GEOGRAPHIC INFORMATION SCIENCE: CONTRIBUTION TO UNDERSTANDING SALT AND SODIUM AFFECTED SOILS IN THE SENEGAL RIVER VALLEY

by

RAMATOULAYE NDIAYE

M.S, University of Cheikh Anta Diop, 2004

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
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Abstract

The Senegal River valley and delta (SRVD) are affected by long term climate variability. Indicators of these climatic shifts include a rainfall deficit, warmer temperatures, sea level rise, floods, and drought. These shifts have led to environmental degradation, water deficits, and profound effects on human life and activities in the area. Geographic Information Science (GIScience), including satellite-based remote sensing methods offer several advantages over conventional ground-based methods used to map and monitor salt-affected soil (SAS) features.

This study was designed to assess the accuracy of information on soil salinization extracted from Landsat satellite imagery. Would available imagery and GIScience data analysis enable an ability to discriminate natural soil salinization from soil sodication and provide an ability to characterize the SAS trend and pattern over 30 years? A set of Landsat MSS (June 1973 and September 1979), Landsat TM (November 1987, April 1994 and November 1999) and ETM+ (May 2001 and March 2003) images have been used to map and monitor salt impacted soil distribution. Supervised classification, unsupervised classification and post-classification change detection methods were used. Supervised classifications of May 2001 and March 2003 images were made in conjunction field data characterizing soil surface chemical characteristics that included exchange sodium percentage (ESP), cation exchange capacity (CEC) and the electrical conductivity (EC). With this supervised information extraction method, the distribution of three different types of SAS (saline, saline-sodic, and sodic) was mapped with an accuracy of 91.07% for 2001 image and 73.21% for 2003 image. Change detection results confirmed a decreasing trend in non-saline and saline soil and an increase in saline-sodic and sodic soil. All seven Landsat images were subjected to the unsupervised classification method which resulted in maps that separate SAS according to their degree of salinity. The spatial distribution of sodic and saline-sodic soils has a strong relationship with the area of irrigated rice crop management. This study documented that human-induced salinization is progressively replacing natural salinization in the SRVD. These pedologic parameters obtained using GIScience remote sensing techniques can be used as a scientific tool for sustainable management and to assist with the implementation of environmental policy.

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Major Professor

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Dedication

To my late father Dr Ibrahima Ndiaye

CHAPTER 1 - Introduction

West African countries have faced a number of environmental problems during the last four decades. Climate variability was particularly pronounced during the late Twentieth Century which coincided with the industrial era in the world's most developed countries and a steady increase in greenhouses gases in the atmosphere. During this time period, the climate of the Sahel went through different periods of alternating dry and wet conditions. Residents of the Sahel were impacted by climatic variability that included a 1930-1960s wet period, the 1970-1980s droughts and a timid increase of rainfall in the 1990s and 2000s. Climate change coupled with human action is altering dramatically the ecosystems of West African (WA). Analysis of the impacts of climate variability suggests that the agro-economic system and natural ecosystems are among the most vulnerable sectors. The economy of the Sahel is highly dependent on these sectors, which are very sensitive to shifts in climate and related variations in water resource availability. For mitigating water stress, new water and land management approaches have been implanted in the region.

In the basin of the Senegal River, where over two million people live, most of the economic activities depend on the riverine resource. Important investments have been made to enhance economic development of the region and reduce vulnerability vis à vis the harsh climatic conditions. For these purposes, Diama and Manantali dams were constructed and irrigated agriculture was developed in the valley. Construction of the salt- wedge Diama dam in 1986, which limits the upsteam penetration of saline ocean waters, has changed the hydrological system of the Senegal River Basin (SRB) and influenced the evolution of local soil characteristics. Irrigated rice cropping is the main target of these fresh water management efforts; rice agriculture requires large amount of water because of locally high evaporation levels. Rice was introduced in several river basins during the colonial period; before the spectacular climate change in the 1970s, the Senegal River valley was called "the Senegal granary".

The shift from traditional to irrigated farming, for the sake of the regional food security, was a resource management strategy that had tremendous environmental consequences in the Senegal River valley and delta (SRVD). Irrigated rice cropping has been identified as the most important cause of environmental degradation through soil salinization. During years of drought and disaster, when farming encountered great difficulties, several irrigated fields were abandoned because of soil salinity exacerbated by high evaporation and sea water intrusion.

1.1- Soil degradation and salinization

Soil salinization is a resource concern because salt concentration in water and soils is a limiting factor to plant growth. Salinization may occur naturally or because of conditions resulting from land and water resource management practices. Three different types of salinization have been identified in the SRB: primary salinization (marine origin); alkalinization (petrographic origin) mostly found in the valley; and sodication, a new type of salinization (of anthropogenic origin). Several authors (Cuppens *et al.,* 1998, Woperies *et al.,* 1998) have mentioned that the delta area is affected by two types of salinity:

1. primary salinization or neutral soil salinity (NaCl) developed during Quaternary alternative regression and transgression phases; and
2. a secondary salinization or soil sodication resulting from human activities.

Studies conducted in the delta have pointed out decreases in soil quality mostly related to a gradual decrease in natural salinization and a gradual increase in the anthropogenic salinization hazard. Additional studies of the salt distribution in the soil will improve our understanding of soil degradation processes, and related spatial and temporal distributions. Regional hydrogeology and land management are strongly related to the spatiotemporal distribution of soil salinization.

Irrigated soils without drainage have higher salinity and alkalinity than those that are irrigated and drained. It has been documented that soil sodication varies according to the type of land use and land management. Salinization is a dynamic phenomenon which needs to be monitored regularly in space and time in order to detect the spatiotemporal trend and pattern of salt affected soil (SAS) and also to better understand the relationships with edaphic factors and land management practices. Geographic data on the spatial distribution of SAS will be very helpful in strategic decision-making regarding soil reclamation and optimal land resource utilization for sustainable development.

The principal objective of this study is to evaluate GIScience tools for identifying the spatio-temporal distribution of soil affected by salinization and differentiate primary salinization and secondary salinization extent in the delta region of the Senegal River Basin. To achieve this goal, GIScience technology is used to assess SAS and hydrological features. Satellite remotely sensed data and GIS tools for monitoring temporal change in land cover are a key to many diverse natural resource applications of these GIScience technologies such as environmental degradation, hydrologic change, and agricultural development.

1.2- GIScience contributions to addressing global change and land change science issues

Satellite images now enable scientific visualization of over 35 years of variations on the earth surface. Computer hardware combined with image-processing and GIS software makes available valuable ways to analyze and visualize the changes within the image data. Grunwald (2006) reported that visible/NIR-MIR spectroscopy, remote sensing, GIS, and increased computing power are some of major developments that have contributed to a gradual shift from qualitative to more quantitative soil-landscape characterization. Geographic Information System (GIS) tools and information derived from satellite data are used in this study to describe the spatial extent of SAS in the SRVD. An important aspect is the development of new information, based on the satellite images and GIS analysis for soil monitoring and forecasting in the SRVD. New information on the character of SAS can be used at local, regional, and national levels by relevant authorities to improve water and soil management and to reduce the impacts of extreme environmental degradation on society. Understanding changes in SAS in the SRVD will help to determine and address the relative impact of human activities (irrigation agriculture and water management) in the region.

According to several remote sensing studies, the salt affected land is often associated with higher reflectivity. Rodriguez *et al.,* (2007) reported that soil reflectance varies with total salt. Salt mineralogy, soil moisture and color, and terrain roughness are additional factors affecting soil reflectance (Metternicht and Zinck, 1997). Remote sensing has a potential application for rapid and large scale mapping of salt-affected lands (Howari, 2003) and can provide useful information for change detection, mapping, and monitoring salt affected soils. Repetitive satellite images of the SRVD areas provide a potentially powerful way to assess conditions at varying time periods and change over time. Chapter Five of this dissertation provides information on the accuracy of information extracted from satellite imagery to discriminate primary soil salinization (or natural salinization) from soil sodication. Chapter Five also presents the SAS trend and geographic pattern over 30 years of analysis. These pedologic parameters collected from space-based sensors can be used as a scientific tool to assist sustainable management and to implement environmental policy.

1.3- Study area

West Africa is composed of several river basins shared by several countries, including the Niger River basin, the Lake Chad Basin, the Volta river basin and the Senegal River basin. The Senegal River Basin (SRB) is divided into three parts: the delta, middle valley, and the upper valley. The delta of Senegal River, the study area for this research, occupies the western part of the SRB. It is located in northwestern Senegal in the Saint- Louis region, with a spatial extent between 15^0 $22^{'}$ N to 16^0 $8^{'}$N latitudes and 14^0 $5^{'}$W to 17^0 W longitudes (Fig.1-1). The delta region has mostly lowland topography (maximum elevation 1.4 m) and an estimated area of 3240 km^2.

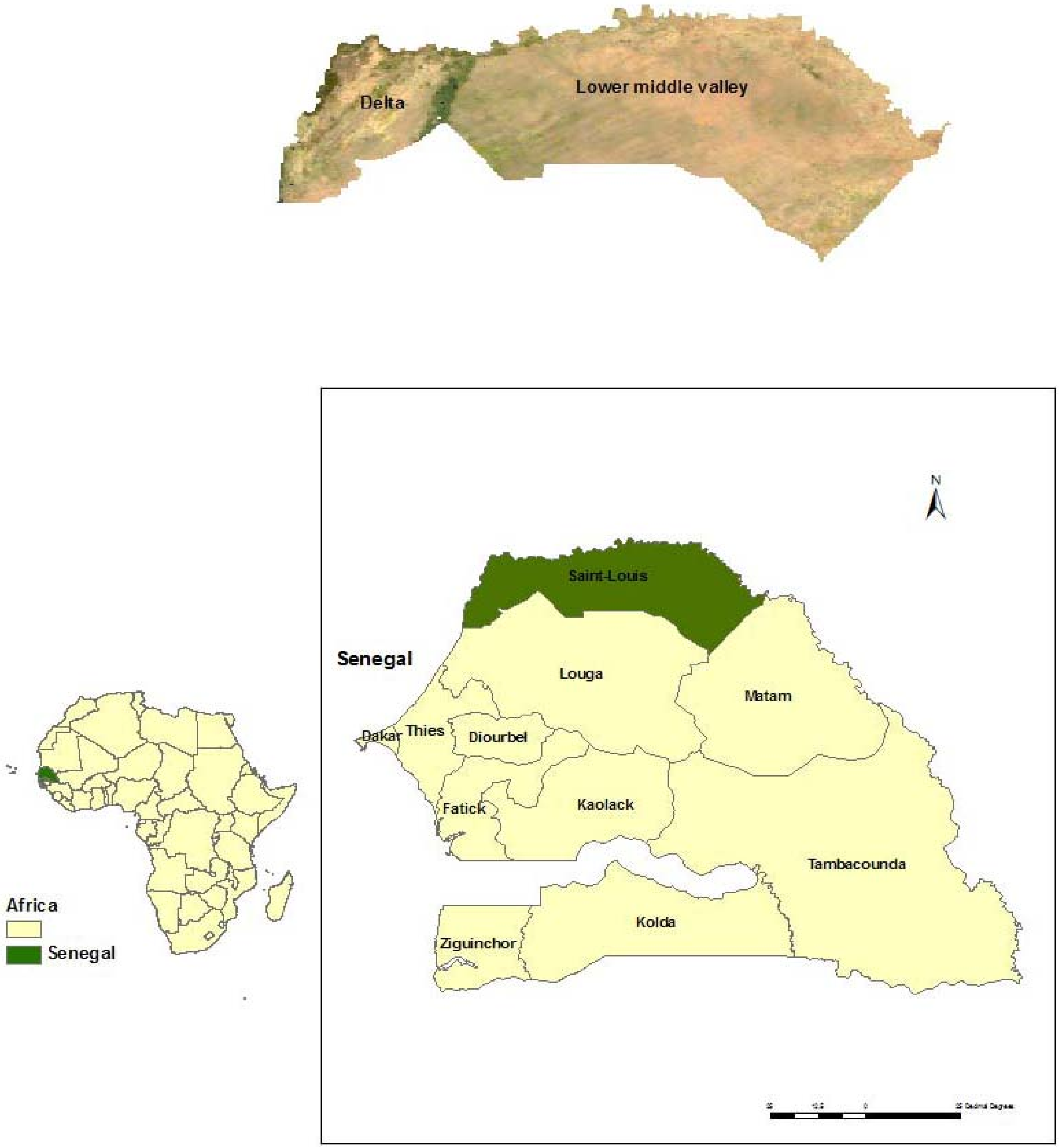


Figure 1.1 - Location of the Senegal River delta and the middle valley regions. Source: www.maplibrary.org

CHAPTER 2 - Literature review

2.1- Global change with an emphasis on water resources and irrigation in West Africa

The history of life on Earth has been punctuated by many dramatic ecosystem variations. In order to understand the implications of global environmental change, it is very important to relate human actions and environment change. According to Stern *et al.,* (1992) environmental systems and human action intersect where changes affect what humans value the most and where humans alter aspects of the environment causing change.

The main driving force behind all air movement within the atmosphere is latitudinal variation in insolation. Milankovitch theory demonstrated that variation of solar radiation is related to the changes in the Earth's orbital position. This theory has been corroborated by numerous research efforts based on different techniques including, dated terrestrial fossil pollen and spores, time series of stable oxygen isotopes from Greenland ice cores, and tree-ring analysis (dendrochronology). A modeling study by Kutzbach *et al.,* (1996) found that replacing late 20th Century orbital forcing with that of the mid-Holocene increases summer precipitation by 12% between 15^0 N and 22^0 N. Oceans also play an important role in global change because of their large extent and conservative thermal properties. Fluidity, salinity, and deepness of the ocean influence the cycling of energy between the land and the oceans (Stern, *et al.,* 1992). The Earth is a complex and variable system in which the atmosphere, biosphere, oceans, and lithosphere are connected. Natural linkages and feedbacks produce shifts in the planetary temperature regime, which directly affect the atmosphere, global circulation patterns, precipitation, and soil moisture.

