information.

Nevertheless, the seasonal difference between these two images was considered on the results obtained, since some of them were influenced by this disparity. The seasonal difference have a significant effect on the images since rainfall affects the amount of vegetation coverage on the area.

4.2.2. Classes selected for the supervised classification

Training areas containing important information of the study area were derived from GPS control points (Figure 4.42) collected during the field campaigns taken place in Santos (April 2004 and March 2006). These control points were homogeneously distributed over the study area taking into consideration logistic and terrain limitations.

![Figure 4.42: Location of control points collected with GPS in April 2004 and March 2006 and delimitation of study area (Santos-Brazil).](image)

Part of Santos basin was not covered in the Landsat images downloaded, this fact constrained the delimitation of the study area that was possible to analyze in these images.

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Training classes as mentioned before, were selected according to the most representative features present in the area like mangroves, *Mata Atlântica* of highlands, *Mata Atlântica* of lowlands, low vegetation, bare soil, urban and industrial areas, water, etc. These classes make emphasis on the types of vegetation existing in the study area and surroundings. Figure 4.43 represents the main characteristics of Santos, which were the basis for the training classes used in the supervised classifications of the two Landsat images (1993 and 2000).

![Urban areas](image1)

![Mangrove](image2)

![Mata Atlântica Primaria (highlands)](image3)

![Low vegetation (restinga)](image4)

**Figure 4.43:** Most important features present in the study area of Santos.

Two other training classes, clouds and shadows, not related with the main features of the area were also classified, since they have a relevant influence on the image. First, because the quantity of clouds present in the image cover different patches of the area, therefore not allowing a proper classification of what is under them, and second because clouds cause a shadows on the surroundings of the covered areas that prevent from identifying what is in this shadowed areas.
A brief description of the selected training classes will be given thus to have a better idea of what they represent and their importance for the local ecosystems. More specific characteristics of these vegetative species can be found in Appendix 4.

**Mata Atlântica of highlands (Versante Primario):** Mainly located on steep slopes and high altitudes (more than 350 - 400 m), characterized by a wide biodiversity since anthropogenic effects at higher elevations are lesser than at low ones. Therefore, this ecosystem has not significant disturbed its original structure and specie characteristics (http://www.mma.gov.br/port/conama).

*Mata Atlântica* is located in the Serra do Mar escarpment, it is now designated a World Biosphere Reserve, which contains a large number of highly endangered species. It has been extensively cleared since colonial times, mainly for farming and urban settlements. The remnant is estimated to be less than 10% of the original (http://en.wikipedia.org/wiki/Mata_Atl%C3%ADntica) and that is often broken into hilltop islands. This robust Atlantic Forest, has an arboreal vegetation of around 30 m, and trees that surpass the canopy, reaching 40 m of height, presents an intense shrubby vegetation on the inferior stratum. It is a forest of great diversity of vegetation with many ferns, including terrestrial orchids and palm trees, among which the Euterpes edulis are found.

**Mata Atlântica of lowlands (Pianura Secundaria):** It has been already affected by anthropogenic activities. It is found in three different stages (EMBRAPORT, 2003):

- **Initial stage:** characterized by a herbs-shrubs structure; with predominance of helophyte species. The average diameter and height are 5 cm and 5 m respectively, the maximum biodiversity is 20 species by ha. Plants have a fast growth and a slow reproductive cycle. The maximum community age is of 10 years. Epiphyte species are rare and sub-forest is completely absent.

- **Intermediate stage:** characterized by a shrubs-tree structure, presence of shadow species (ombrofilia densa-forest evergreen with trees from 20-30 m height). The average diameter and height are 10-20 cm, and 5-12 m respectively, while the average age is between 11-25 years. There are some epiphyte species and sub-forest also present. Growth of herbs is mainly eliminated by shrubs growth.

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• **Advanced stage:** characterized by a tree structure and a wide biodiversity of species. The average diameter is 20 cm, height higher than 20 m, and age exceed 25 years. Epiphyte species are abundant, sub-forest is less abundant than in the intermediate stage (this is one of the primary forest characteristics, in fact it is difficult to differentiate a secondary forest in advanced stage from a primary forest).

**Mangroves:** representative mangrove forest are present in the study area, bordering the estuary and its main arms. Mangroves can be defined as tropical evergreen trees or shrubs, woody trees or shrubs that grow in coastal habitats or mangal (Hogarth, 1999), for which the term mangrove swamp also applies.

Mangrove plants occupy shallow water and intertidal zones in tropical and subtropical coastal regions, usually protected from direct wave action, and thus characterized by muddy or fine sediment substrata. Mangrove forests in the study area are mainly characterized by:

**Red Mangroves** (*Rhizophora*): have reddish-brown bark and dark green leathery leaves 5 to 15 cm long. The white to cream colored flowers are 1.6 to 2.4 cm in size, and produce a dark brown ovoid berry that is 3 cm long.

**White mangroves** (*Laguncularia racemosa*): are evergreen trees of 12 m tall and 30 cm diameter, with rounded or irregular spreading crowns. Bark gray-brown, becoming rough and fissured; inner bark light brown. Pneumatophores often present.

**Black mangroves** (*Avicennia schaueriana*): are characterized by its opposite leaves which are narrow and elliptical in shape, often found encrusted with salt. Propagules are small (2-3 cm in diameter) and bean-like, flattened in shape. The root system of *Avicennia germinans* consists of long underground cable roots which produce hundreds of thin, upright pneumatophores on the ground around the tree. These structures have numerous pores presumable to conduct oxygen to the underground portion of the root system.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Sparse mangrove and mud (intertidal): The part of the shoreline that is submerged at high tide and exposed at low tide.

This transition creates special environmental conditions, however mangrove are able to live also in these conditions as well as others salt-tolerant trees and shrubs, with many other associated organisms, that grows on some tropical and sub-tropical coasts in a zone roughly coinciding with the intertidal zone.

Usually mangrove roots are exposed during low tide.

Low vegetation and/or restinga forests: coastal restingas are low forests which grow on stabilized coastal dunes. Restinga forests host a variety of moist tropical and subtropical habitat types with elements of mangrove, wetland, caatinga, and moist forest. Coastal restingas occur in patches along the coasts of central and southern Brazil.

Brazilian Atlantic coast restingas consist of three well-defined enclaves of restinga forests distributed from northeastern to southeastern Brazil (Lacerda et al. 1984). Along this latitudinal gradient, climate changes from tropical to subtropical.

Restingas grow on sandy and nutrient-impoverished soils that are frequently associated with low-elevation plains (Quaternary or Tertiary) characterized by the presence of beach ridges and lagoonal systems (Flexor et al., 1984; Suguio and Tessler, 1984).

Restinga forests vary from shrub vegetation to 15 m tall forests. The main type of vegetation is a kind of pioneer 5-15 m tall Atlantic forest (Veloso et al. 1991). Such forest is rich in shrubs and tree species of Myrtaceae (Eugenia, Myrcia, Marliera), Leguminosae (Andira), Euphorbiaceae (Croton), and Malphigiaceae (Byrsonima) (Mantovani, 1992; Sacramento, 2000; and Pontes; 2000).
Bare soil: A soil surface devoid of any plant material. Bare soil can be a permanent characteristic of the soil or it can vary depending on the season, if it is rainy or dry. If it depends on the rainfall, it is normal than in rainy periods these areas are covered by some type of basic vegetation that fade or wither when rains stop for a long period of time.

If bare soil is permanent it mainly depends on the type of soil or if it is characterized by rocky formations.

Santos, have a combination of the two bare soils classes.

Urban areas: Residential areas, usually vegetation spots are present as green-parks. They can also be defined as the largest city or grouping of cities in a metropolitan statistical area, which can also be defined as a geographical area constituting a city or town. Census designates urban areas places of 2,500 or more persons.

In Santos there is a strong urban development, mainly situated towards the coast and in low elevation areas.

Industrial areas: land classification system category for areas that are intended to provide suitable locations for industrially related uses. In theory this category does not allow residential uses close to industrial uses, but in the study area sometimes it is difficult to differentiate urban from industrial areas.

Main industrial areas in Santos are located close to the coast nearby Santos port.

Water: In this class are included all kind of waterbodies like rivers, estuary and dams (present at the north of the study area).

The most significant water bodies in the study area are represented by the main arms of Santos estuary.
Clouds and shadows: Included in this class are the clouds present over the study area at the time when the satellite (Landsat) registered the image. Since every cloud produces a shadow on the earth surface, this were also included as a specific class.

4.2.3. Results obtained from the supervised classifications of Santos (Brazil)

Finally, the images were classified based on the likelihood of pixels’ spectral signatures. The same procedure was applied for the supervised classification of Landsat image, June 22/1993, that was taken during the dry season and it does not have any clouds, therefore, this training class was not considered in its classification, but shadows were. Figures 4.44 and 4.45 shows the final results obtained from supervised classifications applied to both images using ENVI software.

![Image of landuse map of Santos based on the supervised classification of Landsat image, April 2000.](image)

Figure 4.44: Landuse map of Santos based on the supervised classification of Landsat image, April 2000.
Chapter 4

Mata Atlântica (lowlands)
Mata Atlântica (highlands)
Low vegetation and/or restinga
Mangroves
Sparse mangroves + mud
Urban areas
Industrial areas
Bare soil
Water
Shadow

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
The apparent errors in the quantity of pixels assigned to some classes and their variation in time,
most probably results as a consequence of the seasonal difference between the images. For
example, an unexpected increase of 0.5% and 0.46% of mangroves (both classes) between 1993
and 2000 might be influenced by the growth of coastal vegetation during wet season, that the
algorithm will assume to be mangrove due to the similarity of their spectral response or space
sharing in the same pixel (30 m). Other changes among the images, for example, a decrease of
1.62% in bare soil, increase of 1.41% in water, decrease of 0.55% of Mata Atlântica (highlands) in 2000,
were expected, as they are related to seasonality and the last to pressure of anthrophogenic activities in the area.

Results of multitemporal analysis and landcover changes based on cross calculations between the
classification matrixes of both images will be discussed in the next chapter, as well as suitability
analysis for the main classes of Santos: forests, mangroves, urban areas, and low vegetation, and
a future projection of this area based on MCE and Markov Chain analysis.

The accuracies obtained for the supervised classifications of Landsat images, June 1993 (80.18%)
and April 2000 (90.99%) represent a good result and a reliable source of information. Nevertheless, there were some evident errors on the classifications of both images, for example, some pixels at more than 100 m of elevation were classified as mangroves, which is not possible
in nature, also pixels classified as Mata Atlântica of lowlands at more than 500 m of elevation is
not true. These incoherencies were corrected by the application of environmental criteria that
took into consideration the physical limitations of the selected ecosystems and the intrinsic
characteristics of the study area. Table 4.12 shows the criteria applied for improving supervised
classifications of both images.

As an important remark, it is feasible to say that most of the times classifications based only on
spectral values are not enough to obtain satisfactory outputs, hence other criteria and factors are
necessary. In this case, ArcMap 9.0 Spatial Analyst tool (raster calculator) were used for the
application of these criteria, which are represented by mathematical and conditional expressions,
using a series of maps (distance buffers and masks). Figure 4.46 shows an example of masks and
buffer maps used for the conditional expressions.

Figure 4.46: Masks (urban and water) and distance buffer (1 Km from the estuary) maps used for
conditional expressions for enhancement of supervised classifications.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications
for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Table 4.12: Main criteria applied for classification enhancement of Landsat images (Santos).

<table>
<thead>
<tr>
<th>Criteria applied</th>
<th>Reclassified into</th>
<th>Restriction constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangroves distant more than 1 Km from the estuary</td>
<td>Low vegetation</td>
<td>Distance (Buffer of 1 Km distant from the estuary)</td>
</tr>
<tr>
<td>Mangroves at more than 13 m height</td>
<td>Low vegetation</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td>Low vegetation at more than 155 m height</td>
<td>Low vegetation, <em>Mata Atlântica</em> lowlands</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td><em>Mata Atlântica</em> lowlands at more than 360 m height</td>
<td><em>Mata Atlântica</em> highlands</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td>Mangroves, <em>Mata Atlântica</em> (lowlands and highlands), low vegetation, clouds, and shadows located in urban areas</td>
<td>Urban areas</td>
<td>Urban settlements (Mask of urban areas based on GIS provided by local partners)</td>
</tr>
<tr>
<td>Shadows or clouds at more than 155 m height</td>
<td><em>Mata Atlântica</em> (lowland or highlands)</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td>Shadows or clouds in mangrove and water areas</td>
<td>Mangrove or water</td>
<td>Mangrove or water areas (Masks of these areas based on GIS provided by local partners)</td>
</tr>
</tbody>
</table>

The application of these criteria significantly improved the previous supervised classifications, allowing also a decrease of pixels previously classified as clouds and shadows. For example, by the application of these criteria (Table 4.12), all pixels classified as mangroves at more than 13 m elevation and distant more than 1 Km from the main arms of Santos Estuary were re-classified as a more coherent and probable type of vegetation, like low vegetation or *restinga*. Figures 4.47 and 4.48 show the final outputs for the landuse maps of Santos, used for a series of analysis like erosion, landcover change and SDSS that will be described in the next chapters.

Figure 4.47: Final and improved classification for landuse map of Santos (Landsat image, April 2000).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
The same criteria applied for Landsat image of April 2000 was applied for satellite image of June 1993. The only difference consists on ignoring the criteria followed in image 2000 for elimination or decrease of pixels classified as clouds, this was not necessary in June image since no clouds appears on the image because of the dry season, characterized by almost no rain.

Figure 4.48: Final and improved classification for landuse map of Santos (Landsat image, June 1993).

4.3. Landcover and description of vegetation for Bahia Blanca study area (Argentina)

4.3.1. Landcover and vegetation classification of Bahia Blanca

The image used for elaborating landuse map of Bahia Blanca study area was: Landsat 7-ETM from April 18, 2004 (Summer – Autumn, rainy season). The image, as the previous ones, was selected according to its quality, spatial coverage and availability.

In the case of Bahia Blanca, multitemporal and landcover change analysis were not considered to be relevant, due to the characteristics of the zone and the main activities (agriculture and cattling) characterizing it. Not significant changes, besides urban expansion, have taken place in this area (personal communication), changes mainly refer to the type of crops cultivated each year (rotation cycles) which is not possible to differentiate having as reference satellite images without reliable training areas of the different crops sowed at that specific time. It is also limited by the spatial resolution of Landsat images (30 m) which is not the most suitable one to differentiate type of crops without precise field information.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Nevertheless, the only image analyzed for Bahia Blanca consist a good source of information for obtaining reliable landuse maps used for erosion analysis.

4.3.2. Classes selected for the supervised classification

Also in this case the training areas used for the supervised classification were derived from GPS control points collected during the field campaign organized in Bahia Blanca during March 2006, they were homogeneously distributed over the study area (4. 49).

Specific classes were selected according to the most representative characteristics of the study area and surrounding specially agricultural fields and grazing pastures. Then, for these classes the appropriate training areas were located. As in the previous case based on the spectral similarities between training classes and the image, it was completely classified.

![Figure 4.49: Location of control points collected with GPS in March 2006 and delimitation of study area (Bahia Blanca - Argentina).](image)

Part of Bahia Blanca basin was not covered in the Landsat image, this fact constrinched the delimitation of the study area that was possible to analyze in this image, for a best representation and appreciation of the area a symmetrical rectangle was chosen as the boundary of the study area to be analyzed.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Training classes were selected according to the most representative features of the study area like: crops (sunflowers, maize, sorghum crops, pastures, saltmarshes, transitional vegetation, urban-industrial areas, intertidal flats, water, bare soil, etc). The selected classes for Bahia Blanca as for Santos, make emphasis on the types of vegetation existing in the study area and surroundings. Figure 4.50 represents the main characteristics of Bahia Blanca, which were the basis for the training classes used in the supervised classifications of Bahia Blanca Landsat image.

Figure 4.50: Most important features present in the study area of Bahia Blanca.
For Bahia Blanca, shadows were also included in the classification, since they were present specially at high elevations in Sierra de la Ventana. However, pixels belonging to this class were completely eliminated with the criteria applied in the post classification, that significantly improved the quality of the classification.

A brief description of the selected training classes will be given thus to have a better idea of what they represent and their importance for the local ecosystems. Important characteristics of this main type of vegetative species are described in Appendix 4.

**Tidal Flats:** generally defined as areas or nearly flat coastal areas, barren mud periodically covered by tidal waters and consisting of unconsolidated sediments. Normally these places have an excess of soluble salt. Intertidal flats can also be defined as saltwater wetlands characterized by daily tidal fluctuations. As the material that forms the mudflats is deposited by the tides or river, they are found in sheltered areas such as bays and estuaries.

Bahia Blanca Estuary is characterized by the presence of intertidal flats all along the estuary.

**Transitional vegetation:** a mix of different types of vegetation which are able to live together sharing neighboring units of vegetation, present in zones influenced by variable factors, specially climatic and type of soils. Generally dominated by shrubs and bushes, distinguishing from a tree by its multiple stems and lower height, usually less than 6 m tall. A large number of plants can be either shrubs or trees, depending on the growing conditions they experience.

This type of vegetation is mainly present on the surroundings of Bahia Blanca Estuary between two well defined types of vegetation saltmarshes and crops fields.

**Saltmarshes:** defined as low coastal grasslands frequently overflowed by tides, also as a type of wetlands which are transitional lands between terrestrial and aquatic systems where the water table is usually at or near the surface.

These land supports predominantly hydrophytes, in the study area the most common species are: *spartina alterniflora, spartina densiflora* and *sarcocornia* which are also present on the inner coast and coastal barrier islands of Bahia Blanca Estuary.
Crops: this area is characterized by intense agricultural activities, a series of rotational crops present all year long. The most important crops in the area are: sunflowers, sorghum, maize, wheat, soy which are seeded and sowed according to different seasonal periods. In March during the field campaign in Bahia Blanca considerable patches of fallow land (cropland that is not seeded) were also present. This type of terrain was often classified as bare soil due to its deprivation of vegetation coverage.

Pastures: usually defined as grasses or herbaceous vegetation cover used for grazing domestic animals.

Pastures in the study area are extensively present and mainly used for cows and horses cattle which represent one of the most important resources of the country itself for internal consumption as well as for exportation all over the world.

Sand plains, sand banks, beaches: there are sandy formations or submerged bank of sand near the shore of the estuary and usually exposed at low tides.

During low tide intervals, a series of sand plains and sand banks are uncovered, they are also a rich ecosystem for crabs caves, locally called “cangrejales”, basically from crab populations *Chasmagnathus granulata*.

Bare soil: defined as areas lacking any type of vegetation coverage or areas with very few vegetation. In Bahia Blanca study area, some of the areas used for agricultural activities as fallow land, were also classified as bare soil since apparently there was not vegetation cover although they were already sowed.

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Urban areas: the main urban settlements in the classification are represented by the biggest districts present in the study area, among them the most important is Bahia Blanca city, but also General Daniel Cerri, Villa Espora, Villarino Viejo, Bordeu which are smaller residential areas. In Santos there is a strong urban development, mainly situated towards the coast and in low elevation areas.

Industrial areas: present in the study area mainly located nearby the estuary and close to its main ports: Puerto Galván and Ingeniero White, specialized in sunflowers and soy oil the first one and grains, cereals the latest.

Industrial areas in Bahia Blanca have increased in the last years due to the ports’ great activity.

Water: in this class are included all waterbodies like rivers and estuaries.

The most significant and biggest waterbody present in Bahia Blanca study area is obviously its important and dynamic estuary.

4.3.3. Results obtained from the supervised classification of Bahia Blanca (Argentina)

The Landsat image, April 2004, used for classification analysis was provided by IADO (Instituto Argentino de Oceanografía) partners in Bahia Blanca. This image was selected for being the most recent from all other images available on the free website http://glcf.umiacs.umd.edu.data, and since it better represents the characteristics (summer season) of the time of the year when the training sites were collected in the study area (March 2006). It is important to mention that during 2004 and 2006 the same types of crops were cultivated in the study area (personal communication).
This is very important since the landuse and landcover strictly related to the agricultural activities present in this study area vary according to the season of the year (types of crops, sowing and harvesting, and preparation of land for agriculture and cattle).

The same procedure used for Santos was followed in the supervised classification of Bahia Bianca study area, based on spectral similarities. Figures 4.51 shows the final results obtained from supervised classifications applied to Landsat image (April, 2004).

![Landuse map of Bahia Bianca](image)

**Figure 4.51**: Landuse map of Bahia Bianca based on the supervised classification of Landsat image, April 2004.

The accuracy and percentages of the supervised classifications performed in this image are summarized in Table 4.13.
Table 4.13: Percentages of the supervised classification and their accuracy (Bahia Bianca).

<table>
<thead>
<tr>
<th>Class</th>
<th>18-April-2004 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wet season</td>
</tr>
<tr>
<td>Crops: sunflowers, soy</td>
<td>3.408</td>
</tr>
<tr>
<td>Crops: sorghum, maize</td>
<td>3.740</td>
</tr>
<tr>
<td>Crops: wheat, barley (low cover)</td>
<td>21.720</td>
</tr>
<tr>
<td>Pastures for grazing</td>
<td>32.361</td>
</tr>
<tr>
<td>Intertidal flats</td>
<td>4.745</td>
</tr>
<tr>
<td>Saltmarshes (spartina, sarcocornia)</td>
<td>0.743</td>
</tr>
<tr>
<td>Transitional vegetation</td>
<td>3.143</td>
</tr>
<tr>
<td>Sand banks, sand bars, sand plains</td>
<td>1.560</td>
</tr>
<tr>
<td>Bare soil and/or sowed land</td>
<td>25.408</td>
</tr>
<tr>
<td>Water – estuary</td>
<td>2.628</td>
</tr>
<tr>
<td>Water (water + sediments)</td>
<td>0.039</td>
</tr>
<tr>
<td>Shadows</td>
<td>0.505</td>
</tr>
<tr>
<td>Accuracy and Kappa factor</td>
<td>88.655 %</td>
</tr>
<tr>
<td></td>
<td>Kappa 0.82306</td>
</tr>
</tbody>
</table>

The accuracy of the supervised classification was of 88.655%, which represent a good result and a reliable source of information.

The difference between both accuracies (Santos-90.998% and Bahia Blanca-88.655%) mainly refers to the variability of vegetation cover in both areas. Santos is mostly represented by a more uniform and extensive vegetation as forest and mangroves, whereas Bahia Blanca study area is represented by “patches” of different types of crops, areas of pastures, estuarine vegetation and the estuary itself which are much more difficult to classify. In this case the appropriate selection of bands was very important in order to have a more reliable classification: bands 3, 4, 5 were also used for the supervised classification, but several tests of combinations of bands and classifications were performed previously to obtain the most satisfactory result.

Nevertheless, there were some evident errors on the classifications in this image, for example, some pixels at more than 45 m of elevation were classified as saltmarshes which is not possible in nature, also pixels classified as transitional vegetation at more than 45 m of elevation is not true. These incoherencies were corrected by the application of environmental criteria that took into consideration the physical limitations of the selected ecosystems and the intrinsic characteristics of the study area. Table 4.14 shows the criteria applied for improving supervised classifications of both images.

As in the previous case, ArcMap 9.0 tools were used for the application of these criteria, which are represented by mathematical and conditional expressions.
Table 4.14: Main criteria applied for classification enhancement of Landsat image (Bahia Blanca).

<table>
<thead>
<tr>
<th>Criteria applied</th>
<th>Reclassified into</th>
<th>Restriction constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saltmarshes, sandbars and intertidal flats distant more than 120 m from rivers and at more than 45 m height</td>
<td>Transitional vegetation</td>
<td>Distance and elevation (Buffer of 120 m distant from rivers and DEM)</td>
</tr>
<tr>
<td>Saltmarshes, sandbars and intertidal flats distant more than 6 Km from the estuary and at more than 45 m height</td>
<td>Transitional vegetation</td>
<td>Distance and elevation (Buffer of 6 Km distant from the estuary and DEM)</td>
</tr>
<tr>
<td>Transitional vegetation at more than 45 m height</td>
<td>Pastures</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td>Shadows at more than 400 m height</td>
<td>Pastures</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td>Pastures at more than 800 m height</td>
<td>Bare soil</td>
<td>Elevation (DEM)</td>
</tr>
<tr>
<td>Bare soil on urban areas and industrial areas</td>
<td>Urban and industrial areas</td>
<td>Urban and industrial (Masks of these areas based on GIS provided by local partners)</td>
</tr>
</tbody>
</table>

The application of these criteria significantly improved the previous supervised classification, allowing a decrease of pixels wrongly classified. For example, by the application of these criteria (Table 4.14), all pixels classified as saltmarshes at more than 45 m elevation and distant more than 6 Km from the estuary were re-classified as a more coherent and probable type of vegetation, like transitional vegetation. Figure 4.52 shows some of the maps used in the conditional expressions, represented by buffer distance and masks maps.