More recently, the cumulative effect of human actions has produced ecosystem changes that are global in scope. Climate experts, scientists from other disciplines, and general public have become increasingly aware of the impact of human action on current and future states of the global environment and human welfare. The 2007 report of the Intergovernmental Panel on Climate Change confirmed that there is overwhelming evidence that humans are affecting the global climate. Most human activities have some albeit indirect potential relevance to global change and the human fingerprint is abundantly seen in the global atmosphere, the world oceans, and land cover on all continents. An immediate concern is human-induced climate change and according to MacDonald and Sertorio (1989), changes in the composition of the Earth's atmosphere due to human activities, now dominated changes that occur naturally. Increases in greenhouses gases (GHG's) into the atmosphere (carbon dioxide, methane, nitrous oxide and chlorofluorocarbons) provide a warming blanket by trapping thermal outgoing infrared radiation emitted by the Earth's surface and the lower atmosphere (MacDonald and Sertorio, 1989). A current exponential rate of increase for atmospheric carbon dioxide has been detected all around the world. Carbon dioxide is a naturally occurring GHG and its atmospheric concentration has increased nearly by 35% since the beginning of the industrial Era. Prior to the industrial revolution in 1765, the Earth's atmosphere contained 280 ppm of CO_2 and by 2005 the concentration reached 380 ppm and it is still rising (Cowie, 2008).

Land transformation is another very important driver of global change that is altering the Earth system. According to Vitousek *et al.,* (1997), land transformation encompasses a wide variety of activities, 10 to 15% of Earth's land surface is used for agriculture or occupied by urban industrial areas and another 6 to 8% has been converted to pasturelands. Effects of land transformation extend beyond the changes in reflectance from transformed lands; carbon emissions from land clearing contribute around 20% to current CO_2 emissions. Natural and anthropogenic influences have combined to change global temperature and precipitation, deplete stratospheric ozone, produce irreversible losses of biological diversity, change hydrological systems and the supplies of freshwater, degrade land, and increase stress on food-producing systems. Similarly, recent increases in the frequency and intensity of extreme events such as drought, floods and severe storms have been noticed and are a direct consequence of the alteration of natural environment systems. Several climate model scenarios predict increased dryness in arid and semi-arid mid latitude land areas as a result of global climate change. As evident from climatic impacts during the 20^{th} Century, drought and flooding are major problems impacting West African countries.

West Africa lies between latitudes 4^0N and 28^0N and longitudes 15^0E and 16^0W and is composed of sixteen countries (which cover an area of 7,800,000 km^2). West Africa includes Mauritania, Mali and Niger along the north, extends to the Gulf of Guinea in the south and the the Atlantic Ocean to the west, and as Far East as Mount Cameroon. This African region has many problems related to the climate change and desertification. It has been divided into four climatic regions, based on the rainfall gradient, which incorporates a high interannual rainfall variability (Fig.2.1):

1. the Saharan-Sahelian zone receiving less than 200 mm of mean annual rainfall (desert),
2. the Sahel situated just in the south of the Sahara desert between isohyets 200 and 500 mm (arid),
3. the Soudanian zone lying between isohyets 500 mm and 1000 mm (semi-arid), and
4. the Guinean climatic zone with an average rainfall between 1000 mm and 1500 mm (sub-humid).

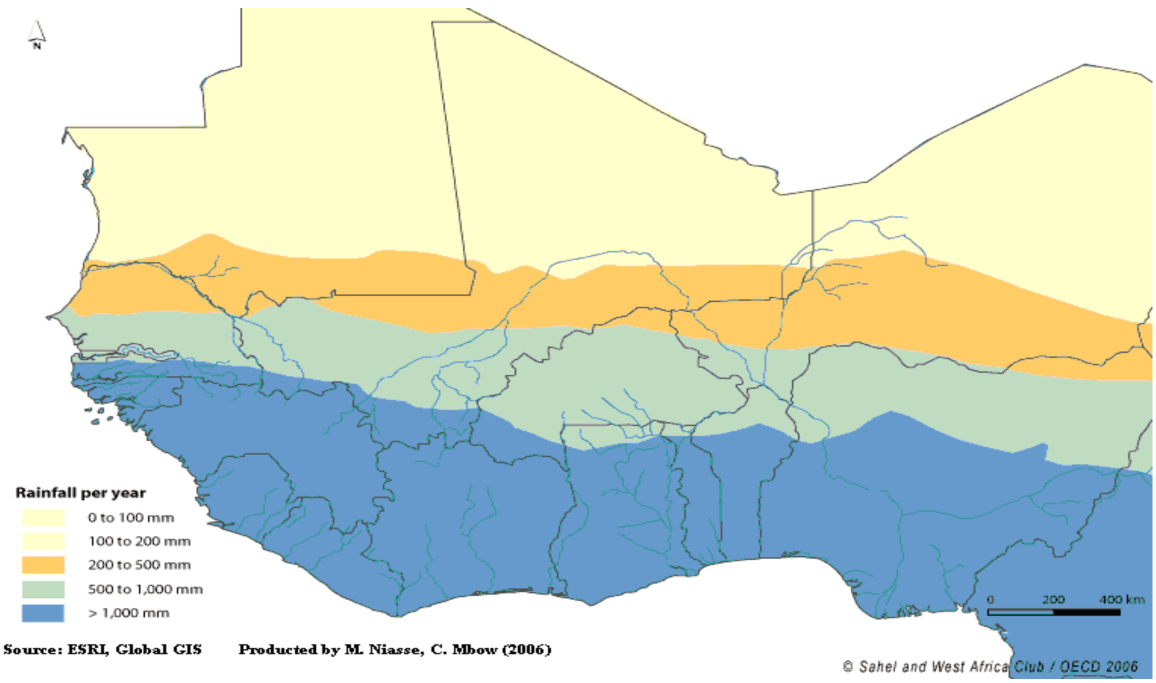


Figure 2.1 West African Bio-climatic zones (http://www.atlas-ouestafrique.org**)**

West Africa covers one fifth of the African continent. The major part of the Sahel zone, is located in West Africa with around 450 millions square miles (Forson and Bationo 1997). The Sahel zone includes portions of Mauritania, Senegal, Mali, Burkina Faso, Niger, and extends into East Africa. Since 1963, a large part of this area has been affected by a long and severe drought. Climate variability is illustrated by three major periods: the 1930-1960 wet periods; the 1970-1980 drought; and the return of rainfall during the 1990s and 2000s. Djomou *et al.,* (2008) found that the spatiotemporal evolution of different climatic zones has been shown through the extension of arid climate (Sahara) and the reduction of wetter climate zones. The decrease in rainfall has been associated with a temperature increase varying between 0.2 and 0.8°C, since the end of the 1970s. Temperature changes in West Africa and particularly in the Sahel have been faster than global warming. Negative aspects of the warmer and drier climate have impacted ecosystems and the economy of this part of the African continent, which has experienced environmental degradation, loss in biodiversity, and severe economic hardship.

Warren *et al.*, (2001) reported that over fifty per cent of the population of the West African Sahel lives in rural areas, where they depend on rain-fed agriculture and/or on pastoralism. Most of West African people depend on the northward movement of the summer monsoon. Summer monsoon rains mean life or death for over 100 million people (Stern *et al.*, 1992). Several major forces of the Earth's weather systems join together to produce the African monsoon and its borders in time and space are variable (Stern *et al.*, 1992). Sea surface temperature changes in the northern and southern Atlantic Ocean, in the Indian Ocean and the El Niño phenomenon in the Pacific, are important driving forces for West Africa's monsoon activity. The monsoon dynamic is also affected by continental surface processes. In the 1970s, the summer monsoon was restricted to the south and failed to reach Sahelian countries, leading to drought and the death of several thousands of people, livestock, and wildlife. Water resource issues are among the most serious of concerns for the population and decision makers in Sahelian countries. Underground water tables have decreased and several flowing rivers and lakes have dried up dramatically during these last three decades.

2.1.1- Water issues in West Africa

According to Rosegrant and Perez (1997), one-half of the water resources in Africa are concentrated in the Central region, while only about 4% are in the Sudano-Sahelian area and about 1% in Northern Africa. However West Africa has an important number of lakes and reservoirs, 52 rivers, and a number of important wetlands. Niasse (2005) reports that there is a high level of water interdependency in the region where 17 countries share 25 transboundary rivers; the Niger River basin is shared by 11 countries, the Lake Chad system is shared by 8 countries, the Volta River system by 6 countries and the Senegal River by 4 countries (Fig.2.2). The river systems of the Sahel zone have their source in high rainfall areas to the south, before flowing northward into the Sahelian area. For example, the Niger, Senegal, Casamance, and Gambia rivers all have their source in the Mount Fouta Djallon region in Guinea, which is in the tropical humid climatic zone. Another group of rivers flow southwards into the Gulf of Guinea and the flow and flood regimes of these rivers differ from north to the south within the region. Examples include the Bandama, the Oueme, and several Nigerian rivers. Several lakes are present within the region; the largest is the Lake Chad, whose main source is the Chari and Logone Rivers (which provide over 90% of Lake Chad's water).

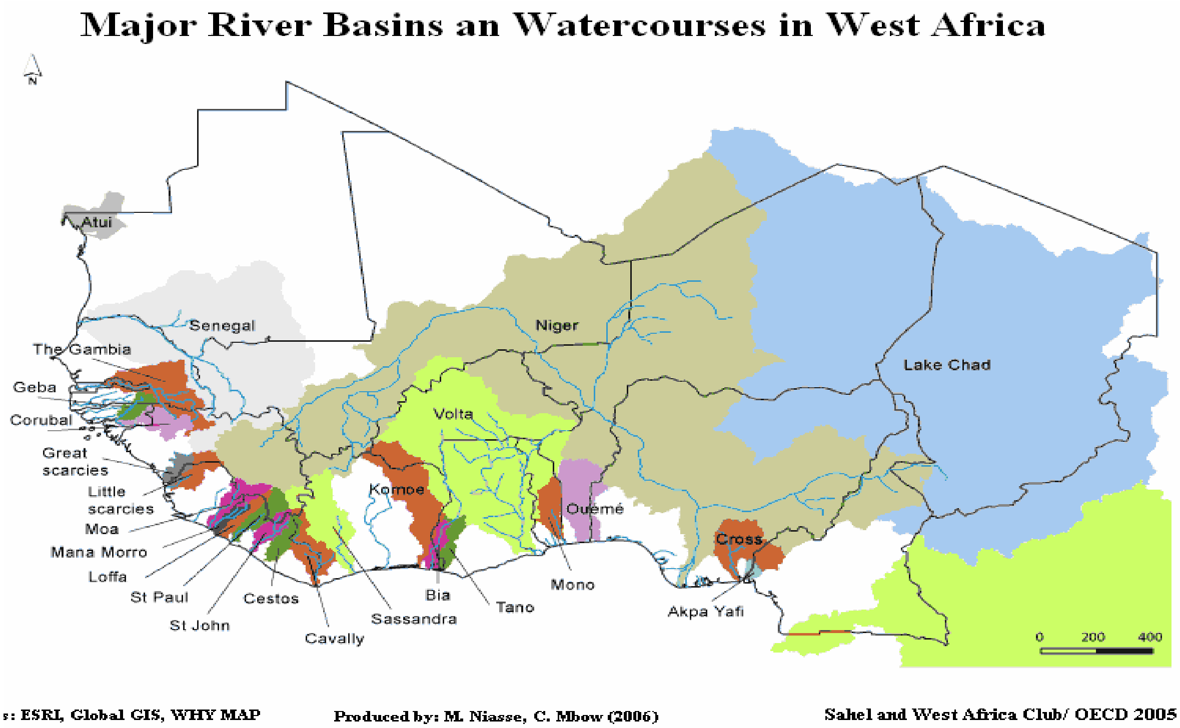


Figure 2.2-Transboundary Watercourses in West Africa (http://www.atlas-ouestafrique.org).

West Africa is a region with abundant groundwater reserves and sandstone aquifers are a very important source of water. Aquifer systems are interdependent and eleven sedimentary transboundary basins have been identified in the region (ECOWAS, 2006) (Fig.2.3). The most important water bearing rocks are the Createaceous sandstones of the Continental Intercalary aquifer found in Niger and the Northern Mali. The Tertiary age Continental Terminal sandstones of southwestern Niger, various areas north of the Niger River, and locations in Senegal and Mali have very important ground water reserves. Other areas include the Voltarian sandstone, the shale aquifer of Ghana, and the Benne shale and limestones of southeastern Nigeria. Several groundwater resources are differentiated depending on water table depth and recharge rate. Locally, ground water is available from near-surface water tables which may be refilled during the rainy season. Ground water reserves from the deeper rock layers are estimated at a thousand billion cubic meters but are non renewable (ECOWAS report, 2006).

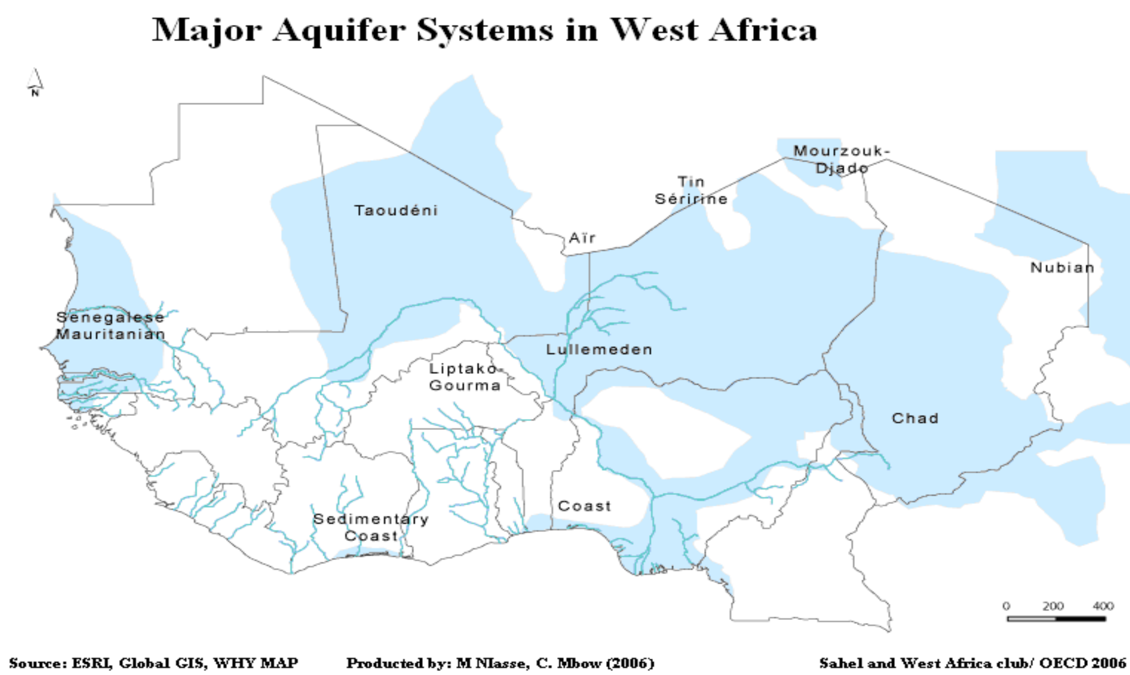


Figure 2.3 - Main Transboundary Aquifer Systems in West Africa (http://www.atlas-ouestafrique.org).

A shortage of freshwater resources is a severe problem in many regions of the world. At the global scale, 1.2 billion people lack access to fresh water and 3.3 million have no effective sanitation, contributing to deaths of more than 3 millions people each year from water related diseases (Turton *et al.,* 2003). The countries of West Africa have not been spared from the concerns of limited water supplies, several countries face water scarcity. However the 2006 ECOWAS report highlights that all West African countries, except Cape Verde and Burkina Faso are not below international standard of water scarcity (1,700 cm^3 of renewable fresh water per year per person).

The major problem is water availability at a desired time and place. The countries of West Africa face a decline in the availability of water resources as a result of their rapidly growing population and the concurrent precipitation decrease. River flow in the North is concentrated in high flows and possible floods during August and September whereas flows in the south are more likely to be spread throughout the year. Since the 1970s, severe drought resulted in a depletion of regional water supplies. Niasse *et al.,* (2004) reported that "since 1970, the mean annual rainfall has decreased by 10% in the wet tropical zone to more than 30% in the sahelian zone while the average discharge of the region's major river systems dropped by 40% to 60%." The Niger, which is the third largest river in Africa, dried up completely for several weeks in 1985. The Senegal River also has seen its flow dramatically reduced since 1960 (Venema *et al.,* 1997).

Water consumption in rural areas is generally restricted to household and agriculture water use. Agriculture is the major user of fresh water but the growing population living in urban areas has helped justify policies and infrastructure to transfer water from agriculture areas to supply urban demands (Stockle, 2001); these changes are putting additional pressure on rural water availability. Human activities have an important impact on surface water availability, groundwater depletion, and water quality. Many fresh water sources are stressed beyond their limit in several river basins. Impacts of climate change and human action on groundwater variation is not well understood in many developing countries.

In West African coastal areas, groundwater supplies are not too deep and the use of pumps to irrigate lands for agriculture is one reason for groundwater depletion. Since 1976, the west coast of Senegal has undergone a lowering of the water table by 0.1 m to 0.2 m (Mayenga 1987). The decline in the discharge of major watercourses has been observed in a significant reduction in riverine surface area. The inland delta of the Niger River decreased from 37,000 km^2 in the 1950s to about 15,000 km^2 in 1990. Lake Chad was one of the largest lakes in the world when first surveyed in 1823 and it was evaluated at 20,000 km^2 before 1970. Lake Chad shrank to less than 7,000 km^2 in the early 1990s (Niasse *et al.,* 2004) and by 2000 it was less than 1,500 km^2. Nyong (2005) showed that by 2001, the Chad Lake was 5% of its former size, just 35 years ago (Fig.2.4). However between 2003 and 2007, there was a notable increase in the water surface area of the lake associated with increasing rainfall (Atlas-ouestafrique) (Fig.2.5).

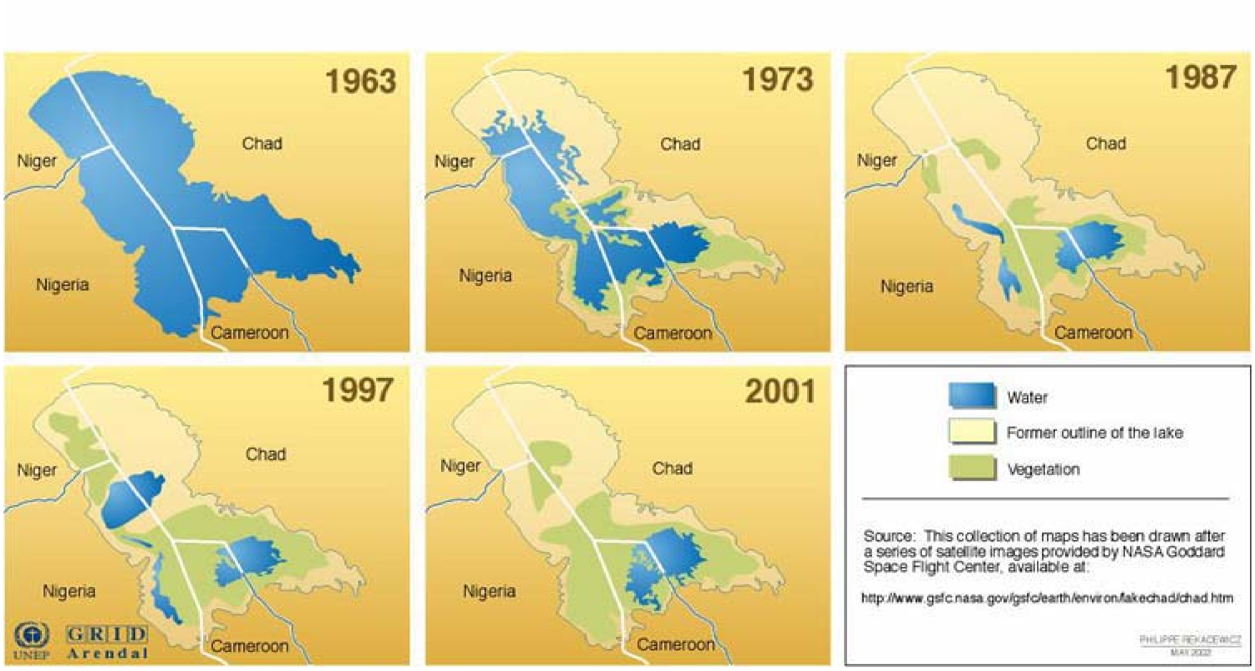


Figure 2.4- Spatiotemporal Change in Lake Chad's surface area (1963-2001) Nyong (2005).

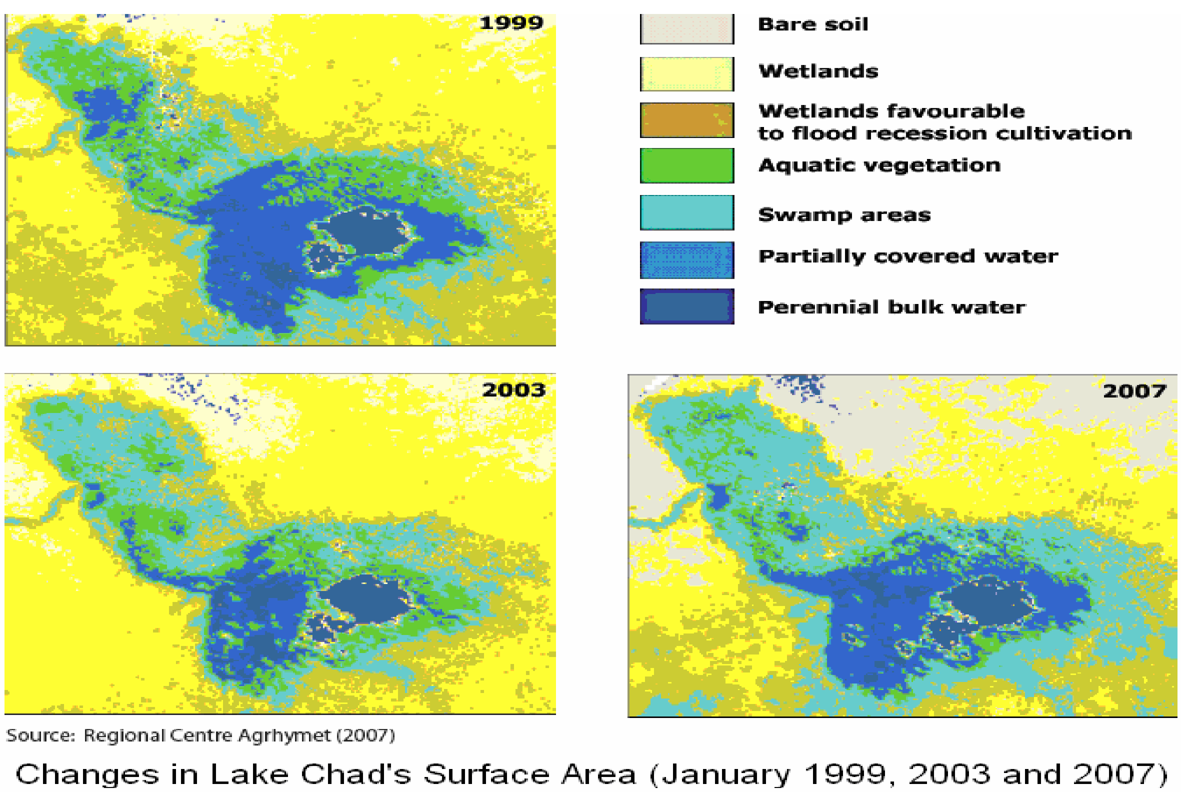


Figure 2.5- Spatiotemporal change in Lake Chad (http://www.atlas-ouestafrique.org).

In addition to water scarcity, water pollution is another important problem affecting the West Africa. Use of pesticides and fertilizers for agriculture has affected the quality of groundwater and surface water. Pollution from fertilizers, pesticide, waste, and animal manure all contribute to West Africa's water stress. Woods (2005) reported that pesticides in rivers and lakes can act to reduce fish reproduction levels as well as lowering water quality to below standards for human consumption. In many rural areas, villagers use contaminated pond and river water for drinking and household tasks. Unfortunately, a severe cholera epidemic has burdened the region since 2003. During the dry season women and children walk, sometimes very long distances everyday to look for potable drinking water. Several management techniques have been implemented in an effort to deal with water scarcity.

2.1.2- Impacts of water management on the environment

Hydrological processes in the West African River basins (WRB) have created a dynamic equilibrium in this region. The problem of local water depletion and availability has caused an increasing dependency on food provision in developing countries. Several large and small dams have been constructed to enable more dependable water supplies (Fig.2.6). Dams enable storage of fresh water during the wet season and in years of excess for when needed, combating hydro-climatic variability. They also facilitate transport of stored water to deficit areas through canals, tunnels or pipes. Thus dams contribute to the economic development of the subregion and help to mitigate flood and drought. A majority of dams built in West Africa are mostly for irrigation purposes or for generation of hydropower. The Akossombo dam on the Volta Basin in Ghana is a multipurpose facility, providing both hydroelectricity and water for irrigation. Manantali dam located in the Senegal River basin in Mali was constructed to generate electricity and also to facilitate navigation on the Senegal River. Diama dam in Senegal is a salt wedge dam blocking salty water from coming up river and helps agricultural irrigation in Saint Louis region.

Water management, with construction of dams as reservoirs, started in colonial times in West Africa and has substantially accelerated in the years after independence. However there are fewer than 150 large dams present in the region, out of total of 1,300 on the continent, and 45,000 in the world (Niasse 2005). According to the ECOWAS report (2006), the region has only two large dams for 100,000 km^2 and for the same surface area China has 240, India has 30, Japan has 670 and United States has 75 large dams. The International Commission on Large

Dams (ICOLD) defined large dams as a dam with the height of 15 meters or more from the foundation and also dams with height between five to 15 meters having a reservoir volume of more than 3 millions cubic meters. Among the 30 largest dams in Africa based on storage capacity, nine are located in West Africa (FAO Aquastat).

Despite the efforts in dam building, the lack of efficient management infrastructure, to boost agriculture and the economy, is a main cause of food stress in the region. An estimated of 700,000 hectares of arable land in Africa remains uncultivated (Grimm and Richter, 2008), and among 75.5 millions hectares of arable land in West Africa, only 1.2% is developed for irrigation and 0.8% is used efficiently (FAO, 2007). Development of irrigation projects can contribute to an improved agriculture management system. Dams have positively impacted a number of agricultural areas by increasing irrigated surface area. Irrigation technology allows for ‘off season’ farming because of the ability to access water for year-round use. However, irrigated agriculture can be a major threat to the water quality in terms of eutrophication and salinization.

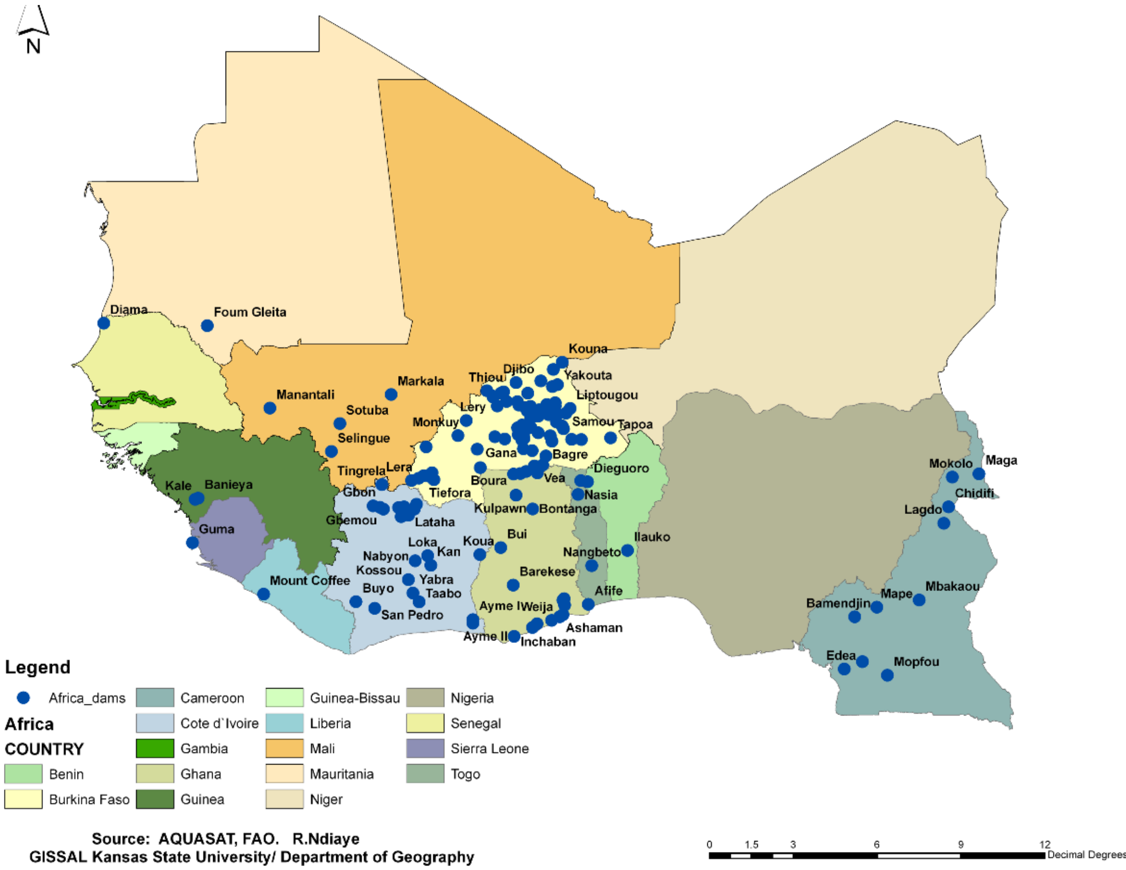


Figure 2.6- West African Dams.