![Figure 4.52: Masks (urban, industrial and water) and distance buffer (6 Km from the estuary and 120 m from rivers) maps used for conditional expressions for enhancement of supervised classifications.](image)

As an important remark, in this case, some criteria or conditions must be simultaneously satisfied, for example for reclassifying saltmarshes distant more than 120 m from rivers will not be enough to base the criteria only on distance since saltmarshes mainly grow near the estuary, which is much more far away than 120 m from rivers. If only distance criteria is taken into consideration,

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all saltmarshes on the estuary boundaries will be classified as transitional vegetation, which will be wrong. Therefore, also elevation criteria must be taken into consideration to avoid these errors since in any case saltmarshes can't grow at more than 45 m height. Most of the time to have a satisfactory and reliable result all these criteria must be followed in a certain order, as one criteria is applied and satisfied then a new one can be applied, synthesizing it is possible to say that one criteria result is the input of a new criteria, and so on.

A proper differentiation of urban and industrial areas was not possible by the supervised classification since it tend to confuse them with bare soil. Consequently, and to include these classes on the overall classification, they were added after the post classification, by the application of specific masks containing these features. In this way, the final classification consider also these areas, being the result completely reliable taking into consideration the source of information (local GIS).

Figures 4.53 show the final output for the land use map of Bahia Blanca, used for erosion and analysis that will be described in the next chapters.

![Figure 4.53: Final and improved classification for land use map of Bahia Blanca.](image)
4.4. Vegetation Indexes

As a complement of landuse analysis and the maps obtained by supervised classifications and to have an extra source of information regarding the vegetation present in both study areas and its quality, NDVI and LAI indexes were also calculated as part of this thesis.

Results of both indexes calculations were represented in maps that facilitates its understanding and their distribution in the study areas in addition this also facilitates their visualization.

4.4.1. NDVI

The Normalized Difference Vegetative Index (NDVI) is a calculation, based on spectral bands, of photosynthetic output (amount of green stuff) in a pixel in a satellite image. It measures the amount of green vegetation in an area. NDVI map (Figure 4.54) was obtained from the Landsat-7 ETM+ satellite image (April, 2000) applying the universal formula for NDVI:

\[
NDVI = \frac{NIR - red}{NIR + red}
\]

The NDVI, like most other vegetative indexes, is calculated as a ratio between measured reflectivity in the red (TM3) and near infrared-NIR (TM4) portions of the electromagnetic spectrum. Characteristics of the Landsat 7 bands were previously mentioned in Chapter 2, Table 2.4. These two spectral bands are chosen because they are most affected by the absorption of chlorophyll in leafy green vegetation and by the density of green vegetation on the surface. Also, in red and near-infrared bands, the contrast between vegetation and soil is at a maximum.

This calculation was performed using ENVI software, that contains a specific command to calculate NDVI, transforming multispectral data into a single image band representing vegetation distribution (ENVI, 2003).

The NDVI equation produces values in the range of -1.0 to 1.0, where vegetated areas will typically have values greater than zero and negative values indicate non-vegetated surface features such as water, barren soil, ice, snow, or clouds (Jensen, 1986).

Figures 4.54 and 4.55 show the final maps obtained from NDVI calculations for Santos and Bahia Blanca. Same procedure, already described, was applied for both images.
Chapter 4
Processing of Landsat images: Supervised Classification

Figure 4.54: NDVI map for Santos study area using Landsat image April 30, 2000.

Figure 4.55: NDVI map for Bahia Blanca study area using Landsat image April 18, 2004.

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4.4.2. LAI

The Leaf Area Index (LAI) map was obtained from the inversion of the empirical relationship between LAI field data measured with LAI-2000 Plant Canopy Analyzer instrument and NDVI map of 30/04/2000. LAI measurements were collected during field campaign in Santos (March 2006).

The methodology for LAI estimation from satellite images depends on the empirical relationship between LAI (measured in the field) and remote sensing data coming from vegetation indexes - VI (Nemani et al., 1993). Multiple test with regression models are used to find the best relationship (i.e. linear, logarithmic) between satellite information (dependent variable) and ground data (LAI measurements, independent variable). The determination coefficient, $R^2$, measures the variability (in percent) of the regression model, thus it is a good indicator of the quality of the regression.

Linear and logarithm regressions were test for LAI estimations in Santos area, giving better results the first one ($R^2 = 0.68$). The inversion equation of this linear regression were used to create LAI map for Santos.

Figure 4.56 shows the two regressions (linear and logarithmic) obtained from the relationships between LAI measurements and NDVI (Landsat image), including their respective equations and $R^2$ coefficients (Napolitano, 2006).

![Figure 4.56: Linear and logarithmic relationships between LAI and NDVI (Landsat image, April 2000).](image)

Final results of LAI analysis are represented in Figure 4.57.
In the case of Bahia Blanca, since LAI field data was not measured and collected in-situ, and taking into consideration that the most representative type of vegetation are traditional crops, LAI values were obtained from bibliographical information source (Bertness and Ellison, 1987, http://topsoil.nserl.purdue.edu/nserlweb/weppdoc/PlantSpecificParameters.html), and another useful website including the most important characteristics of crop morphology http://c100.bsyse.wsu.edu/cropsyst/manual/parameters/crop/morphology.htm.

Figure 4.58 shows the final map of LAI for Bahia Blanca and the table below the selected LAI values identifying the different types of vegetation present in the area.
Figure 4.58: LAI map of Bahia Blanca study area using as main source bibliographical information.

<table>
<thead>
<tr>
<th>Bahia Blanca</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saltmarshes (spartina, sarcocornia)</td>
<td>6.34</td>
</tr>
<tr>
<td>Intertidal flats</td>
<td>-</td>
</tr>
<tr>
<td>Sand banks, sand bars and plains</td>
<td>-</td>
</tr>
<tr>
<td>Transitional vegetation (shrubs)</td>
<td>2.08</td>
</tr>
<tr>
<td>Crops: sunflowers, soy</td>
<td>5</td>
</tr>
<tr>
<td>Crops: sorghum, maize</td>
<td>7</td>
</tr>
<tr>
<td>Pastures for grazing</td>
<td>2.5</td>
</tr>
<tr>
<td>Crops: wheat, barley (low cover)</td>
<td>6</td>
</tr>
<tr>
<td>Bare soil and/or sowed land</td>
<td>-</td>
</tr>
<tr>
<td>Water - estuary</td>
<td>-</td>
</tr>
<tr>
<td>Urban areas</td>
<td>-</td>
</tr>
<tr>
<td>Industrial areas</td>
<td>-</td>
</tr>
</tbody>
</table>

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Chapter 5: Multitemporal analysis for landcover change (Santos)

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Chapter 5

Multitemporal analysis for landcover change (Santos)

5.1. Analysis of landcover change for Santos study area

5.1.1. Introduction of landcover dynamics

Multitemporal analysis represent an important tool for determining changes in time, in this case particularly referring to landcover change, since it is an important feature to be considered for environmental planning and decision making process of local and regional authorities. This chapter deals with the main aspects of landcover change and multitemporal analysis performed with Landsat images of Santos study area.

A series of maps, matrixes and tables indicating changes between the selected classes are included in this chapter. Special emphasis was put in determining changes in vegetation, for example transformation of mangrove into urban settlements or into low vegetation, in order to simplify the representation of the most important landcover changes in the area. In this way it is easier to get a clear idea of the relevant environmental impacts occurring in Santos.

Suitability maps were also calculated using a specialized software, these were the basis of the landcover analysis between both images and an important input for calculating a landcover prediction for 2010 of the same study area.

5.1.2. Methodology for landcover changes

The two Landsat images of Santos (June 18, 1993 and April 30, 2000), that were previously classified as described in Chapter 4, were the main input of a series of analysis for estimating landcover changes between the seven years period of the images 1993-2000 and for a landcover prediction for 2010.

Two methods were used for elaborating landcover change maps, the first using simple conditional expressions in ArcMap 9.0 spatial analyst (raster calculator) module and the second applying fuzzy sets, weights and MCE using Idrisi 15.0 Andes Edition software. The latest, represents a much more reliable result since a series of criteria and factors of Santos were taken into consideration for this analysis. For a landcover prediction of 2010 the same Idrisi software was used, applying Markov Transition Estimator and Cellular Automat Markov Chain concepts based on the suitability maps and matrixes previously obtained for landcover change analysis between 1993 and 2000.

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Chapter 5

Multitemporal analysis for landcover change (Santos)

The methodologies applied for landcover change analysis and prediction will be described in the next sections separately for each case, including in each one of them the respective maps and results obtained.

In order to simplify calculations and avoid as much as possible errors in change detection, an important criteria was applied for all landcover change analysis, it consisted on merging similar training classes. This step was applied in both satellite images, to have a uniform set of images to be compared and analyzed, like this a more homogeneous classification map was obtained. Figures 5.59 shows the final classification maps after the merge of classes with similar characteristics. Since merging of classes was performed with ENVI post classification tools the original classified images were used, thus the same enhancement criteria was applied to the images after the class merging. The training classes that were merged are described in Table 5.15.

Table 5.15: Training classes merged in June 1993 and April 2000 images used for landcover change analysis.

<table>
<thead>
<tr>
<th>Class 1</th>
<th>Class 2</th>
<th>Final class</th>
<th>Landsat image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial areas</td>
<td>Urban areas</td>
<td>Urban areas</td>
<td>1993 and 2000</td>
</tr>
<tr>
<td>Sparse mangrove</td>
<td>Mangroves</td>
<td>Mangroves</td>
<td>1993 and 2000</td>
</tr>
<tr>
<td><strong>Mata Atlântica</strong> highlands</td>
<td><strong>Mata Atlântica</strong> lowlands</td>
<td><strong>Mata Atlântica</strong> forests</td>
<td>1993 and 2000</td>
</tr>
<tr>
<td>Bare soil</td>
<td>Low vegetation</td>
<td>Low vegetation</td>
<td>1993 and 2000</td>
</tr>
<tr>
<td>Shadow</td>
<td><strong>Mata Atlântica</strong> highlands</td>
<td><strong>Mata Atlântica</strong> forests</td>
<td>1993</td>
</tr>
<tr>
<td>Shadow</td>
<td>Clouds</td>
<td>No data</td>
<td>2000</td>
</tr>
</tbody>
</table>

No further modifications or enhancement were possible to completely eliminate the effect of shadows and clouds from Landsat image 2000, so both classes were classified as no data to simplify the analysis and pixel to pixel comparison. **Mata Atlântica** forests will be referred in the next sections and analysis as forest, intending they refer to these type of ecosystems.

Finally, six different classes were considered for 2000 and five classes for 1993, like this when a no data valued pixel is found it will not be considered on the overall landcover change analysis therefore remaining as a no data value also in the final results.

Another important consideration for landcover change analysis and making reference to the instrument malfunction of TM sensor in Landsat 5 (image of June 1993) mentioned in Chapter 2, a masking process was necessary to ignore this defect on the image. Masking of the shifted stripe was applied not only in June image but also in April image. Although the shifted stripe affects only one of the images, since multitemporal analysis is based on a pixel to pixel comparison between both images, they must cover exactly the same area to avoid wrong interpretations of landcover change.

Figures 5.59 shows the final masked images used for landcover analysis.

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5.1. Landcover changes using ArcMap 9.0 software

5.2.1. Methodology used in ArcMap 9.0 for landcover change analysis

The only input for calculating landcover change between 1993 and 2000 using ArcMap 9.0 Spatial Analyst tool, were the final classification maps shown in Figure 5.59. In this case a series of mathematical and conditional expressions were applied to both images using raster calculator module. An example of the conditional expressions used are shown in Figure 5.60 and an explanation of each expression in Table 5.16.

Landcover change analysis based on these expressions is possible since they use a mathematical language in which every class has a numerical value (generally referring to the order in which they appear on the legend), so all the statements are expressed in function of these values and the mathematical operator needed to satisfy a specific condition or order, previously defined by the user. In this way it is possible to compare both images.

Figure 5.59: Final classification maps used for multitemporal analysis, after merging training classes and masking shifted stripe.

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Each expression has a specific meaning or order that performs a calculation giving as result a map, which can represent a mask or a new image containing only those features that the operator wants to emphasize, for example in this case the changes in vegetation taken place between 1993 and 2000 in Santos study area. Generally the result of a conditional expression is the new input for the following conditional. The meanings of the expressions listed in Figure 5.60 are explained in the following table.

Table 5.16: Explanation of conditional expression used in raster calculator module to predict landcover changes between 1993 and 2000 using supervised images.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Explanation</th>
<th>Result</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>con((land93)) = = 1,1,0</td>
<td>Selects all pixels classified as mangroves (value of 1) in image 1993 and reassign a new value, in this case also 1, pixels with values different from 1 will be reclassified as 0.</td>
<td>Mask (values of 0 and 1) map of mangroves existing in 1993.</td>
<td>Is the input for the next conditional, to focus the analysis on mangrove changes between 1993 and 2000.</td>
</tr>
<tr>
<td>con ((maskmangrove93) = = 1, (land2000), 0)</td>
<td>Highlight all the changes of mangroves between 1993 and 2000 by using the previous mask. If the condition is true it substitutes the value of 1 by the value of</td>
<td>Map containing all changes of mangroves into: urban, water, low vegetation, forest and no data.</td>
<td>Is the input for the next conditional, to emphasize only specific changes of mangroves.</td>
</tr>
</tbody>
</table>

Figure 5.60: Conditional (con) expressions and mathematical operators used for landcover analysis in ArcMap raster calculator module.
the class in which mangroves have been transformed, if not a value of 0 is assigned.

| \[
| \text{con}((\text{chgmangrove}_{93\_2000}) = = 2 !) \quad \text{(chgmangrove}_{93\_2000}) = = 3, \text{chgmangrove}_{93\_2000},0) |
| takes into consideration only mangrove changes into: urban (value 2) and low vegetation (value 3) |
| (\text{chgmangr}_\text{urb}_\text{low}) Map containing only changes into urban and low vegetation. |
| Final map that indicates the environmental impact suffered by mangroves in these 7 years period referring only to urban and low vegetation transformations. |

Figure 5.60 and Table 5.16 represents only those conditional expressions referring to mangrove changes, to calculate changes from other classes, for example forest and low vegetation, is only necessary to substitute the value of these classes on the respective values representing mangrove (1) in the previous expressions. Methodology is exactly the same in all cases, varying the input maps and assigned values.

Once all the “changes” maps have been calculated separately for each type of vegetation present in the images (mangrove, forest and low vegetation) and in order to have only one map representing the most important changes of vegetation, the final change outputs are added by a simple addition equation using the same raster calculator module:

\[
\text{chgmangr}_\text{urb}_\text{low} + \text{chgforest}_\text{urb}_\text{low} + \text{chglowveg}_\text{urb}_\text{forest})
\]

where: chgmangr_urb_low, chgforest_urb_low and chglowveg_urb_forest are the maps obtained by the previous expressions explained in Table 5.16 substituting the respective values for the classes of interest.

In this way, a final change map (Figure 5.62) is obtained highlighting only those changes of interest for our study.

Statistical analysis of the changes between 1993 and 2000 were also performed using ArcMap 9.0 Spatial Analyst tool, specifically the Zonal module (tabulate area) (Figure 5.61). A tabulate area (cross table) calculates all the transformations taken place between all the classes, in other words what has been transformed into what. Like this it is possible to quantified the changes between these two images based on several measures of association between the two images.

The original output of the tabulate area quantify the changes among the classes in number of pixels, to make it easier to understand these values were transformed into percentages which can be consulted in Table 5.17.
Results obtained for landcover change (maps and cross tables) applying ArcMap Spatial Analyst tool will be explained in the next section.

5.2.2. Results of landcover change using ArcMap 9.0 software

After applying the series of criteria explained in the previous section a final map with the landcover changes taken place between 1993 and 2000 was obtained. Figure 5.62 shows the final landcover map highlighting only those changes referring to vegetation, indicating the most evident environmental impacts in the area of Santos due to the main critical anthropogenic activities: urbanization and deforestation (of Mata Atlântica and mangrove forests).

Figure 5.62: Map of landcover highlighting vegetation changes occurred between 1993 – 2000, using ArcMap. Areas circled indicate high deforestation of Mata Atlântica.
As seen in Figure 5.62 the most frequent changes in this seven years period regarding vegetation are those indicating low vegetation areas transformed into urban settlements (Silva, 1999) with 20.25%, without taking into consideration changes from low vegetation into forest, that will be explained later. This is the most common pattern taking into consideration the convenient location of low vegetation in the area: at low and middle height, close to water bodies, close to the coast and close to transportation networks, all these characteristics geographical and environmental characteristics put low vegetation areas in a very attractive position for urban development.

One of the most critical change that puts into evidence the great pressure existing on Mata Atlântica forests are those indicating significant transformations of these forests into low vegetation or urban settlements (S.O.S, 1998) that are highlighted in Figure 5.62 with red circles. This situation is considered to be quite worrying referring to land degradation and environmental impact in important plant and animal species that have their main habitat in these forests (Silva and Dinnouti, 1999; Silva and Leitao, 1982; Radambrasil, 1983; Mantovani, 1993; Pontes, 2000). Deforestation of Mata Atlântica have also serious effects on water quality (Procop, 2001) and soil stability, since soils devoid of vegetation coverage loose their natural stability and protection against erosion becoming vulnerable to high events of soil loss either by intensive rainfall characterizing this zone or by anthropogenic activities. Therefore, the loads of sediments transported by local rivers into the estuary cause great impact on its water quality particularly due to recurring turbidity events that increase mortality risk of vulnerable light species (Silva et al., 2005).

Apparently there are not critical transformations indicating high rates of mangrove felling due to urban expansion or replaced by other type of minor vegetation. The most feasible explanation for this situation is that in the last 15 years these natural ecosystems have been declared ecological reserves, therefore protected by national that have increased control from local authorities, consequently fulfilment of environmental laws is more severe (Ellison et al., 1996; Lacerda et al., 2002). Nowadays, anthropogenic action is strictly forbidden in mangrove forests (CONAMA, 2002).

Changes highlighting a transformation of low vegetation into forest was also included in the final map, this to emphasize the influence of climatic seasons on the results obtained by the classifications and their influence on further analysis. For example, this change is quite rare and not usual to take place, it could be justified by intensive reforestation campaigns, where previously impacted areas are being replanted with endemic species. Reforestation campaigns are not representative in Santos, thus the explanation for this apparently low vegetation changes into forest in some areas is related to the amount of vegetation registered by the sensor in each one of the images which significantly varies from one season to the other.

Taking into consideration that in summer (April 2000) there is an increase of vegetation in the area, favored by intense rainfall characterizing this season, that is classified as forest due to its high reflectance in bands 3, 4, 5, that were those bands used for image classification and best representing vegetation (http://web.pdx.edu/~emch/ip1/bandcombinations.html). In the other hand, during winter with a significantly decrease in rainfall there is an obvious decline of vegetation which is evident in the image classification of June. Like this it is possible to logically explain these “apparent” changes mentioned before.
For this reason it is important to perform landcover change analysis using images representing the same season to avoid this type of errors and misclassification, obviously when the main aim of the study is not to stress changes among seasons.

It is important to point out that most of landcover changes have taken place in low-mid elevations areas (Figure 5.63) with soft slopes, while those areas at higher elevations and located in steep slopes remain less impacted and disturbed, this to stress the importance and influence of geographical location and physical characteristics of the terrain, that constraint anthropogenic activities.

![Figure 5.63: DEM and slope maps of Santos study area.](image)

In order to quantify the landcover changes and associations among all classes selected Table 5.17 indicates the percentages of these associations.

Table 5.17: Cross tabulation of classified landcover for 2000 (columns) against landcover for 1993 (rows) expressed in percentages.

<table>
<thead>
<tr>
<th>Classified landcover of 2000 (wet season)</th>
<th>Mangrove</th>
<th>Urban areas</th>
<th>Low vegetation</th>
<th>Water</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>75.96%</td>
<td>1.66%</td>
<td>2.19%</td>
<td>1.14%</td>
<td>1.05%</td>
</tr>
<tr>
<td>Urban areas</td>
<td>0.95%</td>
<td>76.20%</td>
<td>20.25%</td>
<td>1.27%</td>
<td>2.11%</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>0.35%</td>
<td>9.49%</td>
<td>36.07%</td>
<td>0.35%</td>
<td>6.37%</td>
</tr>
<tr>
<td>Water</td>
<td>11.58%</td>
<td>1.27%</td>
<td>0.66%</td>
<td>96.93%</td>
<td>0.58%</td>
</tr>
<tr>
<td>Forest</td>
<td>10.00%</td>
<td>9.15%</td>
<td>34.89%</td>
<td>0.26%</td>
<td>87.52%</td>
</tr>
<tr>
<td>Shadow</td>
<td>1.17%</td>
<td>2.23%</td>
<td>5.94%</td>
<td>0.06%</td>
<td>2.37%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Table 5.17 quantified landcover changes explained in the paragraphs above, for example from this table it is possible to say that most of the classes have changed in less than 25% (values in bold), except for low vegetation that shows the highest percentages of changes specially into forest (34.89% - explained before), followed by urban areas (20.25%). The 87.52% of forest have remained as forest but 6.37% and 2.11% have been transformed into low vegetation and urban areas respectively.

Figure 5.64 shows a general view of the differences (in percentages) between 1993 and 2000, where it is possible to appreciate an increase or decrease of each class in these seven years. All classes showing vegetation (mangroves, low vegetation and forest) indicates a decrease, which was expected due to anthropogenic activities taking place in the area.

The slight increase in water and urban areas for image 2000 is related to seasonal variability, the first case is obvious since the amount of rainfall (summer) in the area enlarge water bodies given as a result an increase of this class, while for an increase in urban areas it is most probably associated to the fact that some pixels without vegetation (bare soil) in image 1993 have been originally misclassified as urban due to the similarity in their spectral responses (http://web.pdx.edu/~emch/ip1/bandcombinations.html). Thus, increasing in this way the number of pixels considered as urban settlements in 1993 image and not really existing, while in image 2000 this misclassification is less probable due to a significant decrease of bare soil existing in the area for this rainy season.

From Figure 5.64 is possible to appreciate that the most abundant class in the area is represented by forest that covers almost 60% of the study area, followed by urban areas (covering almost 20%), while mangrove areas are the smallest (except for water that is not considered for this comparisons) with almost 10% present in the study area. The great coverage of forest in the area emphasize the value of this ecosystem for the overall area and the importance to protect them against urban development and other anthropogenic activities.
Chapter 5

Multitemporal analysis for landcover change (Santos)

5.2. Landcover changes using Idrisi 15.0 Andes Edition software

5.3.1. Methodology used in Idrisi Andes for landcover change analysis

Landcover change analysis using Idrisi software represent a reliable source of information since it includes in the analysis a series of criteria, defined as basis for a decision that can be measured and evaluated. This criteria is strictly related to the study area and can be of two kinds: factors and constraints, which can pertain either to attributes of the individual or to an entire decision set (Eastman, 2001). In this way a complete overview of the problem and scenario is taken into consideration for the study.

Generally, to meet a specific objective several criteria will need to be evaluated, this process is called Multi-Criteria Evaluation - MCE (Voogd, 1983; Carver, 1991). MCE is commonly achieved by one of two procedures: Boolean overlay and weighted linear combination (WLC). The first involves criteria reduced to logical statements of suitability and then combined by means of one or more logical operators such as intersection (AND) and union (OR), in this thesis it was mainly applied for constraints. The second, WLC, involves continuous criteria (factors) standardized to a common numeric range and then combined by means of a weighted average. For this thesis, mainly WLC was used since it allows a more flexible application of the criteria.

The main tool used in Idrisi was GIS analysis, specifically the Decision Support and the Change/Time series modules containing a series of commands that help with the automated assistant for single or multi-objective multi-criteria evaluation problems. By the application of Fuzzy sets membership functions and MCE a series of maps and tables are created based on the interactive effects of several contributing factors and constraints that define how suitable an area or land might be for a specific development or continuation of an existing landuse.

Methodology followed for MCE, which was the basis for landcover change analysis using Idrisi Andes software, will be described in detail in the next sections. Results of the different associations and evaluations applying mathematical expressions and suitability criteria are given as maps and tables that will be explained in each one of the sections covered in this chapter.

5.3.2. Factors and constraints

The purpose of building-up a MCE is to improve the decision making process by combining a set of criteria to achieve a single composite, that will be the basis for landcover change and projection analysis. A set of factors and constraints (Figure 5.65), delineated by vector and raster maps, are the main input to built distance maps (Figure 5.66) using the “GIS Analysis/Distance Operators/Distance” procedure.

The target features from which distance was measured are represented by vector files such us: rivers, roads and coast. Furthermore, constraints that are used to limit the alternatives under consideration were represented by raster images that excluded certain areas like urban settlements, water bodies and protected areas present in the study area.

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Figure 5.65: Contributing factors and constraints used for MCE.

Figure 5.66 shows the distance maps obtained by the application of Distance Operators module.

Figure 5.66: Distance maps from coast, water bodies and urban areas and roads used for MCE.

Table 5.18 indicates the set of factors and constraints taken into consideration for this analysis associated with their specific suitability criteria (best scenario and worst scenario considering height, distance and steepness related to the chosen factors and contraints) considering the classes present in the classified maps (the same used previously - Figure 5.59).

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Table 5.18: Contributing factors and constraints.

<table>
<thead>
<tr>
<th>Class</th>
<th>DEM (height)</th>
<th>Urban areas &amp; roads (distance)</th>
<th>Water bodies (distance)</th>
<th>Slope (steepness)</th>
<th>Coast (distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>+100 m -0 m</td>
<td>+&gt;3 km -0 m</td>
<td>+2 km -0 m</td>
<td>+20° -0°</td>
<td>+8 km -1 km</td>
</tr>
<tr>
<td>Mangrove</td>
<td>+0 m -50 m</td>
<td>+&gt;1.5 km -0 m</td>
<td>+0 m -200 m</td>
<td>+0° -2°</td>
<td>+800 m -&lt;400 m</td>
</tr>
<tr>
<td>Urban</td>
<td>+0 m -&gt;600 m</td>
<td>+0 m -3 km</td>
<td>+0 m -2 km</td>
<td>+0° -20°</td>
<td>+0 m -12 km</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>+0 m -&gt;200 m</td>
<td>+0 m -3 km</td>
<td>+0 m -2 km</td>
<td>+0° -20°</td>
<td>+0 m -1 km</td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
<td>-</td>
<td>+0 m -500 km</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figures 5.65 and 5.66 shows the input maps for MCE. The first step for MCE is the definition of the Fuzzy Sets membership functions that is possible using: the constraints and factors maps (Figure 5.65); the maps obtained with the distance procedure (Figure 5.66); and the suitability criteria described in Table 5.18.

The suitability criteria in Table 5.18 were defined according to: the physical and natural limitations of the considered species or ecosystems; the limitations of the terrain; and behavioral patterns and tendencies of development and urbanization. For example, the best conditions for mangrove growth according to suitable criteria shown in Table 5.18 will be: at elevations less than 50 m; distant from urban settlements at least 1.5 km; distant no further than 200 m from water bodies; located at shallow slopes of no more than 2°; and distant from the coast at least 400 m since at a closer distance there will be more probabilities for anthropogenic influence.

5.3.3. Fuzzy Set Memberships Functions

All contributing factors and constraints were standardized using fuzzy set membership functions. As mentioned in Chapter 3, fuzzy set membership is characterized by a grade (also called possibility) that ranges from 0.0 to 1.0, indicating a continuous increase from non-membership to complete membership of a pixel in a specific category (Eastman, 2001).

Fuzzy Set theory provides a rich mathematical basis for understanding decision problems and for constructing decision rules in criteria evaluation and combination. The Fuzzy module in IDRISI is designed for the construction of Fuzzy Set membership functions and it offers four types of functions: Sigmoidal (S-shaped), J-shaped, Linear and User-defined.

In this case the Sigmoidal membership function was chosen in all cases (Table 5.19), which is perhaps the most commonly used function in Fuzzy Set theory (Eastman, 2001). This procedure rescaled the distance from feature objects (or factors) in non-regular distance range. Preferences of pixel-vicinity were utilized within a certain group of pixel membership and new pixel distribution was defined according to fuzzy set membership functions (Altman, 1994).

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Table 5.19: Suitability criteria used for Fuzzy Set membership functions according to contributing factors and constraints.

<table>
<thead>
<tr>
<th>Class</th>
<th>DEM (height - m)</th>
<th>Urban areas (distance - m)</th>
<th>Water bodies (distance - m)</th>
<th>Slope (Steepness - °)</th>
<th>Coast (distance - m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>a, b</td>
<td>a, b</td>
<td></td>
<td>8000</td>
</tr>
<tr>
<td>Mangrove</td>
<td>0</td>
<td>c, d</td>
<td>a, b</td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>Urban areas</td>
<td>0</td>
<td>c, d</td>
<td>a, b</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>0</td>
<td>c, d</td>
<td>a, b</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>c, d</td>
<td>a, b</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.19 shows the input criteria used in the Fuzzy Set membership function module (Figure 5.67), giving as a result for every class a set of maps (5 maps) associated to the criteria applied to each contributing factor and constraint. Figure 5.67 shows the results of the application of the Fuzzy Set membership functions for forest and the criteria applied in Idrisi software “GIS Analysis/Decision Support/FUZZY” module.

![Figure 5.67: Fuzzy set membership function command and final output (set of maps) after applying suitability criteria for forest.](image)

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For each one of the classes the same procedure must be followed and the set of maps obtained in each will be the next input for the criterion weights module.

5.3.4. Criterion Weights – Weighted Linear Combination

Two of the most common procedures for multi criteria evaluation are: weighted linear combination (WLC) and concordance-discordance analysis (Carver, 1991). In general, for continuous factors, as in this study, weighted linear combination is the most commonly used and the best option (Voogd, 1983). With a WLC, factors are combined by applying a weight to each and followed by a summation of the results to yield a suitability map, i.e.:

\[ S = \left( \sum W_i X_i \right) \cdot \prod C_i \]

Where:  
- \( S \) = suitability 
- \( W_i \) = weight of factor i 
- \( X_i \) = criterion score of factor i 
- \( C_i \) = criterion score of constraints 
- \( \sum \) = sum 
- \( \prod \) = product

Through the “GIS Analysis/Decision Support/WEIGHT” tool, information is break down into a series of pairwise comparisons of the relative importance of factors to the suitability of pixels for the activity or landuse being evaluated. Indeed, it is the derivation of weights process, within the context of the decision objective that provides the major challenge, since a series of criteria must be taken into consideration overall.

The technique used in Idrisi is that of Pairwise Comparison (PC) developed by Saaty (1977) in the context of a decision making process known as the Analytical Hierarchy Process - AHP (Eastman et al., 1995). In the PC process the most important of each possible pair effects was selected and subsequently comparison was established in qualitative terms (Ghribi, 2005). Ratings of the PC used for filling the AHP matrix (Figure 5.68) are rated on a 9-point scale (Eastman et al., 1995). Weights are then derived from the principal eigenvector of a square reciprocal matrix of PC between all contributing factors (Eastman, 2001).

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Figure 5.68: Pairwise comparison matrix using continuous rating scale on the AHP Idrisi module and derived weights from the principal eigenvector assigned to each factor.
The same PC procedure is applied to all classes. The procedure then requires that the principal eigenvector of the pairwise comparison matrix be computed to produce “best fit” weights (Table 5.20), being the result a set of weights (Figure 5.68) for each class associated to all contributing factors and constraints.

<table>
<thead>
<tr>
<th>Table 5.20: Weights derived by calculating the principal eigenvector of the pairwise comparison matrix (CR = consistency ratio).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forests</strong></td>
</tr>
<tr>
<td>Factor</td>
</tr>
<tr>
<td>Slope</td>
</tr>
<tr>
<td>Urban</td>
</tr>
<tr>
<td>DEM</td>
</tr>
<tr>
<td>Coast</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>CR</td>
</tr>
</tbody>
</table>

Table 5.20 it is possible to see the weights (sum is always 1) calculated by pairwise comparison, in each class the criteria analyzed follow a specific order, indicating in this way to which extend one effect (factors and constraints) is more important than the other. For example, for forest the most important criteria to consider its suitability is slope, since higher the steepness more probability for forest development and conservation; followed by urban criteria due to anthropogenic activity stressing forest; the last criteria for forest suitability will be water, since due to climatic conditions of the study area characterized by an intense rainy season, vicinity to water bodies is not essential for forest development. For mangrove, for example, the most crucial criteria for its suitability are elevation and slope, since these ecosystems are able to develop on low elevations and soft slopes, being the least essential among the criteria evaluated for this study area, its vicinity to urban settlements, without intending that it is not important but considering the importance of other criteria it is less significant than the others.

5.4. Suitability Maps and Predicted Landcover

5.4.1. Multi Criteria Evaluation

As indicated before, the primary issue in MCE is concerned with how to combine the information from several criteria to form a single index of evaluation. In order to do this, an attempt was made to create suitability maps for each class analyzed, inserting interactive effects of the contributing factors and constraints previously processed.

Following the “GIS Analysis/Decision Support/MCE” module, previous files containing the factors weights are used for calculating a set of suitability maps, which are created multiplying each factor by its weight, adding the results and then successively multiplying the result with Boolean operation by each of the constraints which exclude reserved areas (i.e. water, protected areas and urban settlements).

Suitability maps depict the sensitivity of areas to develop or keep the analyzed classes: forest, mangrove, low vegetation, urban areas. Water was not taken into consideration since significant landcover changes regarding this feature are not expected to take place in this study area. Once the multi criteria suitability maps have been created for each objective, the An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
multi objective decision problem can be approached, in this case landcover change analysis was the main concern.

The principal eigenvector of weights resulting from pairwise comparison between factors used in the MCE procedure were used to create suitability maps in each case. The MCE command used in Idrisi for the creation of these maps is shown in Figure 5.69. The four (since water is not considered) suitability maps (Figure 5.70) will be the basis for landcover change analysis between images of 1993 and 2000 and the future landcover prediction for 2010.

![Figure 5.69: MCE command with the principal eigenvector of weights resulting from forest pairwise comparison.](image)

Figure 5.70 shows the final four suitability maps obtained from MCE.

![Figure 5.70: Suitability maps resulting from MCE showing the degree of susceptibility of each pixel to host the classes analyzed.](image)

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Suitability maps emphasize the criteria applied to each of the contributing factors and constraints, for example, it is possible to say that for urban areas development the most suitable areas are those located at mid-low elevation and close to the coast and water bodies. Furthermore, for forest areas with the highest suitability are those at high elevation and distant from urban settlements. Regarding mangrove, areas with the highest suitability are those at low elevations and close to water bodies.

5.4.2. Landcover prediction and potential scenarios of change

Markov Transition Estimator (MTE) and Landcover Prediction

A Markovian process is one in which the state of a system at time 2 can be predicted by the state of the system at time 1, given a matrix of transition probabilities from each cover class to every other cover class. The “GIS Analysis/Change-Time Series/Markov” module (Figure 5.71) takes two landcover maps as input (1993 and 2000) and as part of the outputs it produces (Eastman, 2001):

- A transition probability matrix that express the likelihood that a pixel of a given class will change to any other class (or to stay the same) in the next period.
- A transition areas matrix that express the total area (in cells) expected to change in the next time period.
- A set of conditional probability images (Figure 5.72), one for each landcover class. These maps express the probability that each pixel will belong to the designated class in the next time period. They are conditional probability maps since this probability is conditional on their current state.

![Markov transition estimator](image)

**Figure 5.71:** Markov transition estimator (MTE), considering landcover images of 1993 and 2000 and projection for 2010.

The same images used before, June 1993 and April 2000 were used for the Markov transition estimator to predict the 2010 landcover, projecting the 1993 and 2000 images (7 year time period).

Table 5.21 represents the transition probability matrix from which it is possible to say that most of the classes have stayed the same (values in bold), except for low vegetation that shows the lowest probability (24.51%) and has 11.63% of probability to be transformed into urban areas. This table shows a similar tendency to that expressed in Table 5.17 emphasizing changes between 1993 and 2000 using ArcMap software for the analysis.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Table 5.21: Transition probability matrix of landcover 2000 (columns) against landcover 1993 (rows) expressed in percentages.

<table>
<thead>
<tr>
<th>Class</th>
<th>Mangrove (%)</th>
<th>Urban areas (%)</th>
<th>Low vegetation (%)</th>
<th>Water (%)</th>
<th>Forest (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>68.36</td>
<td>1.35</td>
<td>0.66</td>
<td>15.98</td>
<td>13.65</td>
</tr>
<tr>
<td>Urban areas</td>
<td>2.33</td>
<td>70.46</td>
<td>11.63</td>
<td>1.85</td>
<td>13.73</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>2.98</td>
<td>25.63</td>
<td>24.51</td>
<td>1.09</td>
<td>45.79</td>
</tr>
<tr>
<td>Water</td>
<td>1.56</td>
<td>1.75</td>
<td>0.47</td>
<td>95.76</td>
<td>0.45</td>
</tr>
<tr>
<td>Forest</td>
<td>1.5</td>
<td>3.35</td>
<td>8</td>
<td>0.88</td>
<td>86.27</td>
</tr>
</tbody>
</table>

The transition areas matrix is synthesized in Table 5.22, values were transformed from cells to Km² (based on the 30m x 30m resolution of each pixel) in order to quantify changes in area units.

Table 5.22: Transition areas matrix of landcover 2000 (columns) against landcover 1993 (rows) expressed in square kilometers.

<table>
<thead>
<tr>
<th>Class</th>
<th>Mangrove (Km²)</th>
<th>Urban areas (Km²)</th>
<th>Low vegetation (Km²)</th>
<th>Water (Km²)</th>
<th>Forest (Km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>57.66</td>
<td>1.14</td>
<td>0.56</td>
<td>13.48</td>
<td>11.51</td>
</tr>
<tr>
<td>Urban areas</td>
<td>4.36</td>
<td>131.82</td>
<td>21.76</td>
<td>3.46</td>
<td>25.68</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>2.90</td>
<td>24.96</td>
<td>23.87</td>
<td>1.07</td>
<td>44.59</td>
</tr>
<tr>
<td>Water</td>
<td>0.90</td>
<td>1.02</td>
<td>0.27</td>
<td>55.45</td>
<td>0.26</td>
</tr>
<tr>
<td>Forest</td>
<td>9.12</td>
<td>20.42</td>
<td>48.78</td>
<td>5.38</td>
<td>526.15</td>
</tr>
</tbody>
</table>

Figure 5.72 shows the conditional probability maps for mangrove and urban areas, indicating the different degrees of likelihood that these classes will develop or appear in specific areas for 2010. The urban areas map indicates a high chance that they will continue to grow therefore covering great extensions at mid-low elevations, while for mangrove the probabilities to keep extending are logically lower. The same type of maps were obtained for forest and low vegetation.
Chapter 5

Multitemporal analysis for landcover change (Santos)

Cellular Automata/Markov Chain and Landcover Prediction

It is a combined procedure that adds an element of spatial contiguity as well as knowledge of the likely spatial distribution of transitions to Markov change analysis (Ghribi, 2005). One of the basis spatial elements that underlines the dynamics of many change events is proximity: areas will have higher tendency to change to a class when they are near existing areas of the same class (i.e. expansion phenomenon). This can be very effectively modeled using cellular automata. A cellular automaton is a cellular entity that independently varies its state based on its previous state and that of its immediate neighbors according to a specific rule (Eastman, 2001). There is a similarity to a Markovian process, the only difference is application of a transition rule that depends not only upon the previous state but also upon the state of the local neighborhood.

A cellular automaton procedure used as a predictive landcover change is implemented with "GIS Analysis/Change-Time Series/CA_Markov" module (Figure 5.73). CA_Markov takes as input the landcover map from which changes should be projected (2000), the transition areas file produced by Markov in the previous step (Table 5.22) and the set of suitability maps (Figure 5.70) produced by MCE. Then by a iterative process of relocating landcover until it meets the area totals predicted by Markov module. The output is a projected landcover map based on the principle that changes develop as a growth process in areas of high suitability proximate to existing areas (Eastman, 2001).

In this case the output was a projected landcover map of 2010 (Figure 5.75)

![Image from which landcover will be projected](image)

![Set of suitability maps](image)

![Time units to project](image)

Figure 5.73: Markov change prediction based on Cellular Automata process.

5.5. Results of landcover change using Idrisi 15.0 Andes software

After applying the series of criteria indicated in each one of the previous sections two landcover change maps were performed: a map indicating landcover changes between 1993 and 2000 (Figure 5.74) and a map indicating landcover changes between 2000 and the projected map of 2010 (Figure 5.75).

The "GIS Analysis/Database query/Crosstab" module produced a series of tables with the tabulations and associations between the 2 set of images among which comparison and

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evaluations were performed (1993 and 2000, 2000 and 2010). The most important results will be shown in the next section.

5.5.1. Landcover change between 1993 and 2000

As indicated before, changes referring to vegetation were those taken into consideration for analysis. Figure 5.74 highlights vegetation changes as in Figure 5.62, Table 5.23 indicates the cross tabulation of classified landcover 1993 (columns) against classified landcover 2000 (rows).

Figure 5.74: Map of landcover highlighting vegetation changes occurred between 1993-2000 using Idrisi software. Areas circled indicate high deforestation of Mata Atlântica.

Table 5.23: Cross tabulation of classified landcover for 2000 (columns) against landcover for 1993 (rows) expressed in percentages.

<table>
<thead>
<tr>
<th>Class</th>
<th>Mangrove (%)</th>
<th>Urban areas (%)</th>
<th>Low vegetation (%)</th>
<th>Water (%)</th>
<th>Forest (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>85.03</td>
<td>0.48</td>
<td>0.34</td>
<td>18.88</td>
<td>1.55</td>
</tr>
<tr>
<td>Urban areas</td>
<td>3.90</td>
<td>80.68</td>
<td>19.30</td>
<td>4.34</td>
<td>2.97</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>2.76</td>
<td>11.54</td>
<td>39.48</td>
<td>1.22</td>
<td>6.10</td>
</tr>
<tr>
<td>Water</td>
<td>0.56</td>
<td>0.28</td>
<td>0.15</td>
<td>69.28</td>
<td>0.02</td>
</tr>
<tr>
<td>Forest</td>
<td>7.74</td>
<td>7.02</td>
<td>40.74</td>
<td>6.28</td>
<td>89.37</td>
</tr>
</tbody>
</table>

Comparing Figure 5.74 with 5.62 and their respective crosstables it is possible to say that using different softwares for landcover change analysis might vary slightly some of the results. For example in Figure 5.74 changes from forest to urban settlements (2.97%) seem to be more frequent than in Figure 5.62 (2.11%), as well as changes from low vegetation to forest which was mainly justified by the seasonal differences in the images. This seasonal

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difference seem to have a higher influence in the procedures followed by Idrisi, in Figure 5.74 these changes represent 40.74% which are higher than in Figure 5.62 with 34.89%. Also here is possible to say that the most common pattern regarding vegetation changes is referred to low vegetation transformed into urban areas (19.30%), without considering those changes from low vegetation into forest for the reasons explained before. In an overall vision both images show similar tendencies according to their crosstables, which could be taken as a good sign of the reliability of using both softwares.

5.4.2. Landcover prediction for 2010

Another important result based on the MCE, Markov, and Cellular Automata procedure was a projected landcover map of 2010 (Figure 5.75). This possibility is quite significant for performing predictions of landcover in which is possible to anticipate what might be the changes and future scenarios regarding landuse of a specific area.

The results should be considered as an important source of information for environmental modeling and decision making processes. The validity and reliability of these projections depends on the quality of the input information, referring to the existing classified images. Better quality of input sources will give more reliable predictions, for this reason it is important to have good quality images and preferably of the same season.

In this case, the seasonal difference between images of 1993 and 2000 significantly influenced 2010 prediction since all iterations and calculations are based on the previous changes and differences between these two images. Nevertheless, the predicted landuse of 2010 can be considered as an appropriate source of information for future analysis and studies. Figure 5.75 represents the predicted landcover map of 2010 using cellular automata modeling comparing it with the previous classified images of 1993 and 2000.

![Figure 5.75: Landcover maps of 1993, 2000 and predicted 2010.](image-url)

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Landcover changes between 2000 and projected landcover of 2010 will be analyzed in the next section.

From Figure 5.75 it is possible to see that landcover predicted map of 2010 has a more uniform texture, the main reason of this uniformity is due to cellular automata modeling, since this takes into consideration not only the previous state (1993 and 2000), but also the state of the local neighborhood pixels, so considering the expansion of some classes (e.g. forest) this will give a greater weight or probability on their prediction. For example since forest cover a great extension, all pixels included in the neighborhood of this class will be classified as one of them in the 2010 projection. The same for urban areas, all pixels included in a close neighborhood of this class will be classified as one them in the 2010 prediction.

5.4.3. Landcover change between 2000 and 2010

Predicted landcover map of 2010 was used to calculate possible landcover changes within 10 years from the last available image of 2000. These results and the cross tables associated to these changes will be discussed in this section.

The cross tabulation table indicates the associations between all classes using images 2000 and 2010. To better illustrate these landcover changes results are expressed in percentages.

Table 5.24: Cross tabulation of classified projected landcover of 2010 (columns) against landcover for 2000 (rows) expressed in percentages.

<table>
<thead>
<tr>
<th>Class</th>
<th>Mangrove (%)</th>
<th>Urban areas (%)</th>
<th>Low vegetation (%)</th>
<th>Water (%)</th>
<th>Forest (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>83.85</td>
<td>0.13</td>
<td>0.68</td>
<td>16.36</td>
<td>1.28</td>
</tr>
<tr>
<td>Urban areas</td>
<td>3.12</td>
<td>96.09</td>
<td>3.40</td>
<td>3.98</td>
<td>0.99</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>3.12</td>
<td>2.78</td>
<td>59.67</td>
<td>1.23</td>
<td>5.30</td>
</tr>
<tr>
<td>Water</td>
<td>1.17</td>
<td>0.14</td>
<td>0.22</td>
<td>71.43</td>
<td>0.04</td>
</tr>
<tr>
<td>Forest</td>
<td>8.74</td>
<td>0.85</td>
<td>36.03</td>
<td>7.06</td>
<td>92.39</td>
</tr>
</tbody>
</table>

From this table it is possible to see that most of the classes analyzed have high probability to remain the same represented by values in bold, which indicate less impact on the area. Comparing tables 5.17, 5.23 and 5.24, the latest indicates the highest percentages for remaining undisturbed (except for mangrove), this might be a result of the continuity of environmental programs and implementation of law (CONAMA, 2002) in the area, that is a good indicator of a promising improvement of environmental conditions in Santos.

Landcover changes for vegetation are highlighted in Figure 5.76, taking into consideration feasible changes between 2000 and 2010.

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As is possible to see, there is less impact regarding forest being transformed into urban settlements, but one of the most significant changes predicted for 2010 is forest into low vegetation (5.30%), which can be considered as a fact to take into consideration for further protection of these ecosystems in the area.

Also in this case the same tendencies as in the previous changes analyzed for 1993 – 2000 are present also here, this was expected since 2010 prediction is based on these images. The same misclassifications affected by seasonal differences in these original images are carried on to the predicted image as well.

So to have a complete view of the general landcover change tendencies for each one of the selected classes, Figure 5.77 emphasize the main changes among the 3 images between 1993 and 2010. Figure 5.79 shows the similarity between landcover tendencies of classified images of 1993 and 2000 and projected image of 2010.
Chapter 5 Multitemporal analysis for landcover change (Santos)

Differences in landcover between 1993 - 2000 - 2010

<table>
<thead>
<tr>
<th>Class</th>
<th>1993</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>94.42</td>
<td>84.35</td>
<td>74.94</td>
</tr>
<tr>
<td>Urban areas</td>
<td>198.07</td>
<td>187.08</td>
<td>178.63</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>106.64</td>
<td>97.39</td>
<td>94.89</td>
</tr>
<tr>
<td>Water</td>
<td>41.39</td>
<td>57.91</td>
<td>78.71</td>
</tr>
<tr>
<td>Forest</td>
<td>622.75</td>
<td>609.85</td>
<td>607.26</td>
</tr>
<tr>
<td>Shadow</td>
<td>0%</td>
<td>26.65</td>
<td>77.60</td>
</tr>
</tbody>
</table>

Figure 5.77: Differences in landcover categories between 1993 and 2010 of classified and predicted images in percentages and square kilometers.

Figure 5.78: Landcover tendency showing a straight similarity between classified landcover and projected landcover of 2010.

This similarity on landcover tendency is mainly referred to the fact that classified images of 1993 and 2000 are the main input for projecting a landcover for 2010.

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5.4.4. Summary of landcover analysis

Summarizing it is possible to say that there have been some evident landcover changes in Santos from 1993 to 2000, specially focusing on vegetation changes like Mangrove to urban areas or to low vegetation, as well as forests to urban areas and low vegetation. The analysis were focused on these specific changes since these types of vegetation are considered to represent the most important natural ecosystems existing in Santos study area. Based on multitemporal analysis applied to the two Landsat images available and the application of GIS it was possible to define which areas have been transformed into what giving in this way a clear idea of the location of the most threatened areas regarding anthropogenic activities as deforestation and urbanization.

The application of MCE was a very important tool for the success of these evaluations since it allowed the combination of several criteria, carefully selected and representing the main characteristics of the study area, to form a frame of limitations and possibilities that best represent the evolution and previous changes taken place in Santos. This process and the results obtained set the basis for future predictions. For this reason the future tendency for landcover in 2010 is quite similar to that already occurred between 1993 and 2000. Nevertheless, this is quite acceptable taking into consideration that anthropogenic activities and its effects on the area seem to be under control due to more strict laws existing nowadays in Santos (CONAMA, 2002). By MCE analysis it was possible to determine the most suitable areas for specific landcover development in 2010. In this way giving the user of these tools the possibility to predict what could be the scenario of Santos in the near future.