2.1.2.1- Impacts on water resources

Today, big dams and reservoirs are considered vital for economic prosperity and agricultural development all around the world. Thousands of dams are still being built to store water and make it available during the next century; this is especially true in West Africa, where arable lands are underused. While dams do perform a vital function, by managing water resources to reduce the agricultural production risk and nutritional vulnerability, their impact can be damaging for River basin ecosystems.

Water withdrawal for agriculture use, domestic consumption and industry is increasing over time and all scientists agree that water consumption will be higher in 30 years than it is today. Withdrawing surface waters induces changes to the natural hydrology of rivers and streams and changes the water temperature; in addition, ground water overdraft can cause an increase in salinity concentration of the aquifers. Dams can divert the flow of rivers which results in changes, both downstream and upstream. Water resource management associated with large dams creates an artificial flow regime downstream from the dam location. Tiga and Challawa dams located in the Komadugu Yobe river system in Northern Nigeria divert a substantial share of the river flow for domestic use and irrigation. Niasse (2005) reported that the combined effects of climate change and variability and of water diversions of the Yobe River resulted in a significant decrease of the average annual flow, which declined by 37% from the 1964-69 period to the 1970-79 period, and by 26% from the 1970-79 period to the following decade and now contributes only about 1% of the total water inflow to the Lake Chad. A reduction in peak discharges in the River Volta occurred after the construction of the Akosombo Dam and the annual discharge of the Volta River fell very low between 1964 and 1968 as the dam filled (Adams 1993); in 1998 its reservoir fell below its operating level, resulting in severe power shortage. Adams (1997) reported that when the Lagdo Dam on the River Benue in Cameroon was closed to fill the reservoir in 1982, discharge of the Benue at Garoua fell to about 43 per cent of average flows, even though it was a wet year. Impoundment of the Kainji, Bakolori, Kiri and Pankshin dams, located in the Niger delta, reduced the discharge from 7,000 m^3/s to 3,000 m^3/s and the the Kainji hydro-dam, has lowered peak water levels at Lokoja by approximately 11.3 m (Abam, 1999). The nature of hydrological effects has been linked with the purpose of the dam and the seasonal regime of the river. According to Adam (2000), hydroelectric dams are designed to create a constant flow through turbines, and therefore tend to have a similar effect on discharge patterns. Dams for irrigation cause moderate variation in flow regime on a longer timescale, storing water at seasons of high flow for use at times of low flow.

Alteration in the water chemistry and quality has been observed as result of river fragmentation. The degradation of water quality, downstream of dams, by salt, agrochemicals, and toxic leachates is a serious environmental problem (Stockle, 2001). In the SRB the construction of the Diama dam has changed the seasonal dynamics of the saline-fresh water boundary. Downstream from the dam, a reduction in dilution means that waters are richer in salt whereas upstream waters are free of salt. These changes in salinity are changing the ecology of the delta region. Specific changes due to Diama Dam include a change in sedimentary load due deposition behing the impoundment and the presence of invasive species. The impact of a greater depth to groundwater downstream from the dam can be seen by presence of abandoned wells as the aquifer became too deep and freshwaters could not be reached (Photo 2.1). Abam (1999), using average values for some of the main rivers of the world, reported a 79% reduction in sediment load following the construction of dams. In the Niger delta, the reduction in sediment load as a consequence of the dam construction is about 70%. Disturbance of the natural hydrological system is the major cause of ecosystems change.

Photo 2.1- Abandoned wells after the construction of Diama dam in SRB (Bâ, 2006)

2.1.2.2- Impacts on ecosystems

The modification of the land system after the introduction of dams has been observed in several zones Stokle (2001). Several West African wetlands have been adversely impacted by the construction of managed infrastructure along rivers. Many areas have experienced a reduction in size of the annually inundated floodplain. The Selingué reservoir and the irrigation by "the office du Niger" has provoked a decrease of the inundated area of the inner Niger delta by 900 km^2 (Zwertz *et al.*, 2007). The Bakolori Dam on the Sokoto River in Nigeria had similar impacts on floodplain agriculture; the dam reduced the area of rice by 7000 hectares and dry season crops by 5000 hectares, out of a total of 19000 hectares of floodplain land (Adam1997). These improvements for regulating river flow and the creation of the reservoir, and other dike constructions are creating profound environmental changes affecting the biodiversity.

Changes in the chemical composition on the upstream side of a dam can cause the proliferation of invasive species. The Senegal River is invaded upstream of Diama Dam by aquatic plants, *Typha australis*, *Salvinia molesta,* and the Water Lettuce, *Pistia strtiotes,* disturbing the biological equilibrium and ecological characteristic of the river and adjacent floodplain. Many wildlife species cannot tolerate such ecological changes. Shifts in vegetation types and species extinction are among the major threats in most of West African river basins. The tree *Acacia nilotica* is endangered year-round by the presence of freshwater in SRB. Increases in soil salinity has led to an increase of salt-tolerant vegetation (*Tamarix sp*) in several downstream river dam areas.

The disruption of fish migration, along dammed rivers and between those rivers and the sea, has been observed. This alters the fishery resource and several economically important species are declining or extinct. In the Niger River downstream of the Kainji Dam in the 1960s the catch sizes fell and there were changes in the composition of the fish population (Adam, 1993). The population of shrimp has also been decimated by the change in water salinity. Adam (1993) reported that because of the Diama salt wedge dam, there is a loss of some 7000 metric tons of shrimp and fish in the Senegal Delta. Environmental change and the degradation of ecosystems are strongly related to the social life and to economic activities. Economic activities depend on the availability of natural resources.

2.1.2.3- Social and economic impacts of water management

River basin ecoregions of West Africa are also facing unprecedented socio-economic changes. There is a strong relationship between the economic sector and water availability. Impacts of water management infrastructure in particular communities are dependent on the nature of local agriculture and fishing. The United Nations Office for West Africa reported that the population in the region is expected to increase from 290 million in 2005 to about 430 million people in 2020 and that the rural population consists of 145 million people. Population increase will result in an increase in the demand for water, even if per capita consumption declines slightly. The withdrawal of fresh water resources is increasing very rapidly and if West Africa maintains its current level of access to drinking water and food security, water withdrawals would then increase from 11 billion to more than 65 billion m^3 per year (West Africa atlas). There is already a high concentration of people in river basin areas, as they rely on the available resource. Rivers play an important role on the social life and economic activities of people.

Water management, with its accompanying changes in local ecosystems and in natural resource use, has led to changes in human behavior and activities. Before the construction of dams and implementation of areas with large scale irrigation, major activities (farming, fishing and breeding) were organized year round in floodplains and were strongly related to the natural river flow regime. In the traditional system, there was a distribution of land rights among fishermen, livestock breeders, and farmers. Fishermen were more active during river floods because of fish proliferation and stockbreeders used the space after the harvest (Ndiaye *et al.*, 2007). Farmers developed an annual crop rotation according to the water amount in inundated areas. The construction of dams changed river flows and changed the spatio-temporal availability of water. Modern ways of exploiting river ecosystems force adjustment in human behavior because in many West African countries there is specialization by ethnic group toward certain economic activities. Zwertz *et al.,* (2007) pointed out that in Mali, Bonzo and Sonomo people are the fisherman, Fulani as everywhere in the region are herdsmen, and Marka, Bambara and Sonrai are farmers. Forcing a change in activities for these peoples is like a request for them to abandon the culture they inherited from their ancestors.

Decrease in fish populations in certain zones results in a change in activities and sometimes the displacement of people. The number of seasonal fishermen fell in the Niger valley. Similarly, in the Sokoto Valley in Nigeria, fishermen complained of reduced catches following closure of the Bakolori Dam in the late 1970s, and a number of them had taken to traveling hundreds of kilometers to fish at Lake Chad (Adam1997). Dam construction requires relocation of residents of the impoundment area and this generates conflict between decision maker and people. In 1963, 80,000 people were moved from their homes to make way for the Akossombo Dam in Ghana; for the Kossou Dam in Cote d'Ivoire, and Manantali Dam in Mali respectively,70,000 (1970) and 10,000 (1987) people have been relocated (Diop *et al.*, 2009).

Irrigation management and dams have been implemented for rapid agriculture and economic development. Stable food production and electricity supplies are guaranteed in areas with dam and irrigated land. However many people living downstream suffer when the river level drops and the area of annually inundated floodplain is reduced in size as result (Zwertz *et al.,* 2007). These conditions may create conflict between ethnic groups. In this context, the middle and downstream States of Jigawa, Yobe and Borno (Nigeria) complain more and more virulently about the lack of fairness in the sharing of the river water between Kano (the upstream

State) and other riparian States (Niasse, 2005). As most river basins of the region are shared at least by more than one country, there is a high degree of interdependency among West African countires concerning water resources. Niasse (2005) identified that each West African country shares at least one of the region's 25 transboundary river basins. For efficient management of water resources it is necessary to establish coordinated planning among nation states sharing the same basin. Bilateral and multilateral cooperation already exists in the region; examples include the Senegal, Niger, and Lake Chad River basins. Despite the existence of these institution and governance structures, the transboundary nature of many West African rivers and increasing water scarcity has resulted in conflicts between countries and between populations rendering the management of these rivers more difficult. In 1989, a dispute between Senegalese farmers and Mauritanian breeders along the river caused the death of a hundred Senegalese residents in Mauritania, a repatriation of 75,000 Senegalese and 150,000 Mauritanians, and thousands of black people with Mauritanian nationality were deported to Senegal (Niasse, 2005).

Lack of coordinated development between Ghana and Burkina Faso is at the origin of suspicion and controversy regarding the severe power shortage triggered by a water decrease in the Akosombo Reservoir, which fell below its operating level. This decline in water level was linked to an increase in water withdrawal in the upper basin of Volta Lake by Burkina Faso planners through dam building and irrigation development (Niasse, 2005).

Most of the major West African rivers have been dammed in at least one place and numerous changes have been identified in the region: loss of habitat, obstruction of fish and wildlife migration, deforestation, salinization and acidification of soils, and loss of fisheries, crops and pasture land. Management and policy implementation are very important in protection and conservation of natural resources. Management includes the supply of hydro-electricity, clean water, water for irrigation, navigation, and flood control, but also the development of fisheries and environmental protection. West Africa is a region where irrigated agriculture is least developed, however it has been demonstrated that, in most valleys, irrigated agriculture was the basis of infrastructure development. Irrigation agriculture depends on water supplies from surface or ground water and future allocations are threatened by declines in either water quality or quantity resulting from climate change. Climate models suggest a consistent 21st Century response in both mean annual and seasonal temperature change; in all African subregions, projected changes include warmer conditions ranging from 3.6 C degree in the Sahara area by the decade of the 2080s and drier conditions are projected in Sahara as well.

2.2- Soil degradation and salinization with an emphasis on problems in West Africa

Soil degradation occurs with the loss of equilibrium of a stable soil. Erosion is the main factor for soil degradation. Erosion is the term given to soil loss due to the mobilization of topsoil by physical forces such as rainfall and flowing water. The problem of soil erosion is manifest in many regions, for example, during the dust bowl in the Great Plains in the 1930s and in the Sahel from the 1970s into the 80s. The GLASOD (Global assessment of the human induced soil degradation) project (1987-1990) produced a world map of human-induced soil degradation, with data compiled in cooperation with a large number of soil scientists. They identified several types of soil degradation affecting worldwide soil: water erosion; wind erosion; chemical deterioration; physical deterioration and the degradation of soil biological activity. The degree of soil degradation is estimated in relation to changes in agricultural suitability, in relation to declined productivity, and in some cases in relation to its biotic functions. Four levels of soil degradation have been identified (Tab.2.1). The GLASOD project with data stored and analyzed on UNEP's Global Resources Information Database (GRID) allows evaluation of land degradation at different spatial scales, for different regions, and by different causes (Goudie and Alexander, 1997). Figure 2.7 shows the severity of human-induced soil degradation for some West African countries. Water and wind erosion, salinization; which is a manifestation of chemical deterioration, are major factors affecting soils in West Africa.

Table 2.1- GLASOD definitions of degrees of degradation

Light	The terrain has somewhat reduced agricultural suitability, but is suitable for use in local farming systems. Restoration to full productivity is possible by modifications of the management system. Original biotic functions are still largely intact.
Moderate	The terrain has greatly reduced agricultural productivity, but is still suitable for use in local farming systems. Major improvements are required to restore productivity. Original biotic functions are partially destroyed.
Severe	The terrain is non reclaimable at farm lever. Major engineering works are required for terrain restoration. Original biotic functions are largely destroyed.
Very Severe	The terrain is unreclaimable and beyond restoration. Original biotic functions are fully destroyed.