These analysis are quite useful in the creation and proposal of development plans, giving local authorities and planners an important and valuable resource, a future scenario of the study area, to take their decisions; foreseeing the consequences and effects of specific present activities. This facilitates the creation of preventive measures to keep anthropogenic activities under a reasonable control.
### Chapter 6: Erosion processes, model review and selection (Bahia Blanca and Santos)

#### 6.1. Introduction to erosion processes

#### 6.2. Soil erosion processes

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##### 6.2.2. Factors influencing erosion

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- **Soil feature factor**
- **Geological factor**
- **Biological factor**

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- **Sheet erosion**
- **Rill erosion**
- **Gully erosion**
- **Splash erosion**
- **Stream channel erosion**

##### 6.2.4. Erosion models

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- **Physically based models**

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- **R factor**
- **K factor**
- **LS factor**
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- **P factor**

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#### 6.4. Integration of remote sensing and GIS techniques for erosion calculation

##### 6.4.1. GIS and remote sensing facilities

##### 6.4.2. Methodology applied for calculating erosion factors and their map representation using RUSLE

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#### 6.5. Results obtained from RUSLE and USPED models

##### 6.5.1. Erosion risk maps applying RUSLE model

- **Potential erosion**
- **Actual erosion**

##### 6.5.2. Erosion/Sedimentation risk maps applying USPED model

##### 6.5.3. Analysis of erosion process in Santos and Bahia Blanca
Chapter 6

Erosion processes, model review and selection
(Bahia Blanca and Santos)

6.1. Introduction to erosion processes

Soil erosion is one of the most important and serious form of land degradation and also one of the most difficult to control, monitor and predict. Soil loss is a natural process in nature caused by ordinary events as water runoff, rainfall, wind, etc, however, uncontrolled human activity has significantly increased the natural rates of soil erosion worldwide.

Approximately, anthropogenic activities affect 1,094 million hectares of the world’s land, of which 43% suffer from deforestation and removal of natural vegetation, 29% from overgrazing, 24% from improper management of agricultural land and 4% from over-exploitation of natural vegetation (Walling and Fang, 2003). These wrong practices is causing topsoil to erode at alarming rates.

Latin America has the world’s largest resources of cultivable land but unfortunately this reserve is dwindling rapidly (Pla, 1993) more than half of the 576 million hectares of its agricultural potential lands are classified as degraded. More than 100 million hectares have been degraded by the effects of deforestation, while a further 17 million hectares suffer from overgrazing (Pla, 2003).

It is almost impossible to observe or measure erosion process in real time during runoff or erosion events, mainly because of the small spatial and time scales at which they occur (Saavedra, 2005). As a consequence, it is necessary to improve the understanding of erosion and deposition processes as well as soil monitoring methods to efficiently apply erosion models for the prediction of soil loss.

Over the last 20 years, there has been remarkable progress in the development of mathematical tools for erosion and sediment transport modelling, with a tendency towards physically or process-based model development (de Roo et al., 1989; Young et. al, 1989; Desmet et al., 1995; Mitasova et al., 1996; Renschler et al., 1999; Jetten et al., 2003).

Some of the most important types of erosion and current models will be discussed in this chapter, mainly focusing on those selected for analysis and application. Furthermore, application of these models to the two study areas will be analyzed to illustrate the utility of GIS and remotely sensed data in erosion modelling.
6.2. Soil erosion processes

6.2.1. Main characteristics of soil erosion

Erosion is a complex geomorphic process determined by mutual interaction of numerous factors (Suri et al., 2002), it implicates the detachment and removal of soil and rock by the action of running water, wind, waves, flowing ice, and mass movement. The activity of waves, ice, or wind may be regarded as special cases restricted to particular environment.

Erosion is a natural process but human activity has significantly increased the natural rates of soil erosion causing worrying soil degradation levels. Severity of soil degradation is directly related to soil properties and its resilience capacity, defined as the ability of soil to restore itself.

Soil erosion is a very delicate and important issue to deal with. It is estimated that one sixth of the world’s soils are affected by some kind of erosion (mainly water). Erosion involves three main stages: detachment, transport and deposition of soil particles by the erosive forces. The different types of erosion are determined by the source of energy, which are illustrated in Figure 6.79 and can be summarized in four main sources (Lal, 2001): physical, gravity, chemical, and anthropogenic activities (i.e. tillage).

Synthesizing, erosion is a function of the eroding power of raindrops, running water, sliding or flowing earth masses, and the erodibility of the soil; it can be expressed as:

\[ \text{Erosion} = f(\text{Erosivity, Erodibility}) \]

Where:

Erodibility is a soil’s inherent tendency to be eroded or transported by water or wind. It is a function of the physical, mechanical and chemical properties of soil; of vegetal land cover; and the topography.

Erosivity is the soil’s vulnerability to erosion mainly related to rainfall (rainsplash). It depends on the geometric and dynamical properties of raindrops (diameter, terminal velocity, and kinetic energy). The more intensive the rainfall, and the longer the storm, more soil erodes.

Soil erosion begins with detachment, which is caused by break down of aggregates by raindrop impact, sheering or drag force of water and wind. Detached particles are transported by flowing water (over-land flow and inter-flow) and wind, and deposited when the velocity of water or wind decreases by the effect of slope (gentle slopes) or ground cover (lack of vegetation). Dispersion, compaction and crusting, accelerate the natural rate of soil erosion. These processes decrease structural stability, reduce soil strength, aggravate erodibility and accentuate susceptibility of soil particles to be transported by overland flow, interflow, wind or gravity. These processes are accentuated by soil disturbance (e.g. tillage), lack of ground cover (e.g. bare-fallow soils) and harsh climate such as high rainfall intensity and wind velocity (Lal, 2001; Saha, 2004).
Chapter 6  
Erosion processes, model review and selection (Bahia Blanca and Santos)

6.2.2. Factors influencing erosion

The factors that influence overland flow generation and the detachment and transport of materials (soil particles) over the land surface are shown in Figure 6.80, and can be divided into five major classes: climate and precipitation, relief, soil and bedrock properties, vegetation cover and human activity.

Figure 6.79: Sources of energy causing soil erosion (Lal, 2001).

Figure 6.80: Main factors contributing for soil erosion process (Symeonakis, 2001).

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Climate and geology are the most important influences on erosion together with soil characteristics and vegetation, the latest being dependent upon them and interrelated with each other (http://159.226.205.16/curriculum/3w/01/). For example, vegetation, is dependent upon climate, especially rainfall and temperature, and upon the soil which is derived from the weathered rock forming the topography. Vegetation in its turn influences the soil through the action of roots, take-up of nutrients, and provision of organic matter, furthermore protecting soil from erosion. The importance of this feedback is more obvious when the vegetation cover is inadequate to protect the soil, since eroded soil is not able to support a close vegetation cover. The operation of the factors which influence erosion is most readily seen in their effect upon the disposition of storm rainfall. Comparing a high runoff from an eroded catchment and a well-vegetated catchment with a permeable soil, the second will experience higher infiltration, lower surface runoff, and less surface erosion.

Climate factors

The major climatic factors which influence runoff and erosion are: precipitation, temperature, and wind, among them precipitation is significantly the most important. Temperature affects runoff particularly in three ways: changing soil moisture; determining whether the precipitation will be in the form of rain or snow; and changing the absorptive properties of the soil by causing the soil to freeze. The wind (eolian erosion) effect includes: the power to pick up and carry fine soil particles, the influence it exerts on the angle and impact of raindrops, and more rarely its effect on vegetation (i.e. wind-throw of trees).

Precipitation, causing raindrop erosion is recognized as being responsible for four effects: desegregation of soil aggregates as a result of impact, minor lateral displacement of soil particles (creep), splashing of soil particles into the air (saltation), selection or sorting of soil particles by raindrop impact. Detachment of individual soil particles may occur when raindrops strike the surface (Figure 6.81) and overcome the interstitial forces holding the soil particle together. This is commonly referred as “rainsplash” or “raindrop splash” (Thornes, 1990). As the inducing events continue, water infiltrates into the soil at a rate controlled by the intensity of the water hitting the surface and the infiltration capacity of the vertical soil profile. The infiltration capacity is a function of soil characteristics as well as other micro-surface and subsurface characteristics (Saavedra, 2005). Water that does not infiltrate begins to pond on the surface and when a certain depth is achieved on the surface it starts flowing in the direction of the steepest unimpeded slope. This action initiates the hydrological process referred as “overland flow” or “runoff”. Figure 6.81 shows how soil particles may be dissolved or suspended in the overland flow, callusing the process of sediment entrainment or transport.

![Figure 6.81: Raindrop falling on exposed soil and breaking soil particle to be lost in runoff water: a) raindrop velocity, b) raindrop impact (Julien, 1995).](image)

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Soil feature factor

The soil factor is expressed by the erodibility of the soil. Erodibility, unlike the determination of erosivity of rainfall, is difficult to measure and no universal method of measurement has been developed. The main reason for this deficiency is related to two aspects: those which are the actual physical features of the soil; and those which are the result of human use of the soil. The resistance of soil to detachment by raindrop impact depends upon its shear strength (cohesion – c) and angle of friction. Bouyoucos (1936) suggested that erodibility is related to the sizes of soil particles in the following ratio:

\[
\frac{(%\text{sand} + %\text{silt})}{%\text{clay}}
\]

Geological factor

This factor is evident in the steepness and length of slopes. Raindrop splash will move material further in down steep slopes than in down gentle ones, in the first there is more runoff and its also faster. Because of this combination of factors the amount of erosion is not just proportional to the steepness of the slope, but rises rapidly with increasing angle. Mathematically the relationship is:

\[ E = \mu S^a \]

Where: E is the erosion, S the slope in percent, and a is an exponent. Experimental values for a range from 1.35 to 2.

The length of slope has a similar effect upon soil loss, because on a long slope there can be a greater depth and velocity of overland flow, and rills can develop more readily than on short slopes. The relationship between soil loss and slope length may be expressed as:

\[ E = \mu L^b \]

Where: E is the soil loss per unit area, L is the length of slope, and b is an exponent. Experimental values for b are around 0.6 (Zingg, 1940).

Biological factor

Vegetation compensates the effects on erosion of the other factors: climate, topography, and soil characteristics. The major effects of vegetation fall into at least seven main categories: the interception of rainfall by the vegetation canopy; the decreasing of velocity of runoff, and hence the cutting action of water and its capacity to entrain sediment; root effects in increasing soil strength, granulation, and porosity; biological activities associated with vegetative growth and their influence on soil porosity; the transpiration of water, leading to the subsequent drying out of the soil; insulation of the soil against high and low temperatures; compaction of underlying soil.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
6.2.3. Types of erosion

Soil erosion occurs in various forms (e.g. splash, sheet, rill, gullies) depending on the stage of progress in the erosion cycle and the position in the landscape. Sometimes the term referring to erosion indicates where it occurs (e.g. trail erosion, riverbed erosion, slope erosion, cropland erosion).

Soil erosion can be divided into two general categories: geological erosion and accelerated erosion (http://agen521.www.ecn.purdue.edu/AGEN521/epadir/erosion/types_erosion.html).

Geological erosion

Geological or “natural” erosion occurs where soil is in its natural environment surrounded by its natural vegetation. It can be defined as the action of wind, water, ice and gravity in wearing away rock to form soil and shape the ground surface. Except for some stream and shore erosion, it is a relatively slow, continuous process that often goes unnoticed. This has been taking place naturally for millions of years and has helped to create balance in uncultivated soil that enables plant growth. A classical example of the results of geological erosion is the Grand Canyon.

Accelerated erosion

Accelerated erosion is the speeding up of erosion due to human activity. The principal causes for accelerated erosion caused by man’s activities are: agriculture, construction, farming, logging and mining. These activities radically alter the natural state of the environment breaking the delicate balance that nature has developed between rainfall and runoff. It is mainly caused by the destruction of natural vegetation cover that greatly increase the rate of erosion. Fortunately, accelerated erosion can be minimized through careful planning and by implementing appropriate control measures.

Accelerated erosion includes such problems as wind erosion and water erosion caused by rain and poor drainage. This type of erosion can be divided into three main classes according to the physical characteristics of erosion: sheet erosion, rill erosion and gully erosion (http://faculty.plattsburgh.edu/robert.fuller/370%20Files/Weeks11Erosion/Types.htm).

*Sheet erosion:* it is also called sheet wash and is defined as the uniform removal of soil in thin layers of earth-surface material, more or less evenly, from extended areas of gently sloping land by broad continuous sheets of running water, without the formation of rills, gullies, or other channelized flow. Loose soil merely runs off with the rain. The process of sheet erosion is gradual, and difficult to detect until it develops into rill erosion. The potential for sheet erosion depends on the soil type, velocity, and quantity of flow over the surface. Long slopes, steep slopes, and slopes that carry higher volumes of runoff are more susceptible to sheet erosion.

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**Rill erosion**: is the most common form of erosion. Although its effects can be easily removed by tillage. It occurs when soil is removed by water (runoff) from little streamlets (small concentrated channels) that run through land with poor surface draining. As rill erosion begins, erosion rates increase dramatically due to the resulting concentrated higher velocity flows. Rills can often be found in between crop rows as tiny gullies.

**Gully erosion**: is an exaggerated type of rill erosion. Gully erosion results from water moving in rills at increased velocity and volume. It concentrates to form larger, deeper and wider channels, as a result, gullies being larger than rills cannot be fixed by tillage and erodes quickly into large gullies. Gully erosion is an advanced stage of rill erosion, just as rills are often the result of sheet erosion. It can be prevented by quickly repairing rill erosion and addressing the cause of the rill erosion.

As indicating in Figure 6.82, the rill and inter-rill areas and gullies are the source areas for water erosion. Eventually, if sufficient water continues to follow downslope, it will reach well-defined channels, through which both water and sediment will be carried downstream towards the catchment outlet (Nichols and Rennard, 1999).

![Figure 6.82: Erosion and transport on inter-rill and rill areas (Harmon and Doe, 2001)](image)

Other types of erosion referring to water are: splash erosion and stream channel erosion (http://www.answers.com/topic/erosion):

**Splash erosion**: is the result and effect of the energy of falling raindrops. Raindrops typically fall with a velocity of 600-900 cm/s. The energy of these impacts is sufficient to displace soil particles as high as two feet vertically. In addition, the impact of a rainfall on a bare soil can compact the upper layer of soil, creating a hard crust that inhibits plant establishment.

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Stream channel erosion: consists of both stream bed and stream bank erosion. Stream bed erosion occurs as flows cut into the bottom of the channel, making it deeper. This erosion process will continue until the channel reaches a stable slope. The resulting slope is dependant on the channel materials and flow properties. As the stream bed erodes, and the channel deepens, the sides of the channel become unstable and slough off; resulting in stream bank erosion. One significant cause of both stream bed and stream bank erosion is due to the increased frequency and duration of runoff events that are a result of urban development.

Figure 6.83 schematize all these types of erosion.

![Figure 6.83: Different types of erosions.](image)

Erosion is a big problem not only for the inherent stability of soils and protection of land, but it also has other effects related to the detachment of soil particles, the main problems are:

- Eroded sediment (already detached from topsoil) acts as both a physical and chemical pollutant carrying along with it all compounds and elements characterizing the previous terrain from which it was detached.
- When soil particles end up in water bodies this cause physical problems by increasing turbidity which limits sunlight penetration causing changes in water temperature and disturbing and altering fish habitat and spawning patterns.
- Chemically, soil particles transport nutrients such as phosphorus and nitrogen, heavy metals that are an important source for water quality degradation.

Summarizing it is possible to say that erosion is present almost everywhere caused by natural phenomenon or by anthropogenic activities. It is affected by a series of factors previously described. There are different types of erosion and each one of them is related to a level (low, moderate, severe) according to the form in which it develops. Erosion is a serious problem which should be carefully handled due to the effects and consequences that characterize this event. For this reason there exist several tools, basically models, that helps in some degree to prognosticate and prevent soil erosion. Some of the most important erosion models will be mentioned in the next section and those selected for erosion analysis of the two study areas will be described in detail.
6.2.4. Erosion models

Erosion modeling is based on an understanding of the physical laws and landscape processes such as runoff and soil formation occurring in the natural environment. Modeling translates these components into mathematical relationships, describing the fundamental erosion processes of detachment, transport and deposition (Jetten et al., 2003).

Models fall into three main categories, depending on the physical processes simulated, the model algorithms describing these processes, and the data dependency of the model. Table 6.25 summarize the most important erosion and sediment transport models existing nowadays (Saavedra, 2005). The three main categories of models are: empirical, conceptual and physically based modes. The mentioned classes will be briefly described to have an idea of the main principles of each one of them.

Empirical models

Empirical models are generally the simplest of the three model types. They are based primarily on the analysis of field experiments trying to characterize the response from these erosion plots using statistical inference. The computational and data requirements for such models are usually less than for conceptual and physically based models (Li et al., 1996). Usually, these models have a high spatial and temporal aggregation and are based on the analysis of erosion processes using statistical techniques. They are particularly useful as a first step tool for identifying the sources of sediments (Saavedra, 2005).

Nevertheless, empirical models are often criticized for employing unrealistic assumptions about the physics of the catchment system; for ignoring the heterogeneity of catchment inputs and characteristics, such as rainfall and oil types; and for ignoring inherent nonlinearities in a catchment system (Foster, 1996). Even if these criticisms are valid, sometimes the insufficient meteorological networks and data as well as the spatial heterogeneity of soil restrict the use of more efficient models. An empirical model generally base its assumptions in stationarity concepts which neglects this model from predicting the effects of catchment change. However, empirical models are frequently used since they can be implemented in a situation of limited data and input parameters which is normally the case.

Conceptual models

These models are somewhere between empirical and physically based models. Conceptual models succeed to reflect the physical processes governing the system but describe them with empirical relationships. These models are typically based on the representation of a catchment as a series of internal and often linear storages (Sivapalan et al., 2002). They usually incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure. Conceptual models tend to include a general description of catchment processes, without including the specific details occurring in the complex process of interactions. This characteristic allows these models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data. Traditionally, conceptual models lump representative processes over the scale at which outputs are simulated (Arnold, 1996). However, recently developed conceptual models have provided outputs in a spatially distributed manner.
Parameters values for conceptual models are typically obtained through calibration against observed data, such as stream discharge and sediment concentration measurements (Doe et al., 1996; de Jong et al., 1999; Zhou and Liu, 2002). Since parameters values are determined through calibration against observed data, it is often difficult to identify these values; although, as mentioned before, conceptual models play an intermediate role between empirical and physically based models. Even if these models tend to be aggregated, they still reflect the hypothesis about the processes governing systems behavior. This is the main difference between conceptual models and empirical models, since empirical models make no inferences as to the processes at work; instead they rely on observed or statistical relationships between the causal variables and model output (Saavedra, 2005).

**Physically based models**

These models are based on an understanding of the physics of the erosion and sediment transport processes and describe the sediment system using equations governing the transfer of mass, momentum and energy (Doe et al., 1999; Kandel et al., 2004). In principle they can be applied outside the range of conditions used for calibration and, as their parameters have a physical meaning, they can be evaluated from direct measurements and without the need for long hydro-meteorological records (Smith et al., 1995). They are limited only by the relevance of the physical laws on which they are based. Physically based models computes erosion using mathematical representation of fundamental hydrological and erosion processes (i.e. detachment by raindrop impact or by overland flow).

Some examples of physically based models are Aerial Non Point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1989), Water Erosion Prediction Project (WEPP) (Nearing et al., 1989) and more recently the Soil and Water Assessment Tool (SWAT) (Arnold and Fohrer, 2005). Equations in these models are formulated to be used with continuous spatial and temporal data, yet the data used in practice represents point source data. In principle these models are able to simulate the full erosion and sediment yield regime, providing multiple outputs on a spatially distributed basis (Pullar and Springer, 2000). The main advantages of physical based models relies on their relatively transferability, which facilitates predicting soil erosion and sediment yield under different climate and physiographic land use scenarios and their ability to consider environmental issues such as climate change (Banis et al., 2004).

The following table contains a compilation of the most important erosion models representing the three categories described above. Most of the nominated models are a combination of two of the previous models, thus giving a better and more reliable approach to erosion processes and representing as much as possible all characteristics of the system and the problem itself.
Table 6.25: Erosion and sediment transport models (adapted from Merrit et al., 2003 and Saavedra, 2005).

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Spatial scale</th>
<th>Temporal scale</th>
<th>Input requirements</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGNPS</td>
<td>Conceptual</td>
<td>Small catchment</td>
<td>Event continuous</td>
<td>High</td>
<td>Runoff, peak rate, erosion, sediment yield</td>
</tr>
<tr>
<td>ANSWERS</td>
<td>Physical</td>
<td>Small catchment</td>
<td>Event continuous</td>
<td>High</td>
<td>Runoff, peak rate, erosion, sediment yield</td>
</tr>
<tr>
<td>CREAMS</td>
<td>Physical</td>
<td>Pointfield</td>
<td>Event continuous</td>
<td>High</td>
<td>Erosion, deposition</td>
</tr>
<tr>
<td>EMSS</td>
<td>Conceptual</td>
<td>Catchment</td>
<td>Continuous</td>
<td>Low</td>
<td>Runoff, sediment loads</td>
</tr>
<tr>
<td>HSPP</td>
<td>Conceptual</td>
<td>Catchment</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, flow rate, sediment load</td>
</tr>
<tr>
<td>IHACRES-WQ</td>
<td>Empirical/</td>
<td>Catchment</td>
<td>Continuous</td>
<td>Low</td>
<td>Runoff, sediment</td>
</tr>
<tr>
<td>IHACRES-WQ</td>
<td>Conceptual</td>
<td>Catchment</td>
<td>Continuous</td>
<td>Moderate</td>
<td>Sediment, sediment load</td>
</tr>
<tr>
<td>LASCAM</td>
<td>Conceptual</td>
<td>Catchment basin</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, sediment</td>
</tr>
<tr>
<td>SWAT</td>
<td>Conceptual</td>
<td>Catchment basin</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, peak rate, erosion, sediment yield</td>
</tr>
<tr>
<td>AGWA</td>
<td>Conceptual/physical</td>
<td>Catchment basin</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, peak rate, erosion, sediment yield</td>
</tr>
<tr>
<td>QUEST</td>
<td>Physical</td>
<td>Plot/field</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, sediment concentration</td>
</tr>
<tr>
<td>MINEROS2</td>
<td>Physical</td>
<td>Hillslope/small</td>
<td>Event</td>
<td>High</td>
<td>Runoff, peak rate, erosion, sediment yield</td>
</tr>
<tr>
<td>LISIM</td>
<td>Physical</td>
<td>Small catchment</td>
<td>Event</td>
<td>High</td>
<td>Runoff, sediment</td>
</tr>
<tr>
<td>EUROSEM</td>
<td>Physical</td>
<td>Small catchment</td>
<td>Event</td>
<td>High</td>
<td>Runoff, erosion, sediment</td>
</tr>
<tr>
<td>PERFECT</td>
<td>Physical</td>
<td>Plot/field</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, erosion</td>
</tr>
<tr>
<td>SEDNET</td>
<td>Conceptual/empirical</td>
<td>Catchment basin</td>
<td>Annual</td>
<td>High</td>
<td>Suspended sediment, relative contributions from overland flow, gully and bank erosion processes</td>
</tr>
<tr>
<td>TOPOG</td>
<td>Physical</td>
<td>Hillslope</td>
<td>Continuous</td>
<td>High</td>
<td>Erosion hazard</td>
</tr>
<tr>
<td>RUSLE</td>
<td>Empirical</td>
<td>Hillslope</td>
<td>Annual</td>
<td>High</td>
<td>Erosion</td>
</tr>
<tr>
<td>RUSLE-JD</td>
<td>Empirical/Conceptual</td>
<td>Catchment</td>
<td>Annual</td>
<td>Moderate</td>
<td>Erosion</td>
</tr>
<tr>
<td>USPED</td>
<td>Empirical/Conceptual</td>
<td>Catchment</td>
<td>Event/Annual</td>
<td>Moderate</td>
<td>Erosion deposition</td>
</tr>
<tr>
<td>EROSION-JD</td>
<td>Physical</td>
<td>Catchment</td>
<td>Event</td>
<td>High</td>
<td>Runoff, erosion, sediment</td>
</tr>
<tr>
<td>NMMF</td>
<td>Empirical/Conceptual</td>
<td>Hillslope/catchment</td>
<td>Annual</td>
<td>Moderate</td>
<td>Runoff, erosion</td>
</tr>
<tr>
<td>THORNES</td>
<td>Conceptual/empirical</td>
<td>Hillslope/catchment</td>
<td>Annual</td>
<td>Moderate</td>
<td>Runoff, erosion</td>
</tr>
<tr>
<td>EPIC</td>
<td>Physical</td>
<td>Hillslope/catchment</td>
<td>Continuous</td>
<td>High</td>
<td>Erosion</td>
</tr>
<tr>
<td>WATEM</td>
<td>Conceptual</td>
<td>Catchment</td>
<td>Annual</td>
<td>Moderate</td>
<td>Erosion</td>
</tr>
<tr>
<td>WEPPE</td>
<td>Physical</td>
<td>Hillslope/catchment</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, sediment yield, soil loss</td>
</tr>
<tr>
<td>MULE-II</td>
<td>Physical</td>
<td>Catchment</td>
<td>Continuous</td>
<td>High</td>
<td>Sediment yield, runoff</td>
</tr>
<tr>
<td>SBEYIANN</td>
<td>Physical</td>
<td>Catchment</td>
<td>Event</td>
<td>High</td>
<td>Runoff, peak rate, sediment yield, sediment</td>
</tr>
<tr>
<td>SEAGIS</td>
<td>Empirical/Conceptual</td>
<td>Catchment</td>
<td>Annual</td>
<td>High</td>
<td>Erosion, sediment yield</td>
</tr>
<tr>
<td>PESERA</td>
<td>Physical</td>
<td>Hillslope/Regional</td>
<td>Continuous</td>
<td>High</td>
<td>Runoff, erosion, sediments</td>
</tr>
<tr>
<td>SPI</td>
<td>Empirical/Conceptual</td>
<td>Catchment/river</td>
<td>Annual</td>
<td>Moderate</td>
<td>Fluvial erosion, river incision</td>
</tr>
</tbody>
</table>

As it is possible to see from Table 6.25 there are various models that have been formulated and currently used by scientists and land planners to model and somehow predict the complex process of erosion. From these models, RUSLE 3D and USPED were the ones selected, being them the most appropriate ones taking into consideration some of the limitations encountered (i.e. rainfall missing data and not uniform series for all meteorological stations, DEM resolution) for erosion calculation in both study areas. These models were applied for further erosion analysis and elaboration of erosion risk maps of Santos and Bahia Blanca.
6.3. Selected models for calculating soil erosion

Generally speaking it is possible to say that models are acceptable if they meet their objectives or design requirements. The effectiveness and the availability of data are the main guiding principles when selecting a model. For example, physically based models are more appropriate at small catchment scales; however they are difficult to use regionally as they are usually high data demanding, hence a combination of empirical and conceptual models are more commonly used. The range of complexity between the three types (empirical, conceptual and physical) of models is similar with respect to the resource base needed to support the model development, calibration, validation and operation. More difficult constraints face the modeler regarding the location or area where a model will be applied. It is evident that the selection of an appropriate model involves a number of trade-offs, specially referring to existing data and its availability, thus, is this last factor the ultimately defining which type of model can be selected.