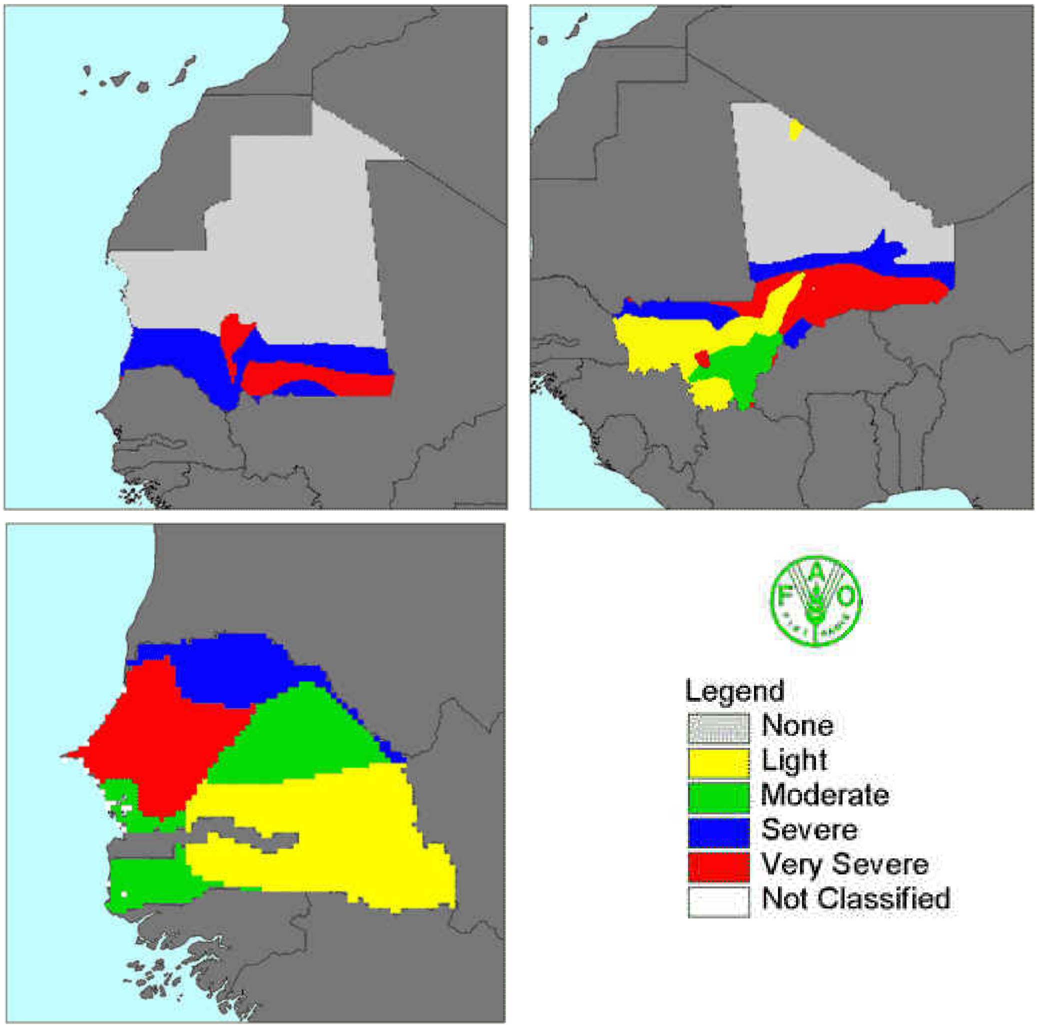


Figure 2.7- Human Induced Soil Degradation for Senegal, Mauritania, and Mali. (FAO: http://www.fao.org/landandwater/agll/glasod/glasodmps.jsp)

2.2.1- Soil erosion

Soil erosion is a natural process, occurring over geologic time, but the rate of soil erosion has been significantly increased by human activity. Accelerated erosion by running water and wind velocity have been identified as the most severe threats to African soils. By removing the most fertile topsoil, erosion reduces soil productivity and can lead to an irreversible loss of natural farmland. Soil erodibility depends on the physical and chemical propriety of the soil. Cohesive soil with more than twenty percent clay and naturally cemented soil or coarse gravel rich soil is not easily eroded by wind or water. According to Dunyo *et al.,* (2004) soil types, vegetation cover type and percentage, land use, and rainfall erosion potential play an important role in the erosion process. In the Sahel zone, sandy soils developed on stabilized dunes, cover a very large area. These granular soils are very vulnerable to water and wind erosion.

Human activities, such as deforestation, overgrazing and agriculture combined with the lower annual rainfall amounts that have occurred since about 1970 have triggered the denudation of land and an increased vulnerability to erosion (Heyward and Oguntoyinbo, 1987). Deforestation and agricultural practices lead to removal of sediment at a rate several times faster than natural processes (Dickinson *et al.,* 2007). Removing vegetation cover exposes the soil surface to raindrop impact and surface runoff, resulting in an overall degradation of land condition. Bushfire, the principal tool when clearing land for agriculture and pastoral activities, results in an 80-fold increase in erosion rate when compared to undamaged herbaceous cover (Heyward and Oguntoyinbo, 1987). Moreover, the expansion of areas under cultivation increases the rate of erosion. In Fandou Beri (Niger) the comparison of an aerial photograph from 1950 with one taken in 1992 shows that cultivated area has expanded from 11.3% to 23.4%, and the rate of land cover change is almost directly related to the erosion rate (Warren *et al.,* 2001).

Several studies in a variety of environments have demonstrated the positive effect of vegetation and litter cover on the reduction of water erosion. The presence of annual vegetation and plant residues on the soil surface can be responsible for a reduction in soil loss (Dunyo, 2004). Buerkert and Lamers (1999) observed in southern Niger that mulching reduced sand flux by between 25 to 50% during rainy season storms. Areas with heavy rainfall and steep slopes are subjected to a high degree of erosion. In Inno State (Nigeria) for 12,689 km^2 of the land area of the state 3962 km^2 is affected by severe sheet erosion, 297 km^2 by gully erosion (Photo 2.2) and 8729 km^2 by slight erosion (Heyward and Oguntoyinbo, 1987). In Senegal, 77% of the degraded soils are due to water erosion. Soil degradation from water erosion in the eastern part of Senegal occurs on soils layered predominantly with ironstone and gravel, the ironstone layers are in the Ferlo area (high relief), the Ndiass plateau (near Thies, steep cliffs and degraded vegetation), south-eastern Sine Saloum, and the eastern Casamance area (Planchon and Dieye, 2002).

According to Fedemma (1999) similar activities also lead to topsoil loss associated with wind erosion, the second largest cause of soil degradation in West Africa. In the Sahel, sandy soils with sparse vegetation are severely degraded due to wind erosion. When the percentage of soil surface cover decreases from 40% to about 20%, soil loss due to wind erosion is increased four-fold (Valentine, 1996). According to Sterk *et al.,* (1997), winds that exceed the threshold wind speed for soil particle movement may occur during two distinct seasons in West Africa: during the dry season subject to the Harmattan which originates from the Sahara desert (northeasterly winds); and with thunderstorm downdrafts during the early rainy season (May-July). The early rainy season is the most important erosion period for the Sahel. Strong winds result in soil particle movement and creates the typical dust storms known over the Sahel region (Sterk *et al.,* 1997) (Photo 2.3). In Senegal, wind erosion affects 3% of the degraded land and it occurs in very sandy soils situated in the "Niayes" region from Dakar to Saint-Louis, the border of the Senegal River basin, the peanut basin in the central North, and the sandy Ferlo area (Planchon and Dieye, 2002). In Southeast Niger, during the 1993 rainy season the calculated soil loss from a plot during four storms was 45.9 mg ha^{-1}, which corresponds to a soil layer with an average depth of 2.7 mm. However, dustfall is a major source of fine particles for the sandy soils of the Sahel which contribute to soil fertility improvement.

There are several approaches to measuring soil erosion. Cesium-137 techniques described by Waren *et al.,* (2001) were used in Fandu Beri to measure soil flux over a 30 year period and erosion ranged from 26 to 46 t ha^{-1} yr^{-1}. However one of the most commonly used approaches is the Universal Soil Loss Equation which uses data on rainfall, runoff, the size and shape of the slope, the soil cover, and the erosion-control practices to predict the amount of soil moved:

(A = RKLSCP)

where: A = soil loss per unit area (tons ac^{-1} yr^{-1}), R = long-term rainfall and runoff erosion factor, K = soil erodibility index, LS = slope length and steepness factor, C = soil cover and management factor, and P = the erosion-control practice factor. The advantage of using this equation is that after getting a predicted soil loss by multiplying all factors together, the value of conservation practices may be ascertained through adjustment of the C and P factors (Keller, 2005). Water and wind erosion are often intimately linked at a location. Disaggregation of soil clods into individual particles due to the impact of raindrops and particle sorting, induced by sheetflow greatly encourage wind erosion processes during the subsequent dry season (Sterk *et al.,* 1997).

Several conservation techniques have been implemented in the region for protecting soils. Mulching, ridging, and mounding are the main techniques that provide positive result in decreasing soil loss. Soil fertility declines are not just a problem of nutrient deficiency; it is also a problem of physical and biological degradation of soils. Mulching induces changes in the topsoil and increases availability of nutrients (mainly P) and decreases amounts of toxic elements such as Al. Buerkert and Lamers (1999) measured, over a 21 month period, the cumulative erosion by wind and water of almost 270 t ha^{-1} of soil in unmulched control plots. Between 160 and 200 t ha^{-1} of soil were deposited in the mulched plots. The authors identified that increases in millet yield after the application of mulched crop residues have been observed in Niger. Crop-ridging and mounding, two important traditional conservation practices throughout West Africa, also help to decrease sediment transport.

Photo 2.2- Gully erosion from over-cultivation, Sahel, West Africa

Source: Courtesy United States Geological Survey

Photo 2.3- Dust storm in the Sahel (Source: *In Planchon, 2002)*

2.2.2-Soil salinization

Soil salinization is the concentration of salts at the surface or near surface of soils. It is one of the major causes of poor soil quality associated with arid and semi-arid regions. Metternicht and Zinck (2008) reported that saline soils are common in the semi-arid and arid region where low rainfall and high evapotranspiration cause sodium, magnesium, and calcium to concentrate in soil horizons mainly in the form of chloride and sulfate. In less arid climates, sodium carbonate and bicarbonate dominate and sodium ions get absorbed on the soil exchange complex, causing the formation of sodic soils (Metternicht and Zinck, 2008). Human induced salinization is a major problem in drylands and is often associated with large-scale irrigation works. Salinization can be divided into two types: natural or primary salinization and human induced soil or secondary soil salinization. In Senegal, natural soil salinization is frequent in the coastal zone where marine intrusion provides a source for salts. Irrigation schemes, such as those on the Senegal River, the Hadeja River in Nigeria, and the Logone River in Camerooun are suffering from the effects of secondary salinization (Yaalon and Yaron, 1966). A general estimation of global extent of salt-affected soil is about 1 billion hectares, which represents 7% of the earth's land extent (Abdelfattah, 2009). According to GLASOD, 76.3 million hectares have been salinized as a consequence of human activities and this represents 3.9% of the 1964 million hectares affected by human-induced soil degradation worldwide (Metternicht and Zinck, 2008). For the African continent salinity and alkalinity affect about 24% of the land (Reich *et al.,* 2001).

The effect of salinization is often exacerbated by inadequate farming practices. Salinity has been associated with irrigated agriculture since its beginning because irrigation water contains dissolved salts (Stockle, 2001). In addition to minerals within the soil, both rain water and irrigation return flows are sources of salts. At the rice irrigation scheme of Foum Gleita, situated in south central Mauritania, irrigation, drainage, and groundwater samples were classified as sodic-alkaline water (Asten *et al.,* 2003). This level of concentrated salt solution eventually leads to physical and chemical soil degradation (Asten *et al.,* 2003). When drylands are irrigated, the water evaporates quickly leaving behind previously dissolved salts on the soil surface, since there is little rain to flush the system. These conditions are found in several parts of West Africa particularly in Senegal, Mali, Niger, Mauritania and Burkina Faso. In certain regions, with an over-irrigated condition and with the lack of drainage, groundwater tends to rise and salts are concentrated in the upper soil horizons (Metternicht and Zinck, 2008). Salt in the soil may inhibit the uptake of water by plant roots; eventually, the soil can no longer sustain a vegetative cover.

In the Senegalese coastal zone, the overdraft of fresh groundwater for irrigation and urban use favors the intrusion of saline water into the fresh water depleted aquifers (Metternicht and Zinck, 2008). In the Mboro Niaye zone (Western Senegal), the freshwater groundwater is in contact with the sea water. With the replacement of human powered water lifting with small motored-powered pumps, the salty waters are mixed with the remaining fresh water. In addition to the ground water depletion, the high rates of evaporation in that area have produced a notable increase in sodium in the soil, from 0.2 meq/100g of soil in 1962 to 3.0 meq/100g of soil in 2004 (Ndiaye 2004).

West African ecosystems are highly vulnerable to climate change and human activities. Feddema (1999) declared that global warming can impact a wide area and eventually the entire continent, while soil degradation tends to affect only areas inhabited by humans and where the human impact on the environment is greatest. Soil, once eroded, is unable to support a normal cover of vegetation and is reduced to a condition in which normal ecosystem functioning cannot take place (Dickinson and Murphy, 2007). Damage caused by soil erosion often takes decades to centuries to repair. However several management techniques and policy interventions have been implemented in order to mitigate and reverse soil and water degradation.

2.3- Geosciences contributions to addressing global change issues in West Africa

As a component of the broader area of Geographic Information Science (GIScience), GIS is made up of three terms: Geographic, Information, and System. A geographic information system can be defined as a system which involves collecting, storing, processing, manipulating, analyzing, managing, retrieving and displaying data. The geographic or spatial component is obtained when the data are referenced to real-world locations. GIS has become an essential tool for spatial analysis, which is a process for turning raw spatial data into useful spatial information. Historically, GIS functionalities have been limited to a set of tools for the input, storage and retrieval, manipulation, and output of spatial data. Lately, these tools have been expanded beyond map-making functions into the domains of problem solving and especially modeling and decision-making. Today the label GIS is attached to many things:

1. -a software product carrying out certain well-defined functions (GIS software);
2. -a digital representation of various aspect of the geographic world, in the form of a dataset (GIS data); and
3. - a community of people who use these tools for various purposes (GIS community) (Goodchild and Maguire, 1991).

These capabilities enable GIS users or analysts to take advantage of the display capabilities of GIS and the analytical power of numerical models. According to Goodchild (1990), the science behind the systems, GIScience builds on the accumulated result of many centuries of investigation into how to describe, measure, and represent the Earth's surface.