Considering the restrictions mentioned regarding quality (i.e. scale) and availability of data two models were selected: RUSLE 3D and USPED. The models selected will be explained in the following section.

6.3.1. RUSLE model

As mentioned before and as Table 6.25 puts into evidence, nowadays there are several erosion models that have been developed to predict soil erosion on drainage basins. From the long list of erosion models broadly applied all over the world, the Universal Soil Loss Equation (USLE) and its variations and improvements as Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) are the most widely used empirical equations for estimating annual soil loss specially in agricultural basins but not only. The USLE and consequently the RUSLE model was developed for sheet and rill erosion based on a large set (i.e. plots-years) of data collected from natural agricultural runoff plots, for this reason it does not account for additional soil losses that might occur from gully, wind or tillage erosion. Although RUSLE was originally developed for agricultural purpose its use has been extended to watersheds with other land uses (http://skagit.meas.ncsu.edu/~helena/gmslab/report/CerlErosionTutorial).

Revisions to the universal soil loss equation implemented in the mid 1990s resulted in a more accurately model to predict soil erosion caused by water, the RUSLE. It predicts the long term average annual rate of erosion on a field slope based on the same previous factors considered by USLE: rainfall pattern, soil type, topography, crop system and management practices, but it takes advantage of new knowledge about these relationships and the capabilities of computer technology. Some of the improvements applied to RUSLE include: new and revised iso-erodent maps; a time-varying approach for soil erodibility factor; a subfactor approach for evaluating the cover-management factor; a new equation to reflect slope length and steepness; and new conservation-practice values (Renard et al., 1997).

Five major factors are used to calculate soil loss of a given site. Each factor is the numerical estimate of a specific condition that affects the severity of soil erosion at a particular location. The erosion values reflected by these factors can fluctuate considerably due to varying weather conditions. Both RUSLE and USLE soil loss equation can be expressed as follows:
A = R * K * LS * C * P

Where:

A = estimated average soilloss (ton ha\(^{-1}\) yr\(^{-1}\));
R = rainfall-runoff erosivity factor (MJ mm ha\(^{-1}\)h\(^{-1}\));
K = soil erodibility factor (ton ha h MJ\(^{-1}\) mm\(^{-1}\) ha\(^{-1}\));
L = slope length factor;
S = slope steepness factor;
C = cover-management factor;
P = support practice factor.

R factor

R is the rainfall-runoff erosivity factor by geographic location. It is the average annual summation (EI) values in a normal year's rain. Storm losses from rainfall are directly proportional to the product of the total kinetic energy of the storm (E) times its maximum 30-minute intensity (I) (Weischmeier and Smith, 1978). Simplifying, R is an indication of the two most important characteristics of a storm determining its erosivity: amount of rainfall (E) and peak intensity sustained over an extended period (I). The greater the intensity and duration of the rain storm, the higher the erosion potential. The erosivity of rainfall varies greatly by location according to its intrinsic climatic characteristics.

R factor is usually calculated by the following formula:

\[
R = \frac{\sum_{i=1}^{N} (EI_{30})}{N}
\]

Where:

E = total storm kinetic energy (MJ ha\(^{-1}\)mm\(^{-1}\))
I\(_{30}\) = maximum 30 min rainfall intensity (mm h\(^{-1}\))
i = index of number of years used to produce the average
j = index of number of storms in a year
N = number of years used to obtain R (22 years minimum preferred)
R = average annual rainfall erosivity

R requires continuous rainfall intensity data at a time interval equal to or less than 30 minutes (Yu et al., 2000). It is not always possible to obtain such a complete precipitation database, therefore, other forms for estimating R factor should be considered. In cases where data is limited and only totals of annual precipitation are available, the Renard and Freimund (1994) equations are the most suitable considering the lack of data. They evaluated 155 locations within USA and developed statistical relationships between the R factor and the total annual precipitation at the location together with a modified Fournier coefficient, F (Fournier, 1960). Thus expressing monthly rainfall amounts as:
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\[
F = \frac{\sum_{i=1}^{12} P_i^2}{P_a}
\]

Where:
\(P_i\) = is the average monthly precipitation (mm)
\(P_a\) = is the average annual precipitation (mm)

The new equations proposed for calculation of \(R\) factor according to Renard and Freimund (1994) were:

\[
R = 0.0483 P_a^{1.610} \tag{1}
\]

\[
R = 587.8 - 1.249 P_a + 0.004105 P_a^2 \tag{2}
\]

\(R\) in this case is also given in MJ mm ha\(^{-1}\)h\(^{-1}\). An important consideration when choosing the equation to represent the \(R\) factor is the amount of annual precipitation, thus, if \(P_a \leq 850\) mm equation 1 is selected, otherwise if \(P_a > 850\) mm equation 2 is the best option.

**K factor**

\(K\) is the soil erodibility factor which represents both a measure of the susceptibility of soil particles to detachment (to erode) and rate of transport by rainfall and runoff. This soil erodibility factor is a quantitative value which is experimentally determined taking into consideration the soil texture, soil structure, the organic matter content and the permeability (Wischmeier, 1971). Some characteristic values for \(K\) factors according to soil texture are shown in Table 6.26.

<table>
<thead>
<tr>
<th>Type of soils</th>
<th>(K) factor Characteristics of these soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>High in clay content</td>
<td>0.05 – 0.15 Resistant to detachment.</td>
</tr>
<tr>
<td>Coarse textured soils – sandy soils</td>
<td>0.05 – 0.2 Low runoff (easily detached).</td>
</tr>
<tr>
<td>Medium textured soils – silt loam soils</td>
<td>0.25 – 0.4 Moderately susceptible to detachment producing moderate runoff.</td>
</tr>
<tr>
<td>High silt content</td>
<td>&gt; 0.4 Most erodible of all soils. Easily detached, tend to crust and produce high rates of runoff.</td>
</tr>
</tbody>
</table>

Organic matter reduces erodibility because it reduces the susceptibility of the soil to detachment, and it increases infiltration, which reduce runoff and thus erosion. Addition or accumulation of increased organic matter through management such as incorporation of manure is represented in the \(C\) factor rather than the \(K\) factor.

Table 6.26: Some \(K\) factor values for common type of soils.
(Source: http://www.iwr.msu.edu/rusle/kfactor)
LS factor

LS is the slope length-gradient factor. The LS factor represents a ratio of soil loss under given conditions to that at a site with the "standard" slope steepness of 9% and slope length of 22.1-m. The steeper and longer the slope, the higher is the erosion risk. L factor and S factor are usually considered together. The slope length factor L computes the effect of slope length on erosion and the slope steepness factor S computes the effect of slope steepness on erosion.

Mitasova et al. (1996) aiming to incorporate the impact of flow convergence proposed the replacement of the slope-length factor (LS(r)) by the upslope contributing area per unit of contour width in the RUSLE-3D. The modified LS(r) factor at a point on a hillslope is:

\[ LS(r) = (m + 1) \left( \frac{A(r)}{22.13} \right)^m \times \left( \frac{\sin \beta(r)}{0.09} \right)^n \]

Where:
- \( A(r) \) is the upslope contributing area per unit of width (m²)
- \( \beta(r) \) is the steepest slope angle (degree)
- \( m, n \) are parameters depending on the type of flow

C factor

C is the vegetation cover and crop management factor or the ratio of soil loss from an area with specified cover and management to soil loss from an identical area under continuous tilled fallow. It is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss (Renard et al., 1997). The C factor can be determined by selecting the crop type and tillage method. C factor represents the effects of plants, soil cover, soil biomass, and soil disturbing activities on erosion.

P factor

P, the support practice factor, represents the effect of contouring and tillage practices on soil erosion. It reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. Wischmeier and Smith (1978) define P as the ratio of soil loss with contouring and/or strip-cropping to that with straight row farming up-and-down slope. The lower the P value, the more effective the conservation practice is deemed to be at reducing soil erosion. As with the other factors, the P-factor differentiates between cropland and rangeland or permanent pasture.

The methodology applied and results obtained as part of each one of the erosion factors previously described will be explained in the next sections. Some variations were applied for factor calculation, taking into consideration specific characteristics of the study areas and limitation on data availability.

Use of RUSLE is limited to estimating gross erosion and the model lacks the capability to compute deposition along hillslopes, depressions, valleys, or in channels; for this reason and considering that this aspect is also an important factor to take into consideration when analyzing soil loss processes another model was selected to cover this lack of RUSLE model.

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6.3.2. USPED model

Other widely used model is the Unit Stream Power Erosion Deposition model (USPED) that calculates soil particles deposition besides soil erosion, therefore a complement for erosion calculations. The USPED allow the identification of sediments sinks which is an important and useful factor so to correlate quantity of sediments being eroded and quantity of sediments being deposited and where. The application of USPED model gave an idea of sediments final destination, if it is mainly on land or water (estuary). This consideration is an important assessment for land and water resource management.

The USPED model is multidimensional, applicable to complex topography, and replaces the traditional slope, length and steepness factor with a physically based analogy that incorporates the processes of soil detachment and sediment transport.

According to Mitasova (1999), an additional benefit of the USPED is that it can predict the spatial distribution of erosion, as well as deposition rates for a steady-state overland flow with uniform rainfall excess conditions. Hence, this model is also applicable to a complex terrain where erosion is limited by the ability of runoff to transport sediment. USPED uses a dimensionless index of sediment transport capacity \( T(e) \) and a topographical index \( E_d \), representing the change in transport capacity in the flow direction, to estimate the spatial distribution of both erosion and deposition. The parameter \( T(e) \) is derived from the unit stream power theory. The upslope contributing area is used as a proxy for water flux at a given location or grid cell. The index \( E_d \) is positive for areas with topographical potential for deposition and negative for areas with erosion potential. The sediment flow rate \( q_s(r) \) at the sediment transport capacity \( T(e) \) (Julien and Simmons, 1985) is described by:

\[
|q_s(r)| = T(e) = K_d(e) \times |q(r)|^m \times (\sin \beta_0)^n
\]

where \( q(r) \) is the water flow rate, \( K_d(e) \) is the soil transportability coefficient, and \( m \) and \( n \) are constants depending on the type of flow and soil properties. Within the 2D flow formulation, water and sediment flow are represented as bivariate vector fields \( q(r) = q(x,y) \), \( q_s(r) = q_s(x,y) \) and net erosion and deposition rate \( D(e) \) is estimated as the divergence of the sediment flow (Mitas and Mitasova, 1998):

\[
D(e) = \nabla \times q_s(r) = \nabla \times [T(e) \times s_r] = K_{pr} \times i_e \times \left\{ [\nabla \times A \times s_r \times \sin \beta_0 \times A_r \times k_{pr} \times k_{pr} \right\}
\]

where \( s_r \) is the unit vector in the steepest slope direction, \( i_e \) [m] is the uniform rainfall intensity, \( k_{pr} \) is the profile curvature or curvature in the direction of the steepest slope, and \( k_{pr} \) is the tangential curvature or curvature in the direction perpendicular to the gradient. As yet, insufficient experimental work has been performed to develop the parameters needed for USPED; therefore, Mitasova (1997) used the RUSLE parameters to incorporate the approximate impact of soil and cover and obtained a relative estimate of net erosion-deposition. It is assumed that the sediment flow at sediment transport capacity can be estimated as:

\[
T_{se} = R \times C \times P \times A_{se} \times (\sin \beta_0)^n
\]

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where \( R = m \cdot K \cdot C \cdot P \cdot e^{K(r)} \); \( LS(t) = A_{L \cdot m} \cdot \sin \beta(t)^n \); and \( m=1.6, n=1.3 \) for prevailing rill erosion. For prevailing sheet erosion, \( m=n=1 \). Then net erosion-deposition \( E_d \) is estimated as a change in sediment flow rate expressed by a divergence in sediment flow:

\[
E_d = \text{div}(T, x) + \text{div}(T, y) = \frac{\partial(T, x \cdot \cos \alpha)}{\partial x} + \frac{\partial(T, y \cdot \sin \alpha)}{\partial y}
\]

where \( \alpha \) [degree] is the aspect of the elevation surface or direction of flow minus gradient direction.

All these complex calculations were tremendously facilitated by the use of ArcMap Spatial Analyst module and Raster Calculator operator. The methodology followed to calculate erosion/deposition by the application of USPED model in ArcMap 9.0 will be explained in the next sections.

### 6.4. Integration of remote sensing and GIS techniques for erosion calculation

#### 6.4.1. GIS and remote sensing facilities

Erosion calculation requires huge amount of information and data, usually coming from different sources and available in different formats and scales, therefore the use of GIS considerable simplify the organization of all data and also the application of complex formulas representing the effects of each one of the factors affecting erosion. The factors that most influence soil erosion are linked to topography, vegetation type, soil properties and land use as seen in Figure 6.84.

Usually when applying GIS and remote sensing techniques these factors are represented as different images and map. For example vegetation cover is represented by landcover maps obtained from satellite image processing (supervised classification). The main source of information for the different factors were:

- for \( C \) and \( P \) factors (representing landcover and landuse of the area) classified Landsat images;
- for the LS factor derivations from the DEM;
- for \( R \) and \( K \) factors pluviometric and pedologic maps respectively

It is a great advantage to use this kind of sources since the maps produced can be easily integrated on GIS. A detailed explanation of how each one of the erosive factors maps were calculated will be given in the next section.

GIS has tremendously helped with the integration of data and its sistematic application. GIS is thus an important tool for coping with the vast number of spatial data and the relation between data from various sources in the erosion modelling process (Saavedra, 2005). The main advantages of linking soil erosion models with a GIS can be summarized in:

- The possibility of rapidly processing input data to simulate different scenarios. GIS provides an important spatial and analytical function which performs the time-consuming process of georeferencing and spatial overlays at different scales (Schoorl, 2002; Shi et al., 2004; Zhang et al., 2002), which greatly facilitates analysis.

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The ability to look at spatial variation: thus areas can be simulated at a user-defined resolution (Xia and Clarke, 1997; Qinke et al., 2002) according to the modeller requirements.

The facility to display the model outputs (i.e. visualization) as maps which improves its understanding and analysis from all external perspectives (Mitasa, 1996)

Determining erosion at larger scales, for example at a watershed scale, like in Santos and Bahia Blanca, put more emphasis on topography, soil and vegetation patterns, while at smaller scales timing and volume of overland flow are more important (Saavedra, 2005). Remote sensing and GIS techniques become valuable tools specially when assessing erosion at larger scales due to the amount of information needed and the great area covered. For this reason use of these techniques have been widely spread and currently there are several studies that show the potential of remote sensing techniques integrated with GIS in soil erosion mapping (Pilesjo, 1992; Metternicht and Fermont, 1998; Reusing et al., 2000; Haboudane et al., 2002; Metternicht and Gonzalez, 2005).

Erosion analysis were performed using ArcMap and GRASS facilities applying specific adaptations of RUSLE and USPED models for GIS, which enormously facilitated the calculations related with the two selected models.

![Diagram of RUSLE factors through GIS](Figure 6.84: Application of RUSLE factors through GIS. (Modified from Moraes, et.al., 2005))
6.4.2. Methodology applied for calculating erosion factors and their map representation using RUSLE

Within a raster based ArcMap GIS software package, the RUSLE 3D model was applied to calculate erosion risk maps. The different factors (R, K, LS, C, and P) needed for RUSLE calculations were adapted to ArcMap 9.0 according to Mitas and Mitasova (1998). The methodology applied for erosive factors calculation and the output (maps) obtained for each one of them will be described in this section. The same calculations and processes were applied for both study areas. Some of the processes were slightly modified according to the inherent characteristics of both study areas and taking into consideration the lack of data specially for rainfall and soil texture.

R factor

In the case of Bahia Bianca and Santos, there were few information available regarding complete rainfall data, often long series of missing data were found in various years and a complete set of 22 years as proposed by Weischmeier and Smith (1978) was not possible. Nevertheless, Reinard and Freimund (1994) equations proposed for estimations of R factor from limited data were applied since they make reference to total annual precipitations instead of a long series of monthly data.

Bahia Bianca and Santos are characterized by important rainfall events, however rainfall distribution is not homogeneous all over the area, for this reason an interpolation of the annual precipitation data available from the different meteorological stations in the zone was applied to have a more representative rainfall distribution all over the area. For Santos, 4 meteorological stations were considered in the calculations (Table 6.27), two of them (Cubatão and Caete) strictly inside the study area. Unfortunately, in order to have a uniform annual precipitation file for all four stations, data was limited to the one with fewer data, Cubatão, from which only rainfall between 2003-2005 was available. This fact tremendously restricted the calculations, however to include this station located in the study area and representing its rainfall tendency, was highly recommended. For Bahia Bianca three meteorological stations were taken into consideration (Table 6.27), two of them strictly in the study area (Rosales and Aerodromo) and a uniform annual precipitation file was available from 1999 until 2006.

In order to have a map representing the precipitation tendency of all the study area an interpolation of data was necessary. The “v.surf.idw” module from GRASS was applied to perform a surface interpolation of the precipitation data available for both study areas based on Inverse Distance Squared Weighting techniques. This operator fills a raster matrix with interpolated values generated from a set of irregularly spaced data points using numerical approximation (weighted averaging) techniques. The interpolate value of a cell is determined by values of nearby data points and the distance of the cell from those input points (http://grass.itc.it/grass60/manuals/html60_user/v.surf.idw.html). In comparison with other methods, numerical approximation allows representation of more complex surfaces (particularly those with anomalous features), restricts the spatial influence of any errors, and generates the interpolated surface from the data points. This program was very useful considering that the input file can be a vector point map (Table 6.27). Another advantage of
this program is that it considers all the stations for the calculation even if they are not strictly inside the study area.

**Table 6.27:** Meteorological stations of Santos and Bahia Blanca considering for annual precipitation R factor calculations.

<table>
<thead>
<tr>
<th>Name of meteorological station</th>
<th>UTM E</th>
<th>UTM N</th>
<th>Elevation (m)</th>
<th>Total average annual precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Santos</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cubatão</td>
<td>355770</td>
<td>7357968</td>
<td>6</td>
<td>1796</td>
</tr>
<tr>
<td>Caete</td>
<td>376134</td>
<td>7358157</td>
<td>200</td>
<td>3014</td>
</tr>
<tr>
<td>Usina</td>
<td>386214</td>
<td>7371159</td>
<td>10</td>
<td>2712</td>
</tr>
<tr>
<td>Represa</td>
<td>324998</td>
<td>7376087</td>
<td>816</td>
<td>3600</td>
</tr>
<tr>
<td><strong>Bahia Blanca</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rosales</td>
<td>585823</td>
<td>5691635</td>
<td>40</td>
<td>382.8</td>
</tr>
<tr>
<td>Bordenave</td>
<td>498044.94</td>
<td>5810981.45</td>
<td>212</td>
<td>594.9</td>
</tr>
<tr>
<td>Aerodromo</td>
<td>573013.27</td>
<td>5712850.05</td>
<td>75</td>
<td>698.6</td>
</tr>
</tbody>
</table>

Once the interpolation for the annual precipitation data is performed, a map representing annual rainfall in the region is obtained for each study area. This map was the input source ($P_a$) for the $R$ factor calculation using Reinard and Freimud (1994) equations. Both equations were used, since Santos and Bahia Blanca have different values for annual precipitation:

$$ R = 0.0483 \frac{P_a^{1.610}}{610} $$

was used for Bahia Blanca since $P_a \leq 850$ mm

$$ R = 587.8 - 1.249P_a + 0.004105P_a^2 $$

was used for Santos since $P_a \geq 850$ mm

Reinard and Freimud equations were applied using “ArcMap/Spatial Analyst/Raster Calculator” tool. Figure 6.85 shows the methodology apply using GIS software ArcMap 9.0 that give as output a $R$ factor map. The same methodology was applied for both study areas.

![Raster Calculator](image)

**Figure 6.85:** Application of Reinard and Freimud (1994) equations for $R$ factor elaboration using Raster Calculator module.

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The R factor maps obtained after this elaboration are represented in Figure 6.86.

![Figure 6.86: R factor maps obtained by Reinard and Freimud (1994) equations.](image)

**K factor**

The K factor maps were elaborated using the results obtained from SWAT (Soil and Water Assessment Tool) program. The “SWAT/usersoil” module use soil texture information like percentages of clay, sand and silt, organic matter and others as the main input for elaborating K factor. Data must be introduced for each one of the soil horizons characterizing the soil structure of each study area (Figures 6.87 and 6.88). This information is not always easy to obtain. For Santos this information was not available, nevertheless, previous studies from Rossi (1999) in Guaratuba, an area close to Santos, were used as reference taking into consideration the similarity of soil texture and characteristics of these two areas. SWAT results obtained from the type of soils introduced were then associated to geologic maps obtained for both study areas. In the case of Bahia Blanca soil information regarding the texture and structure of its soils were obtained from IADO partners and was the information introduced in SWAT usersoil module.

![Table: SWAT code soil horizons CLAY SILT SAND f_org f_hisand K factor](image)

**Figure 6.87:** SWAT results for K factor according to each type of soil present in Santos study area and geologic map (CETEC, 1999) of the area to which K factor were associated.

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<table>
<thead>
<tr>
<th>Soil horizons</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>K factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>M18li3</td>
<td>29</td>
<td>29,2</td>
<td>40,9</td>
<td>0,12</td>
</tr>
<tr>
<td>M17tc3</td>
<td>24,6</td>
<td>39,2</td>
<td>36,2</td>
<td>0,1533</td>
</tr>
<tr>
<td>M24en4</td>
<td>11,02</td>
<td>21,3</td>
<td>67,68</td>
<td>0,125</td>
</tr>
<tr>
<td>M24tc2</td>
<td>35,1</td>
<td>38,4</td>
<td>26,5</td>
<td>0,14</td>
</tr>
<tr>
<td>M21tc3s</td>
<td>21,3</td>
<td>36,2</td>
<td>42,5</td>
<td>0,1425</td>
</tr>
<tr>
<td>M21tc2</td>
<td>26</td>
<td>30,1</td>
<td>43,9</td>
<td>0,155</td>
</tr>
<tr>
<td>E13ac3</td>
<td>27,5</td>
<td>58,1</td>
<td>13,8</td>
<td>0,18</td>
</tr>
<tr>
<td>A11ah4</td>
<td>15,2</td>
<td>28,7</td>
<td>56,1</td>
<td>0,1533</td>
</tr>
<tr>
<td>E25tc</td>
<td>7.9</td>
<td>6,8</td>
<td>85,3</td>
<td>0,05</td>
</tr>
</tbody>
</table>

Figure 6.88: SWAT results for K factor according to each type of soil present in Bahia Blanca study area and geologic map (INTA, 1990) of the area to which K factor were associated.

The final K factor maps for Santos and Bahia Blanca were elaborated by the associations of K factors obtained by SWAT program and the geologic maps of these areas (Figure 6.89).

Figure 6.89: K factor maps indicating the degree of erosion risk according to the susceptibility of soil to erosion obtained from SWAT soil calculations and associated to geologic maps.

K values for Bahia Blanca and Santos vary broadly from 0.01 to 0.2, that indicates coarse textured soils, sandy and easily detachable according to Table 6.26.

It is important to mention that in the case of Santos the geologic map available for this area was smaller than the study area, this difference in size affected the final dimension of erosion risk maps, since the multiplication operation of all erosion factors characterizing the RUSLE is limited by the smallest map input. Nevertheless, results obtained are quite representative for all the study area of Santos.
LS factor

The basis for calculating LS factor was the Digital Elevation Model (DEM) of both areas downloaded from the NASA free website ftp://eосrp01u.ecs.nasa.gov/srtm/version2. From the DEM, slope (S) and slope length (L) are calculated. There are two simple ways to calculate LS factor using GIS software.

According to Mitasova et al. (2001), using the “ArcMap/Spatial Analyst/Raster Calculator” facilities and applying the formulas based on flow accumulation, which are indicated in Figure 6.90, the LS factor is automatically calculated. DEM resolution plays an important role in the final resolution and quality of the LS factor. Spatial resolution for both DEMs is 90 m which give average and acceptable results. The slope map is elaborated with the DEM using “ArcMap/Spatial Analyst/Surface Analysis”.

Figure 6.90: Calculation of LS factor using ArcMap GIS software (Mitasova et al., 2001)

According to Raghunath (2002) and using GRASS “r.watershed” module, it is possible to calculate directly LS factor. The r.watershed command generates a set of maps indicating: the location of watershed basins and the LS and S factors for RUSLE. The following formulas must be applied for obtaining LS factor (http://grass.itc.it/gdp/html_grass5/html/r.watershed):

\[
r\text{watershed} \ \text{el} = \text{DEM} (T=100) \ \text{length.slope} = \text{LS}
\]

Where:
el = elevation, input map on which entire analysis is based
T = threshold of 100, minimum size of exterior watershed basin
Lengthslope = output LS factor map

The LS map obtained by r.watershed must be divided by 100 (LS/100), which is the final LS factor to be used on the RUSLE.

For convenience and best results obtained, LS factor (Figure 6.91) was calculated applying GRASS r.watershed formula, the same procedure was applied in both study areas. Higher values of LS means higher risk of erosion.

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LS factor maps indicating the degree of erosion risk according to the cumulative slope length derived from DEM.

C factor

The crop management factor for both study areas was calculated mainly from literature review, since there was not local data available regarding this factor. Based on the classified images which indicate landuse of both areas similar classes, species or ecosystems were search on different bibliographical sources and therefore assigned to the ones existing in Santos and Bahia Blanca. This was simply done by creating a new column on the attribute tables of the classified images and assigning C values found on literature references to each one of the classes. The main difficulty in this process consist on the selection of the most representative C values according to the species similarity, but not only, since other aspects as geographical location and climate play an important role on the selection process. Therefore, the search was orientated to those areas with similar geographical settings. C factor ranges from 1 to approximately 0, where higher values indicate no cover effect and soil loss comparable to that from a tilled bare fallow, while lower C means a very strong cover effect resulting in no erosion (Erencin, 2000).

There exist several methods for calculating C factor besides literature references, like NDVI and normalization of satellite bands. Since C factor is the most important factor related to vegetation these three methods were tested. However based on the reliability of data and previous studies were C factors were nominated, two of them seem to be more reliable, NDVI and bibliographic references, but for the aim of this thesis and based on the best results obtained by several tests, emphasis will be given to C factors selected from bibliographical data.

Sometimes more than one value was found for a single specie in this case the selection was baseb on the most similar geographical location. Figure 6.92 represents the final C factor maps obtained from literature review where higher values of C represent higher risk of erosion. Table 6.28 indicates the selected C factors for Santos and Bahia Blanca landcover classes based on their similarity of species and geographical location.

Figure 6.91: LS factor maps indicating the degree of erosion risk according to the cumulative slope length derived from DEM.
Table 6.28: Landcover types and corresponding C factor values according to literature review.

<table>
<thead>
<tr>
<th>Class</th>
<th>Santos</th>
<th>Bahia Blanca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mata Atlantica (lowlands)</td>
<td>0.001 (Zihni, 2000)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Mata Atlantica (highlands)</td>
<td>0.001 (Zihni, 2000)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Mangrove</td>
<td>0.003 (Zihni, 2000)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Low vegetation and/or restinga</td>
<td>0.036 (Gadem et al., 2001)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Spare mangrove and mud (Intertidal)</td>
<td>0.003 (Gadem et al., 2001)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Bare soil</td>
<td>1 (Zihni, 2000)</td>
<td>0.1 (Malla, 2002)</td>
</tr>
<tr>
<td>Urban areas</td>
<td>0.14 (Zihni, 2000)</td>
<td>0.14 (Zihni, 2000)</td>
</tr>
<tr>
<td>Industrial areas</td>
<td>0.14 (Zihni, 2000)</td>
<td>0.14 (Zihni, 2000)</td>
</tr>
<tr>
<td><strong>Bahia Blanca</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saltmarshes (spartina, sarcocornia)</td>
<td>0.003 (Gadem et al., 2001)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Intertidal flats</td>
<td>0.003 (Gadem et al., 2001)</td>
<td>0.003 (Gadem et al., 2001)</td>
</tr>
<tr>
<td>Sand banks, sand bars and plains</td>
<td>0.1 (Zihni, 2000)</td>
<td>0.1 (Zihni, 2000)</td>
</tr>
<tr>
<td>Transitional vegetation (shrubs)</td>
<td>0.1 (Zihni, 2000)</td>
<td>0.1 (Zihni, 2000)</td>
</tr>
<tr>
<td>Crops: sunflowers, soy</td>
<td>0.2 (SWAT)</td>
<td>0.25 (Sonneveld et al., 2001)</td>
</tr>
<tr>
<td>Crops: sorghum, maize</td>
<td>0.25 (Sonneveld et al., 2001)</td>
<td>0.25 (Sonneveld et al., 2001)</td>
</tr>
<tr>
<td>Pastures for grazing</td>
<td>0.1 (Malla, 2002)</td>
<td>0.1 (Malla, 2002)</td>
</tr>
<tr>
<td>Crops: wheat, barley (low cover)</td>
<td>0.1 (Sonneveld et al., 2001)</td>
<td>0.1 (Sonneveld et al., 2001)</td>
</tr>
<tr>
<td>Bare soil and/or sowed land</td>
<td>1 (Malla, 2002)</td>
<td>0.14 (Zihni, 2000)</td>
</tr>
<tr>
<td>Water - estuary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban areas</td>
<td>0.14 (Zihni, 2000)</td>
<td>0.14 (Zihni, 2000)</td>
</tr>
<tr>
<td>Industrial areas</td>
<td>0.14 (Zihni, 2000)</td>
<td>0.14 (Zihni, 2000)</td>
</tr>
</tbody>
</table>

Figure 6.92: C factor maps indicating the degree of erosion risk according to the level of protection of a soil type under a certain landcover category obtained from literature review.
P factor

P factor were calculated base on landuse maps obtained from classification processes. As in the previous case, P factor was calculated using literature references (Figure 6.93). The same process described before was also applied in this case. P factor values were selected according to similarity among classes, topography and geographical location, higher values of P indicate higher erosion risk. Table 6.29 represents the most significant P values assigned to each one of the landcover types in both study areas. The P factor values were classified into 3 categories from minimum to extreme erosion.

Table 6.29: Landcover types and corresponding P factor values according to literature review.

<table>
<thead>
<tr>
<th>Class</th>
<th>P factor</th>
<th>Erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Santos</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mata Atlantica (lowlands)</td>
<td>0.8</td>
<td>Medium</td>
</tr>
<tr>
<td>Mata Atlantica (highlands)</td>
<td>0.8</td>
<td>Medium</td>
</tr>
<tr>
<td>Mangrove</td>
<td>0.8</td>
<td>Medium</td>
</tr>
<tr>
<td>Low vegetation and/or restinga</td>
<td>0.8</td>
<td>Medium</td>
</tr>
<tr>
<td>Spare mangrove and mud (Intertidal)</td>
<td>0.8</td>
<td>Medium</td>
</tr>
<tr>
<td>Bare soil</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Urban areas</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Industrial areas</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td><strong>Bahia Blanca</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saltmarshes (spartina, sarcocornia)</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Intertidal flats</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Sand banks, sand bars and plains</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Transitional vegetation (shrubs)</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Crops: sunflowers, soy</td>
<td>0.11</td>
<td>Medium</td>
</tr>
<tr>
<td>Crops: sorghum, maize</td>
<td>0.11</td>
<td>Medium</td>
</tr>
<tr>
<td>Pastures for grazing</td>
<td>0.11</td>
<td>Medium</td>
</tr>
<tr>
<td>Crops: wheat, barley (low cover)</td>
<td>0.11</td>
<td>Medium</td>
</tr>
<tr>
<td>Bare soil and/or sowed land</td>
<td>1</td>
<td>Severe</td>
</tr>
<tr>
<td>Urban and industrial areas</td>
<td>1</td>
<td>Severe</td>
</tr>
</tbody>
</table>

Figure 6.93: P factor maps indicating the level of erosion risk according to the conservation practices referring to landuse maps obtained from literature review.
6.4.3. Methodology applied for calculating erosion/deposition processes using USPED

The USPED was applied in both study areas to have a complete view of soil loss processes, since it enable the distinction of erosive areas and deposition areas. The methodology applied for USPED model was the one proposed by Mitasova et al. (1991) (GIS based) which stress the effect of topography and landcover on soil loss processes.

Parameters as flow accumulation and flow direction are the first factors taken into consideration on a series of trigonometric and mathematical calculations applied at different steps. Each command generates a new map that is the input for the next step. The initial steps emphasize the influence of topographic characteristics (elevation, slope and aspect derived from DEM) on flow behavior.

Results from flow calculations are then associated to other features affecting erosion processes as soil and landcover characteristics that are represented by K and C factors respectively. There are some differences in the application of the USPED formulas depending of which type of erosion is going to be calculated: sheet erosion or rill erosion. Some of the differences can be seen in Figure 6.94, however for more details about the formulas to apply in each case it is suggested to consult the website:

http://skagit.meas.ncsu.edu/~helena/gmslab/reports/CeriErosionTutorial/denix/Model.

The USPED model is easily applicable using “ArcMap/Spatial Analyst/Raster Calculator” module since it calculates all the required parameters without time consuming. The operations and methodology used in the USPED model are represented in Figure 6.94.

![Raster Calculator](image)

Figure 6.94: Representation of some steps followed in the application of USPED model according to Mitasova et al. (2001).
6.5. Results obtained from RUSLE and USPED models

6.5.1. Erosion risk maps applying RUSLE model

Using "ArcMap/Spatial Analyst/Raster Calculator" and once all erosive factors were calculated, they were introduced into the RUSLE as shown in Figure 6.95. Therefore, a series of maps representing erosion risk were obtained for Santos and Bahia Blanca.

Potential erosion

Potential erosion takes into consideration only the intrinsic characteristics of the area: climatic, geological and topographic, represented by R-K-LS factors respectively. To calculate this type of erosion (Figure 6.96) RUSLE formula is reduced to R*K*LS.

![Figure 6.95: Raster calculator module used to calculate erosion applying the RUSLE.](image)

![Figure 6.96: Potential erosion risk maps of Santos and Bahia Blanca including their histograms (pixels for each class).](image)

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Actual erosion

Actual erosion considers all erosive factors including those referring to landcover (C) and landuse (P) which make reference to vegetation cover. This type of erosion is more representative for soil loss processes since it takes into consideration all the possible factors influencing erosion processes. Actual erosion values are considerably lower than potential erosion since vegetation cover which is an effective soil protector is also considered in its calculations.

Figure 6.97: Actual erosion risk maps (RUSLE) for Santos and Bahia Blanca, including their respective histogram classification (pixels for each class).

6.5.2. Erosion/Sedimentation risk maps applying USPED model

The final maps obtained by the application of USPED model represent erosion and sedimentation processes (Figure 6.98), in this way it is possible to distinguish areas at high risk of erosion as well as high risk of sedimentation. These maps give an idea of where sediments are being deposited, giving a complete scenario of soil loss processes.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Figures 6.98 and 6.100 represents the relation of erosion processes regarding each of the sub-basins of Santos and Bahia Blanca watersheds. Statistical analysis using “ArcMap/Spatial Analyst Tool/Zonal/Zonal Statistics as Table” was applied to quantify erosion for each of the sub-basins. In this way it is possible to identify which of the subwatersheds is the most eroded.

Figure 6.99: Delimitation of Santos sub-basins and quantification of erosion for each subwatershed.

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Soil loss (RUSLE) for each subwatershed (Bahia Blanca - Argentina)

From figures 6.99 and 6.100 it is possible to say that the most eroded sub-basins in Santos are Cubatão, Mogi, Jurubatuba, Boturoca and Ilha de São Vicente, while for Bahia Blanca watershed, Sauce Chico and Napostá Grande are significantly more eroded than the remaining one of Saladillo. However, there is a significant difference between the erosion rates of Santos sub-basins and those from Bahia Blanca, being much more higher the ones from Santos watershed.

6.5.3. Analysis of erosion process in Santos and Bahia Blanca

In order to make the analysis of soil loss processes easier, Table 6.30 summarizes all the results obtained by the application of the two different models in Santos and Bahia Blanca associated at specific landcover categories characterizing the study areas. It also includes two other important aspects that influence and determine soil loss processes, NDVI and DEM (elevation). These elements give a completer view of the physical characteristics of the study area specially regarding their vegetation cover and landscape relief, that as mentioned before, are decisive on erosion/sedimentation processes taking place in these areas.

Table 6.30: Different types of erosion (potential and active) calculated by RUSLE and USPED models associated to NDVI and DEM (elevation) factors.

<table>
<thead>
<tr>
<th>Landuse</th>
<th>Santos</th>
<th>RUSLE</th>
<th>Potential erosion</th>
<th>USPED</th>
<th>NDVI</th>
<th>DEM (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mangrove</td>
<td>0.07</td>
<td>24.13</td>
<td>0.13</td>
<td>0.34</td>
<td></td>
<td>6.84</td>
</tr>
<tr>
<td>M Atlantic lowlands</td>
<td>1.43</td>
<td>1214.49</td>
<td>-0.19</td>
<td>0.45</td>
<td></td>
<td>91.59</td>
</tr>
<tr>
<td>Urban areas</td>
<td>15.99</td>
<td>116.15</td>
<td>1.99</td>
<td>0.05</td>
<td></td>
<td>34.64</td>
</tr>
<tr>
<td>Industrial areas</td>
<td>14.77</td>
<td>105.78</td>
<td>-4.82</td>
<td>-0.07</td>
<td></td>
<td>46.57</td>
</tr>
<tr>
<td>Low vegetation</td>
<td>19.79</td>
<td>701.01</td>
<td>-5.62</td>
<td>0.40</td>
<td></td>
<td>44.64</td>
</tr>
<tr>
<td>Mangrove Intertidal</td>
<td>0.08</td>
<td>21.78</td>
<td>1.54</td>
<td>0.01</td>
<td></td>
<td>5.31</td>
</tr>
<tr>
<td>M Atlantic highlands</td>
<td>1.75</td>
<td>1862.90</td>
<td>-2.18</td>
<td>0.45</td>
<td></td>
<td>576.93</td>
</tr>
<tr>
<td>Bare soil</td>
<td>745.09</td>
<td>771.15</td>
<td>-6.43</td>
<td>0.35</td>
<td></td>
<td>389.60</td>
</tr>
</tbody>
</table>

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
From this table it is possible to say that those areas covered by some type of vegetation mainly Mata Atlântica (highlands or lowlands) and mangroves have lower erosion values, from 0.07 to 1.75 ton/ha yr considered as a very low – low erosion, while those devoid of vegetation as urban/industrial areas and bare soil has significantly higher erosion values, specially the last one with 745.09 ton/ha yr which is considered as severe erosion, this taking into consideration those values obtained with the RUSLE model.

The type of vegetation influence as well erosion processes, soils covered by dense and well structured vegetation as Mata Atlântica have an efficient protection of soil while a cover characterized by poor, scarce, transitional or low vegetation have more possibilities to be eroded. In the case of Santos this is clearly evident since soils protected by Mata Atlântica and mangrove forests have very low erosion values while those protected by some kind of low vegetation (i.e. restinga) have significantly higher values (19.79 ton /ha yr) causing mild erosion in these areas. Also mangroves are well known for its efficient role in protecting coastal zones from erosion processes, since they trap eroded sediments with their roots that later tend to deposit and compact (Ellison et al., 1996) stabilizing in this way coastal soils. Erosion on these low coastal areas have the lowest erosion in the areas.

Other important factors influencing erosion rates in Santos are NDVI and DEM, this table highlight its influence in an simple way, for example by comparing those landcover classes characterized by higher NDVI values e.g. Mata Atlântica and mangroves are affected by very low erosion while those landcover classes with lower NDVI values like industrial and urban areas are affected by mid erosion processes. Elevation does also play an important role in determining soil loss since at higher elevations and steeper slopes sediments are easily runoff therefore increasing erosion processes (Jetten et al., 2003). A clear example of the influence of elevation in soil loss is evidenced by mangroves and Mata Atlântica forests, the latest are located and grow generally at high elevations (at least more than 90 m) and even if they constitute one of the best soil protection cover from erosion, have higher erosion rates than those plain areas (no more than 8 m) covered by mangrove. Areas characterized by a low elevation and mangrove cover have the lowest rates of erosion (between 0.07 and 0.08 ton/ha yr – very low). Higher elevation increase the risk of erosion.

The same could be said for Bahia Blanca even if they are not characterized by such effective vegetation cover like Mata Atlântica and mangroves forests, those areas covered by some type of vegetation even if represented by crops, have lower erosion values. In this case, it is

<table>
<thead>
<tr>
<th>Bahia Blanca</th>
<th>Bare soil and/or sowed land</th>
<th>Crops: wheat-barley (low cover)</th>
<th>Crops: sorghum-maize</th>
<th>Crops: sunflowers-maize</th>
<th>Intertidal flats</th>
<th>Pastures for grazing</th>
<th>Saltmarshes (spartina, sarcocornia)</th>
<th>Sandbanks, sand plains,</th>
<th>Transitional vegetation</th>
<th>Urban areas</th>
<th>Industrial areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.24</td>
<td>7.52</td>
<td>-4.32</td>
<td>0.24</td>
<td>237.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops: wheat-barley (low cover)</td>
<td>0.08</td>
<td>1.90</td>
<td>0.17</td>
<td>0.32</td>
<td></td>
<td>191.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops: sorghum-maize</td>
<td>0.07</td>
<td>1.86</td>
<td>2.32</td>
<td>0.45</td>
<td></td>
<td>189.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops: sunflowers-maize</td>
<td>0.07</td>
<td>1.80</td>
<td>0.89</td>
<td>0.49</td>
<td></td>
<td>184.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intertidal flats</td>
<td>0.04</td>
<td>2.40</td>
<td>0.08</td>
<td>0.01</td>
<td></td>
<td>2.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pastures for grazing</td>
<td>0.18</td>
<td>3.03</td>
<td>0.60</td>
<td>0.37</td>
<td></td>
<td>189.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saltmarshes (spartina, sarcocornia)</td>
<td>0.02</td>
<td>1.39</td>
<td>0.15</td>
<td>0.16</td>
<td></td>
<td>9.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandbanks, sand plains,</td>
<td>0.24</td>
<td>2.55</td>
<td>0.03</td>
<td>0.00</td>
<td></td>
<td>2.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transitional vegetation</td>
<td>0.13</td>
<td>1.23</td>
<td>0.30</td>
<td>0.24</td>
<td></td>
<td>9.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban areas</td>
<td>0.23</td>
<td>1.46</td>
<td>0.27</td>
<td>0.26</td>
<td></td>
<td>38.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial areas</td>
<td>0.24</td>
<td>1.48</td>
<td>-0.33</td>
<td>0.16</td>
<td></td>
<td>6.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Negative values in the USPED column stand for erosion processes, while positive values indicate sedimentation processes.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
important to emphasize that although agricultural activities have a significant effect on soil degradation and increasing erosion rates (Pla, 2003), the physical characteristics of Bahia Blanca located at a very plain area constitutes a great advantage for soil conservation. Therefore, it does not suffer from high rates of erosion even if agricultural activities are very intense in this area, consequently reinforcing the important role of elevation in soil loss processes.

The comparison between Santos and Bahia Blanca is a clear example of higher elevation increase the risk of erosion, since Santos study area characterized by the high elevations of Serra do Mar (more than 300 m) and good vegetation cover (Mata Atlântica) shows higher erosion rates than Bahia Blanca characterized by intensive agriculture but very low elevations generally not over passing 240 m (just at Sierra de la Ventana). Erosion rates in Santos are significantly higher than in Bahia Blanca even if comparing the highest rates of erosion for both areas represented by bare soil, but with the enormous difference that in Santos bare soil (745.09 ton/ha yr) is mainly located at high elevations (more than 380 m) while in Bahia Blanca bare soils (7.24 ton/ha yr) are found at no more than 240 m.

Different rates of erosion were obtained by the application of RUSLE and USPED model which could be justified by the fact that this last one does not only predict the location of erosion sources and rates of erosion but also the location of depositional areas as well as calculating deposition rates in the areas where it was applied. The distribution of sediments into two categories (deposition and erosion) significantly decrease the total amount of sediments classified only as eroded, for this reason erosion rates calculated by USPED are quite lower than those calculated by RUSLE. USPED model constitutes an important tool for prediction both soil loss processes, giving like this a complete overview of this problem.

It is important to point out the significant difference between erosion rates of actual erosion (RUSLE) and potential erosion. Potential erosion shows the worst possible scenario in terms of erosion, this is without considering any kind of soil protection and coverage i.e. vegetation or crops and without any support practice applied to the terrain. The considerable difference between these two types of erosion demonstrates the significant importance of appropriate support practices and preservation of a proper vegetation coverage to avoid land degradation in reference to soils loss either as erosion or sedimentation.

The same concepts and associations were applied to each of the sub-basins of Santos and Bahia Blanca watersheds. Table 6.31 shows in which degree each of the sub-basins are affected by erosion and sedimentation processes and how these rates are influenced by NDVI and DEM (elevation) factors. For example, in the case of Santos, Cubatão has the highest erosion rates (31.46 ton/ha yr) and is also characterized by the highest elevations (more than 540 m), while Piazabucu with the lowest elevations (less than 10 m) has also the lowest erosion values, 0.71 ton /ha yr.

In the case of Bahia Blanca the three sub-basins: Sauce Chico, Napóstá and Saladillo are characterized by relative low erosion and depositional values which might be related to the fact that they are mainly located on low elevations (no more than 240 m). The plain landscape of Bahia Blanca greatly favored to keep low erosion values although this area is characterized by intense agricultural activities.
### Table 6.31: Different types of erosion (potential and active) calculated by RUSLE and USPEDI models associated to NDVI and DEM (elevation) factors.