Most of digital spatial data stored in GIS are derived from external sources such as analogue maps, ground surveys using Global Positioning Systems (GPS), and perhaps most importantly remote sensing techniques (Mesev, 2007). Remote Sensing (RS) is the science of deriving information about an object from measurements made at a distance from the object without coming in contact with the object (Swain and Davis 1978). RS makes it possible to collect data on dangerous or inaccessible areas and the applications of RS include mapping, measuring, and monitoring environmental and climate change. Both GIS and RS are technologies that focus on spatial data and both are designed to represent the world's geographic features as reliably and as realistically possible (Mesev, 2007). Some consider RS to be predominantly a data collection technology whereas GIS is one that is principally dedicated to data handling (Mesev, 2007). Both RS and GIS have established ways to convert available data into information for decision-makers.

2.3.1- Application of GIS technologies for understanding environmental systems

RS and GIS are now providing useful tools for advanced ecosystem management. These GIScience tools allow researchers to assess spatial and temporal characteristics of ecosystems. According to Liang (2004), one basic characteristic of optical RS in the 21^{st} Century is the extensive use of quantitative algorithms for estimating Earth surface variables. The capacity to store and quantify data on a spatial basis can be valuable in mapping, measuring, monitoring, planning, and management. GIS people, procedures, and products can help display site conditions and show some of the variables that must be considered in order to make an informed decision (Lyon and Mc Carty, 1995).

Liang (2004) has described several methods and techniques for estimating land surface variables:

- ecological models for detecting vegetation stress which manifest spectrally through a change in leaf area or leaf color must account for dependence on local conditions (meteorology, hydrology and pedology); interpretation of plant stress is through comparison of a physical variable (e.g., Leaf Area Index and chlorophyll) against the expected performance predicted by the physiological model run in the absence of contamination;
- precision agriculture, which is a management strategy, uses remotely sensed data for estimating certain biophysical variables by integrated ancillary data, such as soil, weather, and past management practices to provide higher levels of information that is pertinent for making decision; change detection can be performed by comparing two different seasonal images, by correlating RS signals to specific variables (soil proprieties or nitrogen deficiency), or by converting remotely sensed data quantification into various biophysical variables (e.g., Leaf Area Index or temperature);
- soil properties such as organic matter have been correlated to specific spectral responses and it has been demonstrated that hyper-spectral remote sensing is very useful for estimating some soil properties, such as organic matter, iron content, and texture; soil spectral libraries have been developed and provide a baseline for estimation of soil properties based on analysis of diffuse reflectance spectroscopy; this spectral library approach opens up a new possibility for modeling, assessment, and management of risk in soil evaluation for agricultural, environmental, or engineering applications.

One geographic model for displaying the real world involves a grid of equal sized pixels and this approach is adequate for modeling natural phenomena that do not show obvious boundaries, such as the gradual change of soil properties across the landscape (Grunwald, 2006). Land use and land cover changes (LULCC) and natural hazards have become a major source of interest among scientists and the general public. Image classification and change detection have been used in several studies to map land cover types and with multiple dates of imagery, identify regions of change. Mapping areas of change sometimes shows trends that can be extrapolated into the future. Various images have been transformed using GIScience techniques in order to enhance the information content from change detection. Grunwald (2006) described a method of for moving from qualitative to quantitative approaches in monitoring soils and three major areas were pointed out: 1) landscape characterization (mapping tools and techniques using satellite-based RS), 2) data management using a GIS database management system, and 3) the technology (including the computing power to process the digital information).

Data handled within a GIS can be stored using a vector model and the vector approach has geographic features represented as discrete entities within a structural topology and defined by implicit spatial relationships (Mesev, 2007). GIS can be use to analyze the relationships among features and this approach helps to identify trends and enable decisions according to the on-going changes at a place. Geostatistical techniques are also used for data interpolation. Interpolation, also known as spatial prediction, is a key part of geostatistical modeling (Maguire *et al.,* 2007). The integration of remotely sensed data, GIS, and spatial statistics provides powerful tools for modeling variability and predicting the distribution and patterns of soil characteristics (Mehjardi *et al.,* 2008).

In West Africa where there is a critical lack of digital environmental information, RS and GIS technologies are welcome for gathering the huge amounts of data that will enable resource managers to better understand local ecosystems dynamics, to solve and prevent problems, and to establish an environmental database for planners and decision makers. After the 1970s drought, several initiatives were implemented in order to develop a new framework for analyzing environmental change. Remote Sensing and GIS are becoming important subjects for research and instruction among West African universities and research institutes. During spring 2005, Kansas State University and the University of Cheikh Anta Diop (UCAD) established a solid partnership which involved a proposal for the development of a Digital Geosciences Atlas for Senegal. In the summer of the same year, Michigan State University and UCAD initiated a West African Workshop to create a network of RS/GIS developers and users for bridging the digital divide, improving north-south collaboration, and building linkages with research universities and laboratories in the more developed world. Plans exist for creating a West African network on research and environmental change and building on existing bilateral collaboration in order to understand the changes happening across the region (Verdin, 1996). The most prolific applications of satellite data in West Africa include the activities at institutions such as RECTAS (Nigeria), CENATEL (Benin), Commission du Bassin du Lac Tchad (CBLT), National Water Resources Research Institute (NWRRI, Nigeria), CSE (Senegal) and the Centre for Remote Sensing and Geographical Information Systems (CERGIS, Ghana) (Twumasi and Merem, 2007).

Given that West African countries share borders, rivers, lakes, and groundwater supplies, these nations are confronted with similar environmental problems. Existing organizations provide positive examples of co-operation and experience in joint management at the bilateral and regional levels. Building a geospatial analysis network could help with regional and sub-regional initiatives in development and environmental management. Some of these organizations are: NEPAD (a continental organization for economic development), CILSS (a sub-regional organization for monitoring Sahel drought), and ECOWAS (an economic community). Despite the establishment of RS/GIS capabilities and demonstration projects, applications are still few in number. A digital soil mapping project funded by Bill and Melinda Gates Foundation and Alliance for the green revolution was launched in January 2009. This project, called AFSIS (African Soil Information Service), aims to compile the first high-resolution digital soil maps for the 42 countries in sub-Saharan Africa. Several scientists from the International Center for Tropical Agriculture will collect and analyze soil samples from across the continent and these data will be combined with data obtained from satellite imagery to produce detailed maps (*GlobalSoilMap*). This project will enable scientists, decision makers, and farmers to have access to more detailed information about soil quality for better use and management of soils. Knowing soil properties will allow users and planners to advise farmers about best suited crops, fertilizer needs (quantity and types), and water sufficiency. It is hoped that success with the soils project will help convince African leaders to expand these types of projects into other environmental domains in order to build a digital database for monitoring and assessing land resources.

2.3.2- Using satellite images for mapping land use and land cover change in West Africa

Since 1957, Earth-orbiting satellites have been launched for a multitude of reasons. One of those applications was repeat observation of Earth resources with data from the Landsat series of platforms and sensors. With the new century, RS entered a new era with a series of operating satellites from the NASA Earth Observing System (EOS) program, other international programs, and commercial programs (Liang, 2004). In West Africa several environmental research studies have been done using SPOT (System Pour l'Observation de la Terre), AVHRR (Advanced Very High Resolution Radiometer) and Landsat images to map resources and then using multiple dates of imagery to assess critical environmental change. There is abundant evidence that GIScience approaches work well to capture accurate spatial-temporal data in West African ecoregions. In 2007, Twumasi and Merem used multitemporal Landsat TM and ETM+ data (1985, 1986, 1987, 1999, and 2000) for assessing land use and landcover change in the Niger River Basin (Mali and Niger). After classifying cover types, they found a decline in water bodies and shrubland. These results have been connected to the negative impact of rainfall deficits, the intensification of agriculture activities, the construction of a dam, and patterns of human settlement. Occupation of the area by humans increased from 53,290 in 1987 to 127,859 in 2000, which is an overall increase of 140%. Verdin (1994) examined twenty one lakes in western Niger, by using six AVHRR dry season scenes from 1988 to 1989, combined with good ground truth data. He estimated the area of water bodies using band 5. Results enabled him to conclude that there is a sharp temperature contrast between water and land areas.

Opoyemi (2006) conducted his research on the Llorin area in Kwara State (Nigeria). He used Landsat MSS, TM and ETM+ images respectively from 1972, 1986, and 2001. After classifying the imagery, five classes were produced for each study year with emphases on built-up lands that were made-up by a combination of several anthropogenic activities. However there was an inability to accurately map the small water bodies in 1972 due to the resolution difference of sensors/images. Results from his research show a rapid growth in built-up area between 1972 and 1986 while the period between 1986 and 2001 witnessed a reduction in this class. The authors provided a prediction that further change through 2015 will follow the 1986-2001 trend. In the Senegal River delta Dia (2006) mapped the extent of the 1999 flood using SPOT images and GIS tools.

Mane (1998) used RS techniques to monitor and detect the spatial distribution and temporal evolution of salinity in several managed areas in the delta region of Senegal. Multitemporal SPOT imagery was used along with ground salinity data (measured with an EM38 instrument and spectral data measured with a handheld spectroradiometer.) This research identified the impacts of the topography, ancient marshland beds, and the drainage lines of irrigation waters on salt distribution. The salt affected soils and the degradation risk areas were well delineated in the SPOT images (with classification accuracy between 68 and 86%). Salinity was best identified using the red band of SPOT images (XS2), the brightness' index $[(XS1)^2 + (XS2)^2 + (XS3)^2)/3]^{1/2}$, and the color index (XS2-XS1/XS2+XS1). Hydrologic phenomena were classified into the classes of: strongly flooded, flooded, and muddy. The combination of a digital terrain model of the Saint Louis area and a hydrographic layer allowed the analysis to determined impacted areas in Saint Louis. Research performed on West Africa ecoregions using GIS and RS documents how these GIScience tools are helpful for collecting and analyzing data from both accessible and inaccessible areas. These tools also allow scientists to make comparisons with imagery from prior years and to predict trends and patterns for the future.

However as with every science, GIS and RS are not exempt from error and data inaccuracy. Uncertainty in GIS and RS has been an important issue for GIScientists and uncertainty has been defined as the difference between the content of a dataset and the real phenomena that the data are believed to represent. Goodchild and Maguire (1991) reported that the US Federal Geographic Data Committee (FGDC) has listed five components of quality: attribute accuracy, positional accuracy, logical constancy, completeness, and lineage.

Based on this review of the literature related to environmental problems in West Africa and the contributions that GIScience can provide, it is clear that additional work on the character of changing natural resources will be helpful. A goal of this research is to further our understanding of the use of remote sensing and change detection methods with regard to saline soils.

CHAPTER 3 - Senegal River Valley Environmental Characteristics

3.1- Physical Environment

3.1.1-Geology

The Senegal River Basin (SRB) is situated within the Senegal Mauritanian Basin which is one of the largest marginal basins of northwest Africa. The SRB covers an area about 500,000 km^2 and extends from the northwestern part of Mauritania to the southwestern part of Guinea-Bissau (Fig.3.1). The basin is located on top of the Pre-Cambrian African platform. The northern boundary of the basin is formed by a piece of Precambrian African craton, the Reguibat uplift. The Mauritanides shield, which is a Paleozoic foldbelt that stretches more than 1,800 km from southern Morocco to Sierra Leone, forms the eastern and southern boundary. In the south, SRB boundaries include the mountain chain of the Rockelides and the Man shield, to which the smaller Kayes and Kenieba inliers can be associated. The Senegal Mauritanian basin started forming in Triassic time, due to the seafloor spreading of the Atlantic Ocean; radiometric ages are between 200 and 140 million years (provide a general citation on the geology of West Africa).

Figure 3.1- Map of the Senegal River Basin (Source: OMVS)

3.1.1.1- The pre-quaternary geologic history/tectonics

The margins of the West African coast are structurally dependent on three major episodes: 1) formation of Precambrian basement, 2) the pan-African, Caledonian and Hercynian tectonism, and 3) the formation of the Atlantic Ocean (Barrusseau and Giresse, 1987). During the Paleozoic era several extensional episodes affected the West African craton, which underlies most of the modern West African countries. The most important event was the formation of the Gourma in Mali and the Taoudeni Basin of Mauritania and Mali (Ennih & Liegeois, 2008). The pan-African thermotectonic event, which was very important in the border region of the Precambrian craton, resulted from the remobilizing of the craton's margin and the folding of its sedimentary cover, without, any significant ganitization. The most important effect of these tectonic events occurred, at about 600 m.y. (Dillon and Sougy, 1974). This orogenic event is subdivided into two phases: pan-African I; and Pan-African II or the Caledonian orogeny. The first stage occurred in the northern part, around the Senegalese block, and the second in the south around the Rockelides chain. A third orogenic episode has been identified around the Senegalese block, the Hercynian tectonic. The Hercynian episode partially reworks the Pan-African metamorphism and this event occurred specifically around the Mauritanide belt (Villeneuve, 1991). Obviously, orogenic events were important in the border region of the West African craton.

The morphology and the history of the margins of West Africa are determined by continental disjunction, which is followed by several processes: the change in geometry and migration of plates, sea level variations, and definition of lines of slumping and uplifting (Barusseau and Giresse, 1987). Volcanism occurred in the Dakar region during the Tertiary. The coastal cliffs of Cap Manuel, Gorée Island, and Pointe de Bel Air indicate the existence of strong volcanic activity. In addition, major fractures are evident in the Ndiass and Dakar Horsts. The western part of Senegal is characterized by the presence of structural faults with trends, mainly N-S and NE-SW. These faults separate different tectonic structures: the Ndiass and Dakar Horsts, which are separated by the Rufisque Graben. The Saint Louis and Casamance regions subsided several times while the areas near Louga and Thies tended to rise. Subsidence of the Senegal River delta area is estimated to be between 3 to 5 m every 150,000 years (Sall, 2006). A series of faults, with SW-NE direction and reoriented WNW-ESE characterize the western edge of the "Lac de Guiers"; these faults separate the silty-clay sediment in the west delta and areas to the east which are covered by the continental terminal deposits.

Variability in the volume of the Atlantic Ocean has left a significant mark. A west to east schematic profile of the SRB shows the general patterns of all coastal basins of West Africa. These areas were impacted by a series of alternating transgression-regression events, which started during the Mesozoic and have shaped the stratigraphy of the region.

B- Stratigraphy

The Precambrian basement of the West African shield outcrops in upper Bafing, the Plain of Faleme, north of Kayes (Mali), and to the west of the Assaba Massif (Michel, 1973). The Precambrian consists of metamorphic formations, intersected by a granitic massif of Birrimian age (Middle Precambrian). According to Michel (1973), the Paleozoic covers large part of the SRB with a sandstone layer found in the "Affolé Massif", the "Mandingue plateau", and extends as far as the "Fouta Djallon." The lower Cambrian is predominantly composed of schist and dolomite based on outcrops to the north and east of Kayes as well as in the Malian massif.

Rocks of Mesozoic and Cenozoic age extend toward the western parts of the SRB, as the West African craton was subjected to influences associated with the Atlantic opening. During the Devonian, a series of marine transgressions occurred, which extended as far as to the southeast as Nigeria (Dillon and Sougy, 1974). These marine deposits also include evidence of igneous activity with the Jurassic dolerite intrusion (Ennih and Liegeois, 2008). The SRB contains thick Jurassic limestone layers, which become sandy to the east. According to Michel (1976), several alternate transgression-regressions events have been recorded in the rock record from the Mesozoic to the Subactual in the SRB (Fig.3.2). A late Cretaceous transgression accompanied by development of a shallow epicontinental sea separated West Africa from the rest of the continent in the Turonian. According to Dillon & Sougy (1974), this transgression may have been associated with a eustatic sea level change or epeirogenic subsidence of the region. The end of the Cretaceous was marked by a regression and sands spread westward in Senegal for the first time in the Maestrichian. Sedimentary layers are characterized by dark bituminous shale near Dakar (Dillon & Sougy, 1974).

In the early Eocene, deposits were a sandy to shaley sediment with some glauconite and phosphate; these rocks crop out in many areas of Senegal. Part of the valley bottom of the SRB is covered by marine lacustrine deposits and by aeolian sands. The Lutetian sediments are represented by alternation of marl and limestone with phosphate and a high shell content. The upper Lutetian has alternating beds of limestone and marl (Furon, 1898). Only Tertiary sedimentary rocks outcrop along the lower Senegal valley between Bakel and Bogé. Toward the west, the littoral sandstone facies becomes calcareous with argillitic neritic deposits (Michel, 1973). Phosphate deposits formed during the upper Oligocene.

During the Pliocene to the Pleistocene, under the influences of climatic alteration and sea level fluctuation, the lateritic crust was formed due to the alteration and leaching of the marls. The continental terminal, a layer of variegated clayey and sandy strongly ferruginous rocks, represent the end of the Tertiary humid climate and the beginning of the more arid Quaternary times.

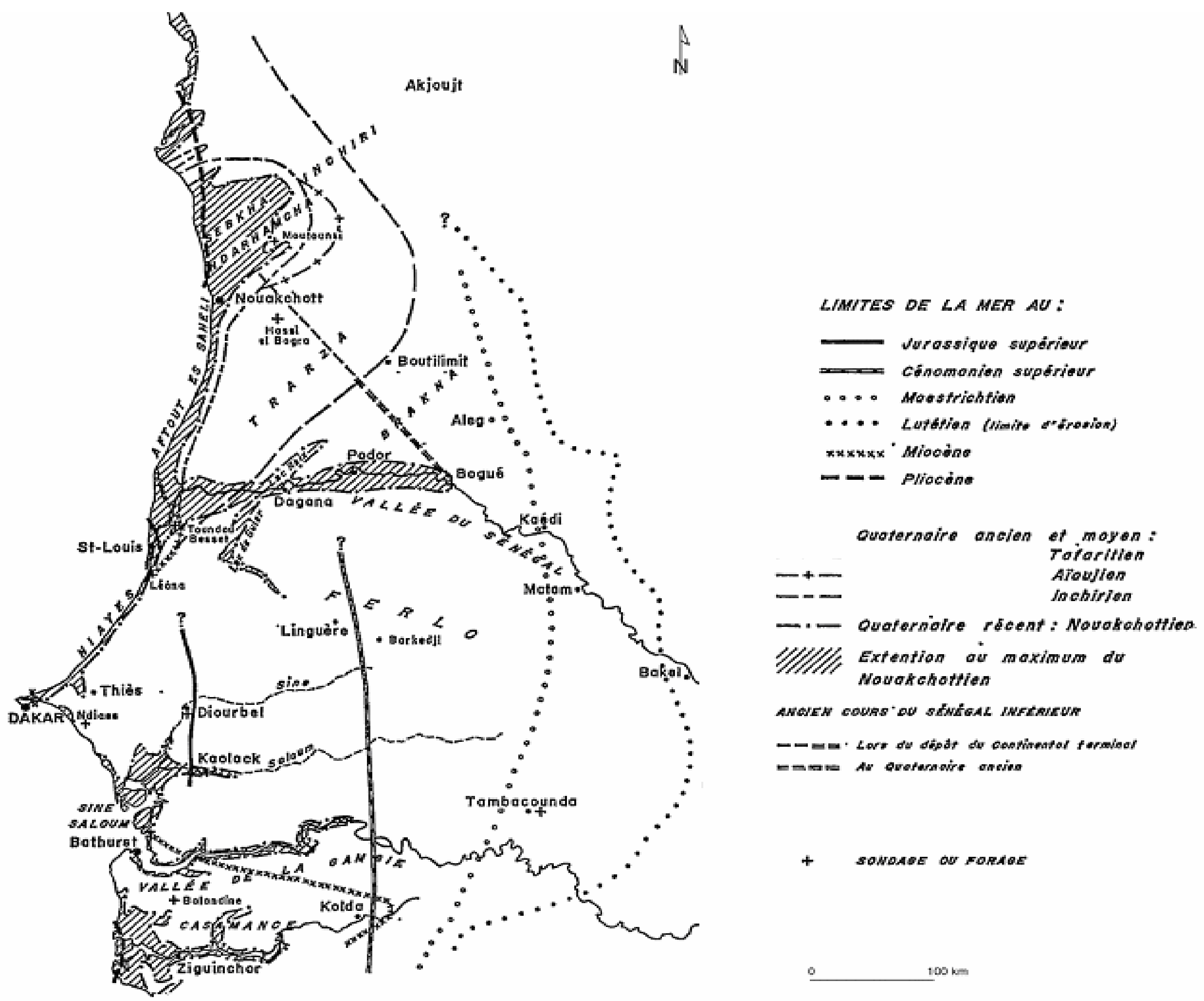


Figure 3.2- Marine transgressions since the Mesozoic (Michel 1973)

3.1.1.2- Quaternary evolution

Studies of the Cap Vert Peninsula drilling records show that the sandy Quaternary is marked by inclusion of the volcanism of "Mamelle". Recent Quaternary geologic history is dominated by climatic influences and sea level fluctuations. Main geological events identified in the north of SRB are the influences of these climate variation and glacio-eustatic sea-level changes linked to early Pleistocene glaciation. The Quaternary is marked by an important bioclimatic change (Michel, 1973) and characterized by several alternating wet and dry periods. Wet periods correspond to the higher transgressing sea levels and dry phases are related to marine regression. Transgression phases correspond to inter-glacial phases and regressions are related to global glacial periods; local names are used for evidence of these events in SRB. The region is covered by Quaternary aeolian sand overlying the older sedimentary substratum dating from the Tertiary period (Elouard, 1959). Along the northern coast of Senegal, the Quaternary aeolian formation covers an area of about 2300 km^2.

During the Holocene, each marine incursion had important ecological and hydro-geological consequences. Quaternary deposits are mainly represented by the juxtaposition of three different dunes system: the red dunes formed during the Ogolien (20,000-11,000 BP); the yellow; and the white dunes or littoral sandbanks which formed during the Tafolian regression (Sall *et al.,* 1978).

A- Quaternary stratigraphy

The base of the Quaternary is formed by a marine sedimentation at the Inchirian (40,000 to 37,000 BP) which corresponds to the transgression preceding the Wurmien glaciation in the Northern latitudes (Barrusseau and Giresse, 1987). It is represented by beach-rock formations in the SRB. The end of the Inchirian is marked by a marine regression and continental erosion of underlying formations occurred. The Senegal River cut deeply into the bedrock and reached 28 m below sea level near the current location of Richard Toll (Michel, 1973).

Toward the end of the Pleistocene during the regressive Ogolian period, red dunes were formed (between 20,000 and 18,000 BP) and the maximum regression reached minus 100 m (Wright *et al.,* 1985). Ergs constituted by longitudinal dunes orientated NE-SW formed in the northwestern parts of Senegal with an elevation variant between 10 and 15 m. The red color of the dunes is caused by iron oxidation. Another phase, the so called "Ouljian transgression" has been identified at the beginning of the Tchadian (12,000 to 7,000 BP). These changes in sea level are accompanied by the formation of valleys and hydrographic networks perpendicular to the coast (Sall *et al.,* 1978) and establishment of lagoon systems behind coastal dunes.

The major phase responsible for much of the current geomorphologic configuration of the SRB coastal area was the Nouakchotian transgression (7,000 to 4,200 BP). The transgression progressed from the west towards the east and during the maximum transgression around 5,500 BP several embayments were created in between major dune areas (Fig. 3.3). Before the marine Nouachottian transgression, the Senegal River cut across the dunes. According to Michel (1973), the 1.0 to 2.5 m sea level rise during the Nouachottian caused the penetration of the sea water into the interdunal depressions. At Saint-Louis East, sea water penetrated between the Ogolian dunes and created the SW-NE depressions of Khout, Nguisset and Ndiasséou (Sall, 2006). Isupova and Mikhailov (2006) reported that the present Senegal delta was a bay extending some 200 km inland. This transgression is characterized by extended sand beaches rich in bivalve shells and peat deposits (Michel, 1973). The river built high natural levees which are not submerged by its present rise. The sea water has remobilized the sand dune material forming the Nouakchotian terrace. Several authors cited by Sall (2006) have located these terraces in several different places: between Djeuss and Lampsar creeks; along Aftout es Saheli depression, and around Rao. These geological variations help explain the origin of the natural neutral salinity, dominating the western part of the basin. In eastern parts of the SRB, soil salinity has a petrographic origin and is derived from weathering of metamorphic rocks (Diene, 1998).

During the Tafolian (4,200 and 2,000 BP) the climate turned arid once more and the process is reversed, with another regression observed. Yellow and white dune formation took place during this regression phase and extended along the coast. Aeolian phenomena continue to remobilize and reshape these two types of dunes up to the present. New changes have been observed in river hydrography during very recent geologic times. The ancient mouth has been sealed off by the development of the sand bank (Langue de Barbarie) and the position of the main subsidiary river mouth has shifted location with the ever changing balance between river flows and oceanic forces. The main mouth has gradually moved from Saint Louis Island to its present position (30 km further south).

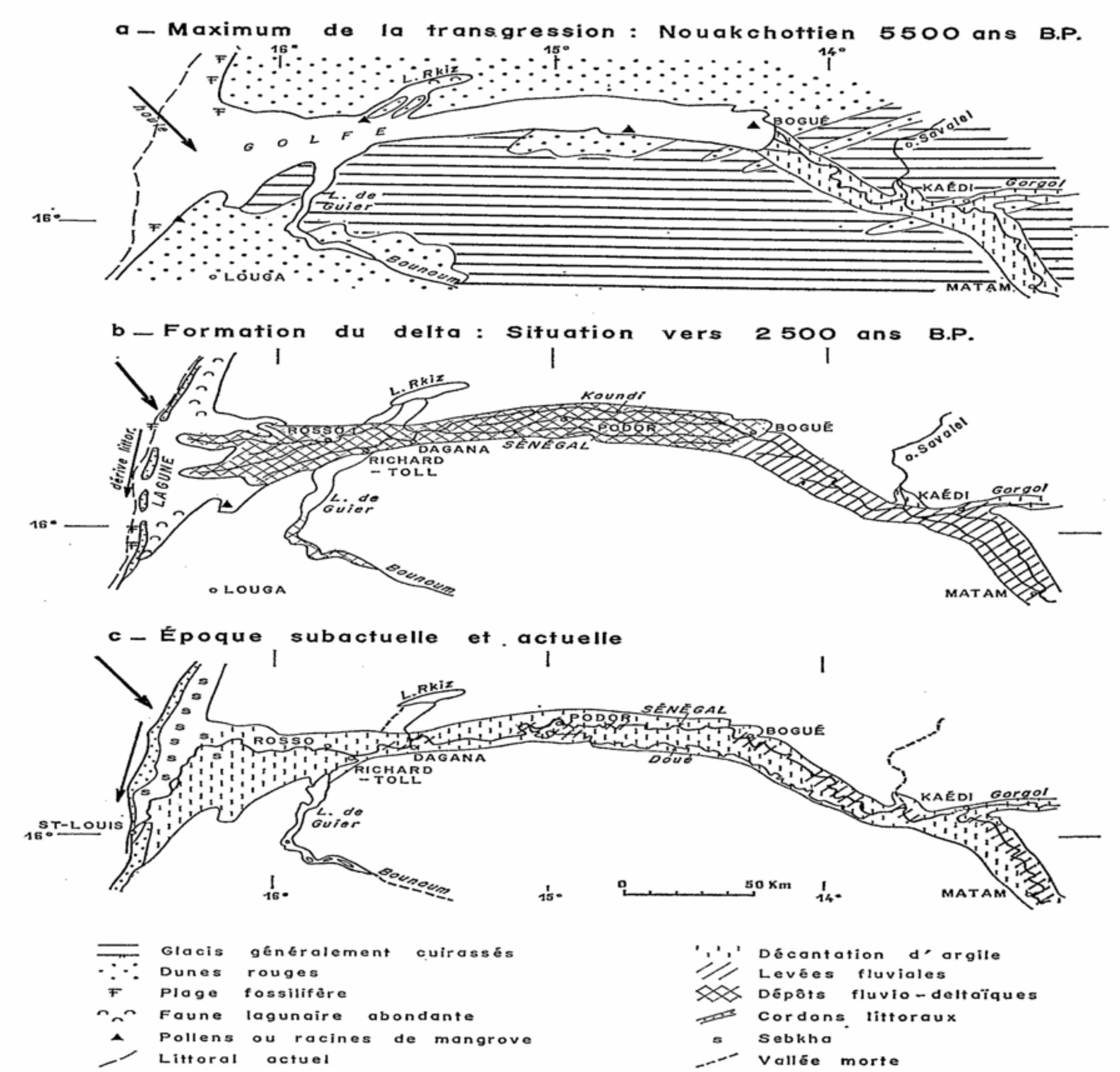


Figure 3.3- River basin evolution from the Nouakchotian to the present (Michel, 1973)

3.1.2- Geomorphology

The Senegal River Basin covers a surface area of about 300,000 km^2. The high plateau in northern Guinea represent 31,000 km^2 or 11% of the basin, 155,000 km^2 are situated in western Mali (53% of the basin), 75,500 km^2 are in southern Mauritania (26% of the basin) and 27,500 km^2 are in northern Senegal (10% of the basin) (OMVS). The geology of the SRB shows that the general morphology can be subdivided into three homogeneous areas according to the topography and the nature of the landscape (Fig.3.4):

1. the upper basin extending from Guinea to Bakel in Senegal and is characterized by a high plateau with a height of 1,000 m a.s.l;
2. the lower basin, mostly lowland topography, is located between Bakel and Dagana (the highest elevation is situated near Bakel at 50 m a.s.l) and,
3. the delta from Dagana to the mouth of the river in the coastal area (elevation does not exceed 1.4 m a.s.l. and the delta is a source of biological diversity and wetlands).