<table>
<thead>
<tr>
<th>Sub-watershed</th>
<th>RUSLE (ton/ha yr)</th>
<th>Potential erosion (ton/ha yr)</th>
<th>USPEDI (ton/ha yr)</th>
<th>NDVI</th>
<th>DEM (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santos</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pereque</td>
<td>5.40</td>
<td>725.39</td>
<td>-2.73</td>
<td>0.39</td>
<td>465.39</td>
</tr>
<tr>
<td>Cubatão</td>
<td>31.46</td>
<td>1084.51</td>
<td>-1.48</td>
<td>0.42</td>
<td>540.82</td>
</tr>
<tr>
<td>Quilombo</td>
<td>7.34</td>
<td>2478.69</td>
<td>-0.27</td>
<td>0.44</td>
<td>478.34</td>
</tr>
<tr>
<td>Piazabucu</td>
<td>0.71</td>
<td>6.17</td>
<td>0.01</td>
<td>0.21</td>
<td>8.74</td>
</tr>
<tr>
<td>Mogi</td>
<td>24.02</td>
<td>2425.63</td>
<td>-1.84</td>
<td>0.40</td>
<td>374.40</td>
</tr>
<tr>
<td>Jurubatuba</td>
<td>14.98</td>
<td>2408.15</td>
<td>-1.07</td>
<td>0.45</td>
<td>493.76</td>
</tr>
<tr>
<td>Ilha de San Vicente</td>
<td>8.97</td>
<td>84.41</td>
<td>-0.26</td>
<td>0.03</td>
<td>21.81</td>
</tr>
<tr>
<td>Boturoca</td>
<td>16.94</td>
<td>1264.38</td>
<td>-0.86</td>
<td>0.43</td>
<td>195.01</td>
</tr>
<tr>
<td>Bahia Blanca</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sauce Chico</td>
<td>2.10</td>
<td>3.90</td>
<td>-0.51</td>
<td>0.35</td>
<td>239.49</td>
</tr>
<tr>
<td>Napostá Grande</td>
<td>1.83</td>
<td>3.79</td>
<td>-0.74</td>
<td>0.33</td>
<td>210.20</td>
</tr>
<tr>
<td>Saladillo</td>
<td>0.22</td>
<td>2.04</td>
<td>-0.05</td>
<td>0.38</td>
<td>144.98</td>
</tr>
</tbody>
</table>

In general it is possible to say that both study areas are characterized by stable conditions regarding erosion/deposition processes. In most of the cases more than 50% of the total area can be consider stable in soil loss processes, followed by mid to low erosion rates, without taking into consideration potential erosion for the reasons explained before that gives considerably higher erosion values. In general for both study areas, rates of erosion are a bit higher than those from sedimentation, which means that these areas are mainly influenced by erosion processes. Figures 6.101 and 6.102 emphasize some of the differences obtained by the application of RUSLE and USPEDI models and potential erosion. These differences are more evident in Bahia Blanca. Percentages of the degree of erosion/deposition affecting the study areas is also shown in these figures.

![Different types of erosion (Santos)](image)

**Figure 6.101:** Differences in percentages of the degree of erosion/deposition processes obtained by the application of different models and types of erosion in Santos.

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Chapter 6  Erosion processes, model review and selection (Bahia Bianca and Santos)

Different types of erosion (Bahia Bianca)

<table>
<thead>
<tr>
<th>Potential (%)</th>
<th>RUSLE (%)</th>
<th>USPED (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high erosion</td>
<td>0.73</td>
<td>0.6</td>
</tr>
<tr>
<td>High erosion</td>
<td>1.09</td>
<td>0.59</td>
</tr>
<tr>
<td>Middle erosion</td>
<td>3.33</td>
<td>0.78</td>
</tr>
<tr>
<td>Low erosion</td>
<td>26.53</td>
<td>6.33</td>
</tr>
<tr>
<td>Stability</td>
<td>68.33</td>
<td>9.16</td>
</tr>
<tr>
<td>Low sedimentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate sedimentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High sedimentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very high sedimentation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.102: Differences in percentages of the degree of erosion/deposition processes obtained by the application of different models and types of erosion in Bahia Bianca.

Unfortunately, validation of erosion-sedimentation results was not possible since in-situ field measurements were not available, nevertheless, results tend to be quite reliable if compared to previous studies (Rossi and Pfeiffer, 1999; Tengberg et al., 1997; Bacchi et al., 2000; Cavalieri et al., 1996; de Almeida et al., 2001; Cerri et al., 1998; da Silva et al., 2005; Kuntschik, 1996, Moraes et al., 2005) performed in nearby areas with similar characteristics. In the case of Bahia Bianca the same situation exists, in-situ field measurements were not available for a validation and comparison of results obtained, nevertheless, according to personal communication and previous studies (Guerschman et al., 2003, Schnepf et al., 2001, Hernando et al., 2002, Gargano et al., 1998, Isaach et al., 2006) performed in nearby areas, the results obtained in this research can be considerably highly reliable.

Finally it is possible to say, even if nowadays, there are numerous models intended to calculate erosion, although the application of these models is not always an easy task to achieve. However, models are the only current tools that enable an approximate quantification of soil loss processes, facilitating the recognition of high risk areas and consequently the development of an efficient planning to prevent future events and avoid possible effects of erosion at these areas.

Using the existing models, the areas vulnerable to soil erosion can be identified where appropriate treatment and management measures can be formulated. Since the models assume uniform characteristics within an area/sub-catchment, accuracy is enhanced, as the area of interest is sub-divided in as smaller sizes/grids. Use of remote sensing and GIS techniques can greatly help in doing this exercise.

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Chapter 7

Development of a Spatial Decision Support System for Santos

7.1. Spatial Decision Support Systems (SDSS)

7.1.1. Introduction to SDSS

The aim of developing a SDSS was mainly targeted to help Santos local authorities with the decision making processes for improving urbanization problems in the city.

Decision support tools are interactive software-based systems intended to help decision-makers to compile useful information from raw data, documents and personal knowledge to identify and solve problems, evaluate alternatives and make decisions to achieve specific objectives. A DSS are numerical techniques based on various methods as Multi Criteria Analysis (MCA), for choosing the best among a number of alternatives.

SDSS are DSS with spatial components i.e. for finding where to optimally locate the alternative chosen with DSS (Feoli et. al, 2006). DSS and SDSS are represented by different criteria and variables including factors (criterion that enhances or detracts from the suitability of a specific alternative) and constraints (serve to limit the alternatives under consideration).

Environmental issues are always spatial oriented therefore SDSSs are usually supported by GIS that are adequate to represent and work on spatial variability. GIS-based decision support systems allow considering different scenarios which can be easily modified by changing input data contained on the GIS.

The SDSS was designed to evaluate urban problems in Santos, as there is a considerable number of people living in protected areas as mangrove ecological reserves, which put significant pressure on these ecosystems, thus making their relocation an important issue to be solved by local authorities. Furthermore, since there is a significant population growth characterizing the region, the proposal of suitable areas for future urban development is also a main concern for local authorities.

The SDSS output consisted on suitability maps indicating the most “suitable” areas for urban development, taking into consideration a series of criteria represented by constraints (e.g. conservation areas, distance to rivers) and factors (e.g. slope, erosion) which are previously defined based on the main characteristics of the study area. Final outputs facilitate local authorities with the selection of appropriate areas for people relocation and those areas suitable for future urban development.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
7.1.2. Main principles of SDSS

Nowadays, SDSS are considered as an important tool for the decision making process since they give a series of possibilities of how a problem or situation should be solved and approached. There are however, a series of considerations that must be taken into consideration when developing a SDSS, for this reason, this section will describe the main principles of SDSS.

It is important to mention that the natures of decision problems are basically of three types, e.g. unstructured, structured and semi-structured (Dragan, 2005):

- Unstructured (Heuristic, common knowledge, experience, inductive approach);
- Structured (Theoretic approach, construction of programmed tasks);
- SDSS or semi-structured (Computers and decision makers).

By definition, a multi-criteria SDSS is a system that helps solving a semi-structured decision problem, based on the following characteristics: tools to explore the space solution with the appropriate alternatives; support various decision making styles; and allow interactive and recursive problem solving. Therefore, the aim of a SDSS is to support a decision maker in taking “better” decisions.

SDSS are typically structured, since they have a theoretical approach that tend to solve a problem by the construction or development of GIS-structured based models. The most common SDSS structure for problem solving scenario is based on a series of steps that can be summarized as follows:

- Problem definition, identification of the situation that wants to be solved,
- Set the goals for which the SDSS is going to be created,
- Definition of factors and constraints (criteria) indicating what are the limitations existing and that must be taken into consideration for solution proposal,
- Data collection to facilitate the description of the state of the real scenarios,
- Application of judgements and weights to the selected criteria,
- Aggregate all the information for suitability analysis of the objective,
- Post aggregation that is mainly characterized by sensitivity analysis,
- Set of decision rules and procedures to be followed in the solving process generally based on MCE,
- Definition of strategies to select which procedures shall be applied to achieve the original objective and help with the conflict resolution.

Decision Support Systems are mainly based on decision matrices in which alternative solutions are described by factors and constraints. A factor is a criterion that enhances or detracts from the suitability of a specific alternative. A constraint is a limit to the alternatives under consideration.
Chapter 7 Development of a Spatial Decision Support System for Santos

7.1.3. Integration of GIS techniques for developing a SDSS

SDSS is closely associated to GIS analysis, which is useful for a number of reasons, principally taken into consideration that environmental issues are always spatially oriented. Therefore, GIS are the best tools for developing SDDS because they can handle spatial data very easily and efficiently, and since GIS software is able to perform an enormous number of calculations using complicated formulas with very little time consuming. Furthermore, in a GIS context is also possible to distinguish policy decision e.g. selection of an appropriate location for a specific activity, and also for resource allocation decisions e.g. proposal of an agricultural land management plan (Dragan, 2005). Another important asset for using GIS is that they can also act as a process modelling tool, which was of great advantage for developing the SDSS referred in this thesis. The development of the SDSS for Santos study area was mainly based on modeling facilities of GIS.

SDSS are usually supported by GIS that are adequate to represent and work on spatial variability. In this way, it is possible to show different scenarios modifying input data contained on the GIS.

7.2. Methodology applied for developing the SDSS for Santos

7.2.1. Definition of the problem and goals for creating the SDSS

Since the first step for developing a SDSS consists on defining the problem and identification of the situation that wants to be solved, a brief description of the problem to be analyzed by the SDSS is given in this section.

Santos is characterized by important natural ecosystems as Mata Atlântica and mangrove forests (Silva and Dinnouti, 1999; Veloso et al., 1991; Silva and Leitão, 1982), therefore, an efficient control of anthropogenic activities and urban planning play an important role on the preservation of these fragile and unique ecosystems (SOS, 1998). Nowadays in Santos, there are approximately 60,000 people living in protected or not suitable areas for this purpose. In most of the cases the areas occupied are natural reserves of mangroves and forests, thus putting great pressure on these species. For this reason the elaboration of a SDSS within this thesis, was intended to be a useful and reliable tool to help local authorities with the decision making process for solving one of Santos most critical threats affecting the city at the present time: urbanization.

The main goal for developing a SDSS consisted on determining more suitable places for urban development and consequently allowing first the relocation of people currently living in inappropriate areas to proper ones, and second a future planning for urban settlements.
7.2.2. Definition of factors and constraints to be applied in the SDSS

One of the most important steps for developing a SDSS is the definition of a proper criteria that best typify the study area and which frame the SDSS according to certain limitations (constraints) and current conditions (factors) of the area. The best allocation for urban settlements is evaluated through the definition of alternatives (areas) described by a series of factors (X) and constraints (C). Factors are given a weight (W) by decision makers using methods as pairwise. Then, all this information is combined in a suitability index through MCE, summing for each area unit the weighted standardised factors and multiplying by all the constraints considered. The result is a continuous map of suitability (S), that expresses the degree of fulfilment of the objective. Figure 7.103 shows a brief design of this explanation.

![Figure 7.103: Integration of MCE in the SDSS development (Dragan, 2005).](image)

The main source for determining the criteria consisted on a GIS elaborated for Santos study area. It contains a series of maps and tables provided by: local partners i.e. roads network, protected areas, rivers, industries; or obtained from previous satellite image analysis and erosion models i.e. landuse maps, DEM, slope map, erosion risk maps, among others. Figure 7.104 represents the dataset contained on the GIS built for Santos within the research of this thesis and its integration on the elaboration of the SDSS.

![Figure 7.104: Scheme of Santos GIS and its integration as datasource for the elaboration of the SDSS.](image)

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After evaluating the most important variables driving the alternative solutions and the availability of information and datasets, the criteria shown in Table 7.32, classified as constraints and factors, were chosen for elaborating Santos SDSS.

**Table 7.32:** Criteria applied for SDSS elaboration (Source: Ecomanage, 2007).

<table>
<thead>
<tr>
<th>Constraints (limitations, suitability values 0 or 1):</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constraint and representation map</strong></td>
</tr>
<tr>
<td>Distance from water bodies and rivers Distance buffer maps</td>
</tr>
<tr>
<td>Limit of conservation areas Mask of protected areas (natural parks)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factors (limitations, suitability values ranging from 0 to 1):</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factors and representation map</strong></td>
</tr>
</tbody>
</table>
| Land cover/land use Landsat supervised classified images | Each land cover/land use type was given a different degree of suitability (increasing) within a scale from 0 to 5, it can be summarized as follows: Mangroves, Spare mangrove and mud, Urban areas, Industrial areas, Water: 0  *Mata Atlântica* of highlands: 1  *Mata Atlântica* of lowlands: 2 Low vegetation and restinga: 3 Bare soil: 5 Suitability values were then standardized by the formula:  \[
\text{Suitability} = \frac{(\text{Landcover} - \text{min})}{(\text{max} - \text{min})} 
\]
| Slope Slope map derived from DEM | If slope \(\geq 30^\circ\), suitability = 0, otherwise suitability decreases from 1 to 0 between \(0^\circ\) and \(30^\circ\). |
| Distance from industries Distance buffer from industries | If distance \(\leq 500\) m, suitability = 0; If distance \(\geq 1500\) m, suitability = 1; Otherwise, suitability increases from 0 to 1 between 500 m and 1500 m. |
| Erosion degree Erosion risk maps (RUSLE) | Min and max levels of erosion were calculated on the area by raster band statistics. If erosion is max, suitability = 0; If erosion is min, suitability = 1; Otherwise, suitability increases from 0 to 1 between min and max levels, according to standardised values:  \[
\text{Suitability} = \frac{(\text{max} - \text{erosion})}{(\text{max} - \text{min})}. 
\]

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7.2.3. ArcMap 9.0 modelling facilities used for SDSS elaboration

"ArcMap9.0/Analysis Tool/Model" module was used for the elaboration of Santos SDSS. All the required data described in Table 7.32 was available in Santos GIS. Figure 7.105 shows the maps representing the criteria mentioned before and how they are introduced into the Model tool of ArcMap.

The main set of maps used for SDSS were:

- Landcover / landuse map (obtained from supervised classification of satellite image Landsat TM 7- April 2000)
- Dem (slope map obtained from surface analysis tool in ArcMap)
- Rivers and water bodies (obtained from local partners and classified images)
- Industries (CETESB database)
- Limits of conservation and protected areas (obtained from local partners)
- Erosion risk maps (obtained from RUSLE model)

The use of ArcMap modelling facilities is of great advantage for SDSS elaboration since in this way information can be easily updated and changed according to the user requirements and needs.

![Figure 7.105: ArcMap tool module and maps used in the elaboration of SDSS.](image)

Once all maps representing factors and constraints previously defined were introduced into ArcMap modelling tool, the next step is the construction of the scheme model. Figure 7.106 represents the scheme model applied for the elaboration of Santos SDSS.

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All factors and constraints are multiplied separately, resulting in a single map for each one of them (Figure 7.107).
Then the final output is given by the product of these single factors and constraints maps, which contain all the information and criteria previously defined. The final output is a suitability map that expresses the degree of "suitability" for urban development in the area of Santos. Those areas classified with high suitability will be the ones proposed for future urban settlements or for relocation of current ones. Figure 7.108 represents the final suitability map obtained by the application of modeling facilities in ArcMap indicating the appropriate areas for urbanization activities in Santos, which was the main objective of the SDSS.

![Santos suitability map for urbanization](image)

**Figure 7.108**: Suitability map for urbanization obtained by the product of the weighted factors and constraints maps.

In Figure 7.108 it is possible to appreciate the most suitable areas for urbanization indicated by green color, those in yellow indicate possible areas for urban development, while those in red are not considered appropriated for urbanization mainly because they represent protected areas of *Mata Atlântica* and mangrove forests. Also in this case most suitable areas for urban development are located near to the coast and at low elevations which was also defined on the suitability analysis performed in Chapter 5. Also proximity to water bodies is an important factor taken into consideration for urbanization activities, however in Santos some of these areas are not consider as suitable for urbanization since important mangrove reserves are located on the estuary coasts.

Suitability criteria obtained for urbanization activities should be seriously taken into consideration for planning activities on the area, thus to avoid future environmental problems related to anthropogenic activities.
7.3. Analysis and conclusions of the SDSS elaborated for Santos

The SDSS is a powerful tool to support decision-making processes. This system should be dynamical, allowing users to generate new criteria based on the available data or even to change already existing thresholds values.

The SDSS output consisted on suitability maps indicating the most "suitable" areas for urban development. The SDSS will facilitate local authorities with the decision making process of where to re-locate people whom nowadays are living (approximately 60,000 persons) in protected areas (i.e. mangroves) as well as for effective future urban planning in the area. In most of the cases these people belong to the lowest social class, characterized by very low incomes and living in extreme poor conditions, which make the difficult task of relocation even more difficult. These people must be conveniently moved as soon as possible to adequate and safe areas.

The SDSS indicates the most appropriate places for doing so, taking into consideration a series of local factors and constraints such as, topography, water bodies, existing urban settlements, erosion and landuse, that are the basis of the analysis performed to determine "suitable" locations. The SDSS constitutes an important tool for the decision making process that facilitates the proposal of feasible solutions and viable recommendations for improving present problems avoiding a worsening of the current scenario in the future.

GIS and its applications, that allows an integration with most of the existing models, was an important asset for the elaboration of the SDSS taking into consideration the great amount of information needed to elaborate the SDSS. The use of GIS also makes the models results accessible to a broad range of users.

The current SDSS version will be improved introducing new parameters provided by local partners (including stakeholders), taking into consideration laws and regulations of the study areas. Once suitability maps have been elaborated considering new criteria, the more proper areas for urban development in Santos will be finally identify. Other important factors (cost-benefits analysis) will be considered for future analysis, applying non-spatial DSS, e.g. using DEFINITE software. Important factors to be considered in the future will be:

- How much space is necessary to allocate 60,000 people in the chosen areas, providing them proper quality of life;
- Analysing their current income activities (i.e. fishing) and the possibilities to continue these activities living in the new areas;
- The existing normative for protected areas and national / regional parks;
- The existing town planning schemes introducing new industrial areas;
- The urban development costs (i.e. sewage plants, roads, electrical power plants and distribution, water, etc.).

In this way an entire scenario of the current situation of Santos will be possible to analyze, therefore basing the complex decision making process on more reliable and complete data that will significantly influence criteria selected for the current analysis.
Chapter 8

Synthesis of the research, realization of the aim and objectives, limitations encountered

Coastal areas are the most productive ecosystems all over the world but at the same time also the most vulnerable and threatened, for this reason a special emphasis has been put on studying these environments stressing the importance of using appropriate tools and modern technologies as remote sensing and GIS to achieve reliable results that can be used as information sources for current and future planning of anthropogenic activities.

The study areas that this thesis approach are characterized for being under significant environmental stress specially caused by poor urban planning and other anthropogenic activities like intensive agriculture.

Santos is characterized by the presence of valuable and unique ecosystems as Mata Atlântica and mangrove forests that are currently under great stress due to strong urban development in the area, which is also affecting the quality of its estuary. For this reason and so to have an appreciative idea of water quality conditions of Santos Estuary a quality index was also calculated applying Fuzzy set principles and based on water, sediment and organism samples collected by CETESB in 1999 and 2000. The quality index highlighted those areas with bad, moderate and acceptable pollution in the estuary.

In the case of Bahia Bianca, it is characterized by extensive crop fields and pastures for grazing which make of it one of the most important provinces in Argentina for grain and wool exportation. These area is under stress due to the intense agricultural activities which cause soil erosion and land degradation, however it is less environmentally affected than Santos.

One of the main aims of this thesis consisted on the creation of a complete information system using GIS and remote sensing techniques as data sources for a series of elaborations and analysis principally based on satellite images. In this way classification of images for landuse analysis, multitemporal analysis for landcover change detection, analysis of soil loss processes using erosion models (RUSLE and USPED), and the elaboration of SDSS for analyzing urbanization problems in Santos were possible due to the great advantages of GIS.

Since the amount of data to be handled in the database for the elaboration of all these analysis becomes enormous as it contains spatial sources along with maps, and the data covers large geographical regions in both cases, a GIS was used to store, retrieve, manipulate, analyze and display data; this would not have been possible without the application of GIS based processes. The GIS in both cases were designed to carry out complicate calculations and operations on the data stored in its database according to specific orders applied depending on the processes being analyzed i.e. erosion and the expected output.

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Use of Landsat satellite images was in most of the cases the main source of information which was of great help since in-situ data was quite difficult to obtain, for this reason satellite images or its derived products (i.e. classified maps) were broadly used in all the analysis mentioned above. These products constitutes a reliable source of information when no other data is available.

A review of erosion models was made in order to analyze and describe existing approaches in their capacity to represent erosion and deposition. Input data requirements and the efficient accommodation of remote sensing data for the implementation of two well known models, RUSLE and USPED, was also evaluated. RUSLE and USPED models were selected based on the relatively low input data requirements, the optimum accommodation of satellite data available and their adaptability to GIS based processes. The application of RUSLE model, a variant from the famous USLE originally developed by Wischmeier and Smith (1978), enables the analysis of the impact of flow convergence in complex topography, such as found in Santos study area, by replacing the hillslope length and steepness factor by an algorithm incorporating the upslope contributing area (Saavedra, 2005). In the case of Bahia Blanca, topographical characteristics (plain) of the area facilitated the application of this model.

The application of USPED model developed by Mitasova et al. (1998) enhanced erosion analysis required for the fulfillment of the objectives of this thesis, since it consent a whole perception of soil loss processes, calculating not only net erosion but also deposition and divergence in the sediment transport capacity, which was a great advantage for analyzing land degradation in Santos and Bahia Blanca.

Erosion modeling is an important tool for assessment of soil loss processes and elaboration of soil erosion risk maps which are useful references for planning future activities, decreasing current erosion effects as well as preventing future soil degradation. Based on the soil loss estimations, obtained by the application of RUSLE and USPED models, vulnerable areas were identified for undertaking various treatment measures. Different types of erosion were calculated, actual and potential, this to emphasize the role of vegetation cover in soil protection from erosion processes, since the latest does not consider this factor on its calculations, its erosion rates (1862.90 ton/ha yr for Mata Atlântica of highlands) were considerable higher than those obtained by actual erosion (1.75 ton/ha yr for the same landcover) which in fact consider vegetation in two of its factors, C (crop management factor) and P (support practice factor).

Furthermore, the possibility of these models to be combined with GIS provided a convenient platform for handling, compiling and presenting large amounts of spatial data essential for watershed management. The use of GIS also makes the models results accessible to a broad range of users and easy understandable not only for scientists and experts but also by local authorities not having such a specialized background.

From the spatial distribution analysis it was observed that stability and low erosion rates characterize most of the terrain in both study areas. More than 68% of Santos watershed is considered stable with erosion rates less than 10 ton/ha yr, while only 1% to 3% is affected by very high erosion with erosion rates higher than 100 ton/ha yr. The same situation for Bahia Blanca where more than 50% of its watershed is stable, while only 0.6% to 4% of the area suffers from very high erosion. Therefore soil loss processes seem not to represent a high risk for soil degradation in none of these study areas. Nevertheless, there are some areas

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specifically located at high elevations and steep slopes that should be carefully taken into consideration for their high erosion rates mainly influenced by topography than vegetation.

Sedimentation rates were also quite low, since only 2.05% of the total watershed of Santos suffers from high sedimentation, existing in Bahia Blanca the same condition of only 3.85% of the total area being affected by high sedimentation. There are important differences in erosion rates between Santos and Bahia Blanca, which seem to be mainly influenced by the topographic characteristics of each area. Santos which is characterized by higher elevations has greater erosion rates varying from 0.07 ton/ha yr in plain areas (i.e. mangroves) to 745.09 ton/ha yr in high elevated areas where bare soil is mostly found. Bahia Blanca mainly characterized by a uniform and homogeneous topography has considerably lower erosion rates varying from 0.02 ton/ha yr in coastal areas covered by saltmarshes to maximum 7.24 ton/ha yr in more elevated areas.

Regional erosion/deposition patterns and rates obtained were compared with previous studies performed in both study areas (Rossi and Pfeiffer, 1999; Tengberg et al., 1997; Bacchi et al., 2000; Cavalieri et al., 1996; de Almeida et al., 2001, Guerschman et al., 2003, Schnepf et al., 2001, Hernando et al., 2002) which could be consider as a theorical validation of the values obtained by the application of these two models. Unfortunately, in-situ data and measurements of soil loss were not available in none of these study areas.

This methods may also find practical use in land use planning and land management, so to complement valuable information given by soil loss processes and its implications on land degradation, landcover analysis were also elaborated for this thesis. Landcover changes were identified in a 7 years period for Santos study area, allowing the identification of the most frequent alterations in vegetation cover that emphasize the effect of certain anthropogenic activities characterizing Santos study area, these are: deforestation and urban development.

Also future predictions were evaluated by application of Multi Criteria Evaluation that constitutes a valuable tool for environmental planning since it takes into consideration important criteria that frame the calculations and therefore allows reliable outputs based on constraints and factors that describe the study area. Identification of areas where anthropogenic activities have caused serious land change, and predicting where these pressures will continue to take place, was an important asset for the achievement of the objectives of this thesis.

Based on all the information accumulated and results obtained the final objective of this thesis was also accomplished by the elaboration of a SDSS to tackle one of the most serious problems affecting Santos nowadays, urbanization. The elaboration of the SDSS represents a valuable tool to help local authorities with the decision making process, providing a reliable source of information to plan future urban settlements and improve those already existing.

The main limitation found for the elaboration and accomplishment of the planned objectives of this thesis, was always the lack of information and data, either because it does not exists or because it is not shared by local or national institutions that monopolize historical data. Nevertheless, missing data was possible to substitute by different means, looking for other alternatives and other sources of information, basically in internet and open websites, like this the lack of information was overcome in the most reliable and efficient way. Therefore, consenting the development of this thesis and the realization of all its planned objectives.

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All the aims of the thesis originally proposed were successfully achieved, furthermore interesting and practical results were obtained, which could be taken into consideration for future environmental studies in Santos and Bahia Blanca.

The environmental impact assessment considered in this thesis was approached from four complementary perspectives: analysis of present landcover, modeling the scenarios of landcover change, predicting future landcover change, and assessing impact of human activities on vegetation, soil and consequent land degradation.

All the analysis and processes elaborated within this thesis were based on a GIS structure. Nevertheless, problems were encountered in the building up of this GIS structure mainly related to data gathering and availability. For this reason the main sources of information for this thesis were basically open sources, possible to find in internet and which can be easily downloaded. The same case was faced for the acquisition of satellite images, since economical restrictions impeded to buy high quality images both in spectral and spatial resolution, Landsat images, downloaded from the free website: http://glcf.umiacs.umd.edu as well as DEM from: ftp://eo3srl01u.ecs.nasa.gov/srt were used as main sources for a series of analysis. However, satellite images downloaded are considered to be a reliable source of information.

A significant attempt to integrate data available and collected during this research with other tools as erosion models and SDSS was possible taking into consideration the adaptability of the three main components: the original sources, the models selected and the techniques applied for the different elaborations within this thesis.

Satellite images provided important information related to vegetation cover and landuse of both study areas. Satellite images as well as the results obtained from their processing, can be easily manipulated and integrated to a GIS structure. Vegetation cover is represented by landcover maps obtained from Landsat supervised classification and information provided by local partners. This kind of outputs can be easily integrated with other digital sources such as DEM and NDVI which allows a complete overlook of the problem.

Although classification of satellite images is very useful and its results can be considered acceptable (for Santos and Bahia Blanca classifications accuracies of 80%, 90% and 88% were obtained), the fact of relying only on a spectral classification among the pixels’ digital values, was not enough for obtaining good results in distinguishing different vegetation types. Several errors in classifying certain classes were encountered, like bare soil misclassified as urban areas. For this reason and in order to improve the results obtained from supervised classification a series of criteria based on environmental and physical constraints of the existing species (e.g. mangrove is not able to grow at more than 10m of height) were applied based on a GIS structure using conditional and mathematical operators. The application of these constraints, significantly enhanced the previous results obtained by supervised classification. These classified maps were then used for all the environmental analysis applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
performed in this thesis, like landcover change, soil loss process and development of a SDSS for targeting urbanization problems in Santos.

Landcover changes were analyzed through multitemporal techniques which consists on the comparison of at least two different satellite images covering the same area and preferably of the same season; consequently quantifying and evidencing changes occurred within all the landcover classes, this was possible by the application of cross table analysis and Multi Criteria Evaluation (MCE).

Santos landcover change analysis highlighted the most vulnerable areas regarding anthropogenic pressures, mainly deforestation and urbanization. Multitemporal analysis were performed using two different methods, one based on geographical comparisons using GIS Raster Calculator module and the other based on MCE and suitability criteria applied to the selected classes. The second method consists a more reliable tool for landcover change analysis since a series of factors and constraints are taken into consideration for the multitemporal analysis. Results obtained emphasize that areas mostly affected by anthropogenic activities are located on low and medium elevations, while those areas characterized by high elevations and steep slopes are less influenced by human activities. Similar results were obtained by the application of these two methods, where most of the classes in both cases seem to remain as themselves, between 70% and 90% of the area represented by each class does not suffer any impact or transformation into other class, which is quite significant in terms of environmental impact. However, low vegetation appear to have the greatest transformations, some of them justified as expected changes into urban settlements, but other changes into forests are principally generated by the seasonal difference existing between the images of June 1993 (winter) and April 2000 (summer), which affected the quantity of bare soil pixels classified as urban areas (during winter this is higher) due to their spectral similarity. Multitemporal analysis applying MCE tend to stress landcover changes, for example forest transformed into urban settlements are a bit higher (2.97%) when applying MCE than when just applying mathematical and conditional operators (2.11%). MCE made available a flexible way of dealing with qualitative multidimensional environmental effects, factors and constraints. In an overall vision both results show similar tendencies according to their crosstables, which could be taken as a good sign of the reliability of using two different methods in different softwares: ArcMap and Idrisi/Andes.

Landcover prediction of 2010 was obtained through interpolation of surfaces based on the input landcover maps of 1993 and 2000. Landcover trend map of 2010 highlight an apparent decrease of anthropogenic effects and a more uniform landcover. This could be justified by the improvement in application of environmental laws in the area (CONAMA, 2002). It can also be influenced by the effect of Markov and Cellular Automata analysis applied for this purpose, since this last procedure base its analysis not only on previous landcover states but also on the state of the local neighborhood pixels. Considering the extension of some classes (e.g. forest) this will give a greater weight to pixels close to it to become part of this class.

The possibility to predict future landcover is quite significant for performing environmental assessment and preventing uncontrolled anthropogenic activities in this way foreseeing possible scenarios regarding landuse and landcover after a specified number of years.

Another important factor that was taken into consideration for land degradation and environmental impacts of human activities in these two areas, was the calculation of erosion.
risk maps using two different models, the RUSLE and USPED, the latest one also gives a quantification of deposition processes. The rates of soil erosion observed in both areas are related to natural and human factors. The human impacts on the soil erosion can be interpreted from landuse changes over long periods and large areas. The most important factors contributing to soil erosion are: landuse/land cover, slope, lithology, soils, drainage, lineaments, geomorphology, rainfall intensity and current management methods.

Using the selected models, the areas vulnerable to soil erosion and deposition were identified, in this way it is possible to indicate where appropriate treatment and management measures should be formulated. Use of remote sensing and GIS techniques can greatly help with the application of these models where satellite images were easily adapted.

Erosion models need huge amount of information which in most of the cases is just experimental or simple not available. Specific and detailed data is necessary for erosion model calculations, nevertheless, important effects of terrain shape are not considered, therefore results are subject to errors and do not necessary represent completely the natural conditions of the terrain (Perrin et al., 2001). Erosion modeling is an important tool for assessment of soil loss processes and elaboration of soil erosion risk maps which are useful references for attempting a decrease in current erosion rates and planning future activities thus not to increase soil degradation.

Erosion rates, except for those values obtained by potential erosion, tend to be quite low for both study areas. Potential erosion indicates considerable higher values (1862.9 ton/ha yr for bare soil) than those obtained by RUSLE and USPED (1.75 ton/ha yr and -2.18 ton/ha yr for bare soil) models, but this significant difference is mainly related to the fact that this type of erosion does not consider any type of vegetation cover. The importance of plants rely on the fact that they provide protective cover on the land and prevent soil erosion since:

- Plants slow down water as it flows over the land (runoff) and this allows much of the rain to soak into the ground;
- Plant roots hold the soil in position and prevent it from being washed away;
- Plants break the impact of a raindrop before it hits the soil, thus reducing its ability to erode;
- Plants in wetlands and on the banks of rivers are of particular importance as they slow down the flow of the water and their roots bind the soil, thus preventing erosion.

The loss of protective vegetation through deforestation, over-grazing, ploughing, and fire makes soil vulnerable to being swept away by wind and water. In addition, over-cultivation and compaction cause the soil to lose its structure and cohesion and it becomes more easily eroded. Erosion will remove the top-soil first and once this nutrient-rich layer of soil is gone, few plants will grow in the soil again (Pla, 2003). Without soil and plants the land becomes desert-like and unable to support life - this process is called desertification. It is very difficult and often impossible to restore desertified land, for this reason proper management of soils should be an important issue to tackle by local authorities in order to prevent land degradation.

Erosion and sedimentation maps obtained through RUSLE and USPED models were associated to the landuse maps resulting from supervised classification Landsat images of both study areas. Using ArcMap 9.0 zonal statistical analysis these correlations were clearly

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outlined, showing how each of the most important classes in the landuse maps (forest, mangroves, crops, bare soil, urban and industrial areas) are affected by soil loss processes. For example in Santos, *Mata Atlântica* (highlands and lowlands) have the lowest erosion values together with mangroves, while bare soil has the highest erosion values. These results were more or less expected considering that these two types of vegetation represent an efficient soil cover due to their intrinsic physical characteristics, for example, mangroves are recognized as excellent sediment trappers that help with coastal stabilization. Correlations between erosion and topographic aspects of the terrain, represented by DEM, were also elaborated, emphasizing in this way the important role of natural characteristics of the terrain in soil loss processes.

Type of vegetation cover is one of the most important physical characteristics for soil loss stability, yet, other factor as important as vegetation cover is topography of the terrain. These characteristics and others as rainfall intensity, type of soils, management methods, and landuse are the main factors to be considered for soil erosion calculations. In Santos and Bahia Blanca it seems that erosion processes are mainly determined by topographic characteristics of each area. Lower erosion rates are found on plain terrains: in Santos mangroves at 6.84 m have very low erosion rates (0.07 ton/ha yr), while low vegetation at 44.64 m have higher erosion rates (19.79 ton/ha yr), for Bahia Blanca intertidal flats at 2.76 m have very low erosion rates 0.04 ton /ha yr while bare soil at 237.8 m have higher erosion rates (7.24 ton/ha yr). Nevertheless, in Santos, *Mata Atlântica* of highlands is mainly found at elevations of more than 576.93 m, but erosion rates are still very low (1.75 ton /ha yr), this fact highlight the importance of a good vegetation cover in those areas at high risk of erosion.

However, erosion rates obtained for Santos and Bahia Blanca, are quite lower than expected, very high erosion values were found only on steep slopes of Serra do Mar and Sierra de la Ventana, respectively. More than 65% and of the total watersheds are considered stable which means very low erosion rates of 1 ton/ha yr, while only 4% and 2% (without considering potential erosion) of Bahia Blanca and Santos respectively, suffer from very high erosion with rates of more than 100 ton/ha yr.

Unfortunately, validation of erosion-sedimentation results was not possible since in-situ field measurements were not available, nevertheless, results tend to be quite reliable if compared to previous studies (Rossi and Pfeiffer, 1999; Tengberg et al., 1997; Bacchi et al., 2000; Cavalieri et al., 1996; de Almeida et al., 2001; Cerri et al., 1998 among others) performed in nearby areas with similar characteristics. In the case of Bahia Blanca the same situation exists, in-situ field measurements were not available for a validation and comparison of results obtained, nevertheless, according to personal communication and previous studies (Guerschman et al., 2003, Schnepf et al., 2001, Hernando et al., 2002, Gargano et al., 1998, Isaach et al., 2006) performed in nearby areas, the results obtained in this research can be considerable highly reliable.

Even if nowadays, there are numerous models intended to calculate erosion, although the application of these models is not always an easy task to achieve. However, models are the only current tools that enable an approximate quantification of soil loss processes, facilitating the recognition of high risk areas and consequently the development of an efficient planning to prevent future events and avoid possible effects of erosion at these areas.
Models combined with GIS provide a convenient platform for handling, compiling and presenting large amounts of spatial data essential to watershed management. The use of GIS also makes the models results accessible to a broad range of users.

Finally, the elaboration of a Spatial Decision Support System for analyzing urbanization problems in Santos was also possible by the application of GIS.

An efficient control of anthropogenic activities and urban planning play an important role in preservation of forest and mangroves ecosystems. For this reason the elaboration of a SDSS within this thesis, was intended to be a useful and reliable tool to help local authorities with the decision making process for solving one of Santos most critical threats: urbanization.

The SDSS was designed to evaluate urban problems in Santos, as there is a considerable number of people living in protected areas as mangrove ecological reserves, which put significant pressure on these ecosystems so making their relocation an important issue to be solved. In most of the cases these people belong to the lowest social class, characterized by very low incomes and living in extreme poor conditions, which make the difficult task of relocation even more difficult. These people must be conveniently moved as soon as possible to adequate and safe areas.

The SDSS indicates the most appropriate places for urbanization, taking into consideration a series of local factors and constraints such as topography, water bodies, existing urban settlements, erosion and landuse. The SDSS was an important asset that facilitated the proposal of feasible solutions and viable recommendations to improve urbanization problems in the area of Santos and surroundings.

The use of better satellite images (spatial and spectral resolution) will without doubt enhance the results obtained, for this reason it is highly recommended the future acquisition of actual and better satellite images so to improve and verify results obtained within this thesis as well as performing more detailed studies. It is important to provide regional authorities with the right tools as remote sensing and GIS and reliable planning sources like SDSS thus, helping them in the decision making process for efficiently face current problems avoiding a worsening of the present scenarios.
Bibliography and References

- Almeida de, G., Faria, M., Ridente, J., and Canil, K. Prevenção e controle da erosão urbana no estrado de São Paulo. XXVII Congresso Interamericano de Engenharia Sanitária e Ambiental.
Bibliography and References


An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Bibliography and References

- de Jong, S., et al., 1999. Regional assessment of soil erosion using the distributed model SEMMED and remotely sensed data. Catena, 37(3-4)
Bibliography and References

- Ecomanage, 2007. Deliverable 4.15: A comprehensive system software tool accessible on line to the participants of the project for SDSS that integrates: Image Processing, GIS, Multi-Criteria Analysis, Cost benefit assessment etc. (Draft version).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
- Ghribi, M., 2005. GIS applications for monitoring environmental change and supporting decision making in developing countries. ICS-UNIDO Publication.
- http://agron.scijournals.org
- http://159.226.205.16/curriculum/3w/01/cause/index.html
- http://www.pdx.edu/~emch/ip1/bandcombinations.html

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
- http://c100.bsyse.wsu.edu/cropsyst/manual/parameters/crop/morphology.htm
- http://159.226.205.16/curriculum/3w/01/cause/index.html
- http://web.pdx.edu/~emch/ip1/bandcombinations.html
- http://en.wikipedia.org/wiki/Mata_Ant%C3%A2ntica
- http://es.wikipedia.org/wiki/Bah%C3%ADa_Blanca_(ciudad))
- http://faculty.plattsburgh.edu/robert.fuller/370%20Files/Weeks11Erosion/Types.htm
- http://gclf.umiacs.umd.edu
- http://gclf.umiacs.umd.edu/data/landsat/
- http://grass.itc.it/grass60/manuals/html60_user/v_surf.idw.html
- http://riap.inta.gov.ar
- http://skagit.meas.ncsu.edu/helena/gmslab/reports/CeriErosionTutorial/denix
- http://topsoil.nserl.purdue.edu/nserlweb/weppdoc/PlantSpecificParameters.html
- http://web.pdx.edu/~emch/ip1/bandcombinations.html
- http://www.agro.uba.ar/lart
- http://www.britannica.com
- http://www.cetesb.sp.gov.br/legiciamentoo/legislacao/estadual/resolucoes/
- http://www.fao.org/dochrep/007/ae341e/ae341e05.htm
- http://www.gisdevelopment.net/downloadpubs/scope13/chapter05.html
- http://www.iwr.msu.edu/rusle/kfactor.htm
- http://www.mapquest.com/maps/map.adp?formtype=address&country=AR&addtohistory=&city=Bah%C3%ADa+Blanca
- http://www.omafra.gov.on.ca/english/engineer/facts/00-001.htm
- http://www.portodesantos.com/
- http://www.soilandhealth.org/01aglibrary/010137veg.roots
- http://www.worldwildlife.org/wildworld/profiles/terrestrial/nt/nt0160_full.html

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).


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An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Bibliography and References


An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).


- Personal communication, 2006. Conversations with local partners, IADO. Bahia Blanca-Argentina.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).


An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).

- Thenkabail P.S., Gamage, M.S.D.N. and Smakhin V.U. The use of remote sensing data for drought assessment and monitoring in south west Asia. 2-45.


- Van den Berg, M., Birnbaum, L., Bosveld, A., 1998. Toxic Equivalent factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. Environmental Health Perspectives 106 (12): 775-792.


An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 1: Terminals of main industries located in the Port of Santos
(http://www.portodesantos.com/)

Photo 1: Bulk liquid Terminal (Granel Química, Potenza, Brasterminais, Argemil).

Photo 2: Bulk liquid terminal (Petroquímica União, Stolthaven, Transultra, Dibal, União, Tequimar, Petrobrás).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
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Photo 5: Terminal of fertilizers.

Photo 6: Terminal of citrus, Citrosuco industry.

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Photo 7: Juice containers, general load (Citrovita, Rodrimar).

Photo 8: Solids terminal (e.g. fertilizers, sodium sulfate, wheat). (Cargill Citrus, Termares, Deicmar).

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 1

Photos of the Port of Santos

Photo 9: Sugar cane terminal.

Photo 10: Passengers terminal.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
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An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
### Pollutants analyzed in water, sediments and marine organisms

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### Pollutants analyzed in water, sediments and marine organisms

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An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 3 Photos of Bahia Blanca Estuary and agricultural activities in the area

Photo 11: Bahia Blanca Estuary

Photo 12: Bahia Blanca Estuary at low tide, uncovering crab caves “cangrejales”.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 3

Photos of Bahia Blanca Estuary and agricultural activities in the area

Photo 13: Halophyte vegetation present in the estuary.

Photo 14: Halophyte vegetation represented by Salicornia sp.

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Appendix 3
Photos of Bahia Blanca Estuary and agricultural activities in the area

Photo 15: Halophyle vegetation represented by Spartina sp.

Photo 16: Estuary at low tide, broad muddy extensions remain uncovered.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 3 Photos of Bahia Blanca Estuary and agricultural activities in the area

Photo 17: Estuary at low tide, uncovering solid waste discharges.

Photo 18: Intensive agricultural fields, characterizing this area.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 3

Photos of Bahia Blanca Estuary and agricultural activities in the area

Photo 19: Maize crops.

Photo 20: Sorghum crops.

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
### Appendix 4

Main characteristics of the vegetation species present in the study areas

#### Study area: Santos (Brazil)

<table>
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<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>LAI</td>
<td>9-12 (Box, 1989) 6-16 (Lieth, 1975)</td>
<td>11-23.3 (Lieth, 1975)</td>
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<td></td>
</tr>
<tr>
<td>Rooth Depth (m)</td>
<td>7.3±2.8 (Canadell, et.al., 1996)</td>
<td>18 m (Community) (Neps tad, 1994 or Canadell, et.al., 1996)</td>
<td>7.2 ± 0.7 (Bertness, 1987)</td>
<td></td>
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<tr>
<td>Total root Biomass (Mg ha⁻¹)</td>
<td>16.7 (Cattanio, 2004)</td>
<td>27.9 (Cattanio, 2004)</td>
<td>61.7 (Cattanio, 2004)</td>
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<tr>
<td>Total fine root Biomass (≤2 mm) (kg m⁻³)</td>
<td>0.57 (Jackson, et al., 1997)</td>
<td>0.33 (Jackson, et al., 1997)</td>
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<tr>
<td>Live fine root Biomass (kg m⁻³)</td>
<td>4.1 (Jackson, et al., 1997)</td>
<td>7.4 (Jackson, et al., 1997)</td>
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<tr>
<td>Live fine root length (km m⁻²)</td>
<td>% Root Biomass in upper 30 cm</td>
<td>% Fine Root Biomass in upper 30 cm</td>
<td>69 (Jackson, et al., 1996)</td>
<td>57 (Jackson, et al., 1997)</td>
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An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
**Appendix 4**

**Main characteristics of the vegetation species present in the study areas**

<table>
<thead>
<tr>
<th></th>
<th>root6 (ref. Malasya), (Cairns, et al., 1997) - Koopmans and Andriess, 1982</th>
<th>1.9 (Cairns, et al., 1997) - Buschbacher, 1988, Uhl et al., 1988</th>
</tr>
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<tbody>
<tr>
<td><strong>Root Biomass Density RBD (Mg/ha)</strong></td>
<td>5.8 - 6.03 (Sundarapandian, et al., 1996)</td>
<td>6.3 - 9.4 (Sundarapandian, et al., 1996)</td>
</tr>
<tr>
<td><strong>Root/Shoot Ratio</strong></td>
<td>0.19 (Jackson, et al., 1996)</td>
<td>1.7-2.3 includes roots &lt;3 mm (Sundarapandian, et al., 1996)</td>
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<tr>
<td><strong>Above Biomass Density ABD (Mg/ha)</strong></td>
<td>81 (ref. Malasya), (Cairns, et al., 1997) - Koopmans and Andriess, 1982</td>
<td>5.88 (Cairns, et al., 1997) - Buschbacher, 1988, Uhl et al., 1988</td>
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<tr>
<td><strong>Total Above ground Biomass (ton/ha)</strong></td>
<td>293.44 (Röhrig) 440 (Box, 1989)</td>
<td>0.2792 (Lugo et al., 1974) dryweight</td>
</tr>
<tr>
<td><strong>Total Biomass (ton/ha)</strong></td>
<td>293.44 (Röhrig) 440 (Box, 1989)</td>
<td>450 Röhrig</td>
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<td></td>
<td>293.44 (Röhrig) 440 (Box, 1989)</td>
<td>0.2792 (Lugo et al., 1974) dryweight</td>
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<td></td>
<td>293.44 (Röhrig) 440 (Box, 1989)</td>
<td>150 (Röhrig)</td>
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<td><strong>Leaf litter fall (t ha(^{-1}) year(^{-1}))</strong></td>
<td>7.66 (Sundarapandian, et al., 1996)</td>
<td>5.3 (cattanio, 2004)</td>
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<tr>
<td><strong>Total litter fall (t ha(^{-1}) year(^{-1}))</strong></td>
<td>6.2 (Perez, 2003) 6.6 (cattanio, 2004)</td>
<td>5.75 (Twilley, 1986)</td>
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<tr>
<td><strong>Net Primary Productivity NPP (ton/ha(^{-1}) yr(^{-1}))</strong></td>
<td>14.2022 (Röhrig) 20.5 (Lieth, 1975)</td>
<td>3.550 (Lugo, 1974)</td>
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<tr>
<td><strong>Canopy Density (%)</strong></td>
<td>9-12 (Box, 1989) 6-16 (Lieth, 1975)</td>
<td>6.8 cattanio, 2004</td>
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</table>

An information system to analyze and monitoring coastal areas for planning sustainable development. Applications for Santos Estuary (Brazil) and Bahia Blanca (Argentina).
Appendix 4  Main characteristics of the vegetation species present in the study areas

Study area: Bahia Blanca (Argentina)

<table>
<thead>
<tr>
<th></th>
<th>maize</th>
<th>sorghum</th>
<th>soybean</th>
<th>sunflower</th>
<th>Wheat spring</th>
<th>Wheat winter</th>
<th>grass</th>
<th>Pasture</th>
<th>Spartina Alterniflora</th>
<th>Shrubs</th>
<th>Juncus gerardi</th>
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<tr>
<td>(1) Max root depth (m)</td>
<td>1.5-2</td>
<td>1.4-1.8</td>
<td>1.4-1.8</td>
<td>1.7-2.2</td>
<td>1.2-1.6</td>
<td>1.5-2</td>
<td>0.8</td>
<td>0.74 (3)</td>
<td>7.2 ± 0.7 (Bertness, 1987)</td>
<td>10.2±0.8 (Bertness, 1987)</td>
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<tr>
<td>(2) Max Root Depth (m)</td>
<td>1.52</td>
<td>1.5</td>
<td>1</td>
<td>0.30</td>
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<tr>
<td>(1) Root/Shoot</td>
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<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td>(1) Max LAI m² m⁻²</td>
<td>4.7 (1)</td>
<td>6-10 (1)</td>
<td>4-7 (1)</td>
<td>4-5 (1)</td>
<td>4-6 (1)</td>
<td>5-8</td>
<td>4(1)</td>
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<td>Max LAI potential</td>
<td>3.5</td>
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<td>LAI usado en graficos LAI argentí</td>
<td>7</td>
<td>7</td>
<td>5</td>
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<td>6</td>
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<td>2.5</td>
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<td>2.08</td>
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<td>(1) Biomass transpiration coefficient ((kg m⁻³/kPa)/m)</td>
<td>6.0-8.5</td>
<td>6.0-8.5</td>
<td>3.5-6.0</td>
<td>3.5-6.0</td>
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<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
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<td>(2) Max canopy height (m)</td>
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<td>(2) Max rate of residue decay</td>
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<td>NPP T ha⁻¹ yr⁻¹</td>
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