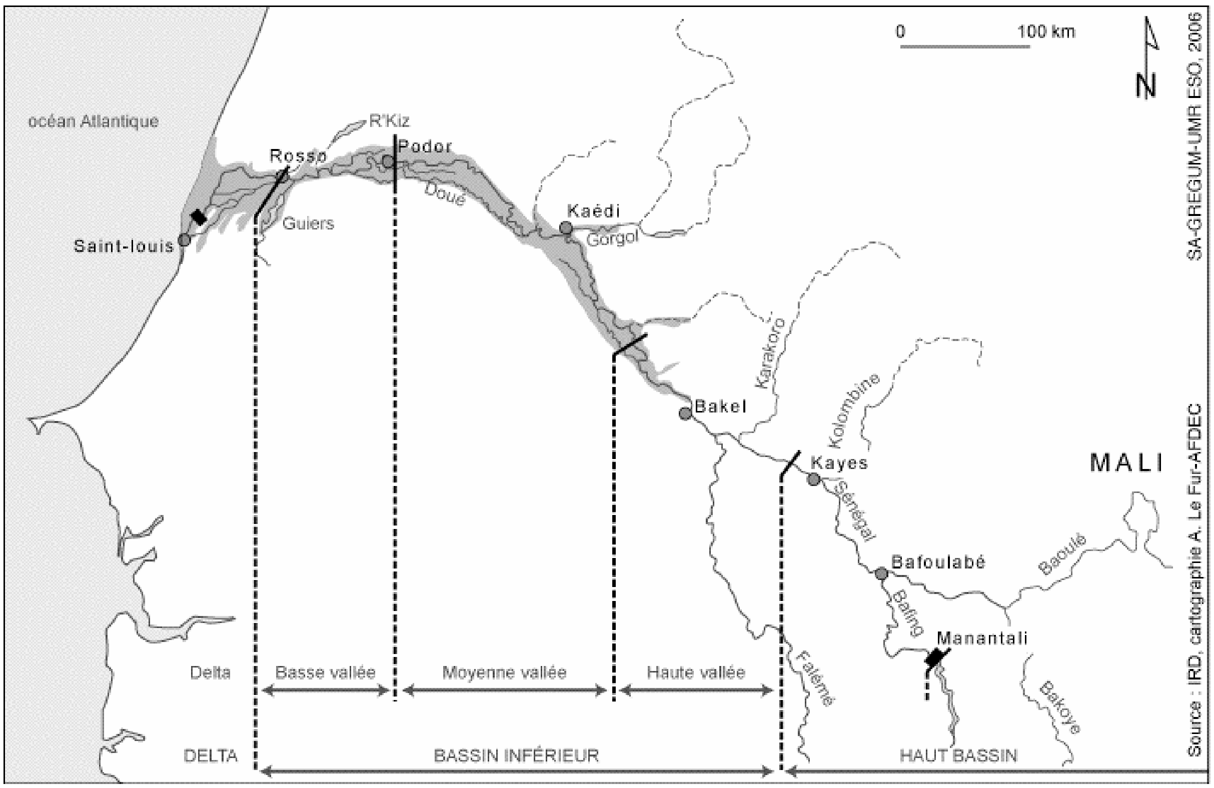


Figure 3.4- SRB subdivision (Laverien *et al.*, 1990) in Sall (2006)

This geomorphologic subdivision can be related to all components of the local ecosystem, including hydrology, soils, vegetation, and also human settlement. The geologic and geomorphic history of the Senegal River delta and valley features have helped shape the local topography, which is characterized near the coast by a series of dunes separated by inter-dune depressions (Fig.3.5).

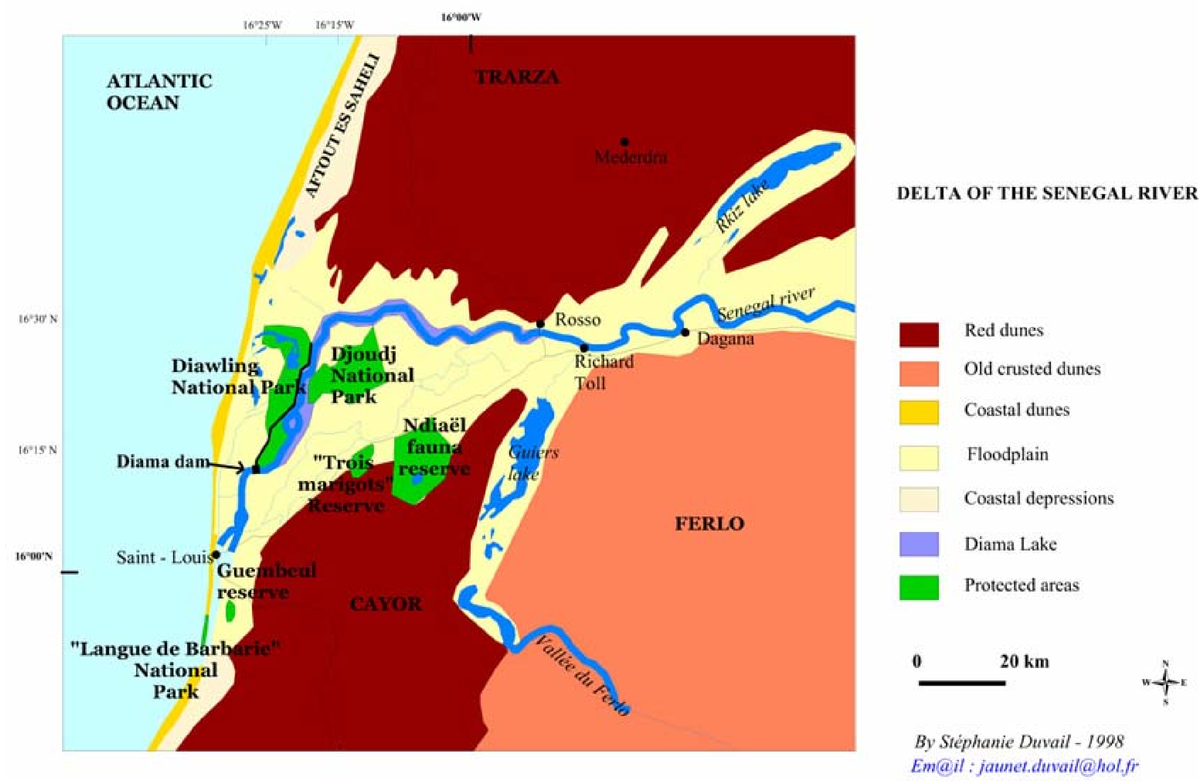


Figure 3.5- Geomorphology of the delta and the lower valley (Duvail, 1998)

3.1.2.1 - Interdune formations

The Interdunal depressions are areas often inundated by river water (high flows of the river produce a wide floodplain) with halomorphic weakly drained soils (Isupova & Mikhailov, 2006). Three types of sedimentation environments have been identified in the depression landform areas: fluvio-deltaic, lagoon, and estuary.

The fluvio-deltaic environment is shaped by river floods. These alluvial depressions are inundated during the peak of the flood when only the highest parts of old levee system remain dry (Michel, 1973). Depressions are submerged four to ten weeks a year and the water drops it suspended load. In the lowest part of the interdunes, where the water is stagnant for a longer time period, these clay-rich deposits can reach three meters in thickness. During the dry season evaporation of water causes a salt crust to form (which is locally called sebkha (e.g., Ndiael)) and these clay-rich deposits develop mud cracks (Photo 3.1).

During the dry season, aeolian exportation generally exceeds the fluvial sediment input (Tricart, 1957) and this results in the deepening of these interdunal depressions over time. Given the amount of energy needed to keep larger size particles in suspension, sand is typically not transported further than two to three kilometers. Two large natural depressions connected to the river are Lac de Guier in Senegal and the Riz Lake in Mauritania.

Lagoon environments are also inundated when the river floods. The dry season can be characterized by sebkha undergoing aeolian action. Wind erosion and deposition results in numerous small clay-rich dunes and salty silt sediment outcrops (Tricart, 1957). Aeolian action also results in modification of the process of delta formation as distributaries can be closed by sand banks or nebkhas which change the direction of water flow. Over time, these processes have contributed to the southward migration of the mouth of the Senegal River.

Estuary environmental dynamics are also disturbed by the annual river floods. For 4 to 5 months, swampy areas are submerged by fresh water and silty sediments. Depressions, which are below sea level, are occupied by salt marshes. According to Isupova and Mikhailov (2006), the effect of strong ocean waves and alongshore sediment drift triggered the development of sand pits within the coastal dune area. The position of the mouth of the river depends on the balance between river flows, sediment transport, longitudinal coastal drift, and dune activity. The slope of the continental plateau near the mouth is stepper and favors tidal wave and sea water intrusion (Gac *et al.*, 1986).

Photo 3.1- Soil with mud-cracks in Ndiael depression (Ndiaye 2008)

3.1.2.2- Dune formations

Dunes landforms are characterized by an undulating topography with irregular crest succession. Several sets of dunes are observed along a transect from the coast toward inland areas: first, the littoral sandbank (white dune); then the Tafolian yellow dunes; and the Ogolian red dunes.

Red Ogolian dunes are fixed by shrubby steppe and the presence of the vegetation decreases the erosional action of the wind on these formations. These dunes are also called continental dunes because inland location. They cover Trarza and a large part of Brakna in Mauritania and extended toward the south of the Senegal River delta. In Senegal they are found today near Besset and Béret (Sall, 2006). Old crusted red dunes also are observable to the east of Lac de Guier, in the Ferlo pastoral zone. In addition, an area of small Ogolian dunes is present in the floodplain of the Senegal River between Bakel and Matam.

Yellow or Tafolian dunes extended inland for about 100 km with a general NW-SE orientation. These landform systems are remobilized littoral dunes of yellow color and slight oxidation. These dunes are very mobile and tend to invade interdune areas and progressively the continental dunes. The vast prevalence of active sand dunes along the NW Senegalese coast results from the relatively high power of the trade winds, mostly during the dry season. This active system is composed of sand deposited by the northwest swells on the coast. These littoral dunes can be differentiated from Ogolian dunes by their sediment composition. Compared to the red dunes, the sands of the littoral dunes are better sorted.

Beach deposits are well sorted white fine sand. The large amount of beach sand available has resulted in the white dune landform system, which is also called the littoral sandbanks. These dunes parallel the coast and their formation is dependent on the effects of ocean swells. Near the mouth of the Senegal River, the NW swell has lead to the formation of the narrow, sandy "Langue de Barbarie" (Photo 3.2). This coastal dune complex has a NNW-SSE orientation and constitutes a barrier between the river and the Atlantic Ocean. However, this littoral sandbank is fragile and unstable due in part to the tidal ebb and flow dynamic. There has been a recent tendency for the complex to shift seaward. In an attempt to limit flooding in Saint Louis, a breach that is 4 m wide was cut into the "Langue de Barbarie." The erosive power of the ocean swells have been enlarging the cut and thereby threatening its effectiveness.

Photo 3.2- Langue de Barbarie (www.saintlouisdusenegal.com)

3.1.3- Conclusion

The geologic structure and stratigraphy, of the Senegal River delta and valley, are dominated by Quaternary events. The complexity of the local geomorphology can be explained by the combined effects of climate variability, wind erosion and deposition, riverine processes, changing Atlantic Ocean levels, and wave action. The area is a vast floodplain slightly interrupted by the Ogolian red sand dunes in the south west and the east. The delta region is characterized by a complex hydrologic network. Lac de Guiers, a lake replenished by the Senegal River floods, constitutes a natural boundary between the delta area and the middle valley. In addition, there exists a series of depressions, which are rich in clays deposited by the river during flood events (Ndiael, Khant, and Djoudj), tidal creeks, lagoonal areas, and temporary lakes (Djoudj, Gorum, Lampsar, and Djeuss). During the dry season, these depressions are covered by a salt-crust, locally known as sebkha, formed by the evaporative processes. Barbiero *et al.,* (2004) reported that the sequence of transgression-regression cycles may have had a significant influence on soil formation. Sandy soils originated from the red deposits associated with Pleistocene sand dunes during the Nouakchottian transgression whereas the clay soils are better linked to the Taffolian regression.

3.1.2- Soil types

Soil development or pedogenesis is strongly related to local geomorphology, climatic variations, and to the topography of the region (Michel, 1973). Several soil types have been identified and classified (Fig.3.6); according to Loyer (1989), these include:

- White dune sands have granular structure and are poor in organic matter, their texture is coarse sandy (over 99 percent sand), and the pH is acid to neutral (Ndiaye, 2004);
- Brown or red brown dune soils have granular structure (90% of sand) but are richer in organic matter than white dunes, they are traditionally used to cultivate millet and sorghum, their temporal differentiation is very low;
- Colluvial hydric soil located at the lower slope;
- Vertic hydromorphic soils, these vertisols are present in depressions;
- Halomorphic soils are more or less differentiated and are at the fluvio-deltaic levees;
- Soils with little pedogenesis differentiation forming sub-actual levees, and
- Raw mineral soils lying on the sand bank; these soils also are located in the south west of the delta, where they tend to cover lateritic soils or "sols Dior" (Photo 3.3).

Photo 3.3- Raw mineral soil or "sol Dior" (low differentiation) (Ndiaye 2009)

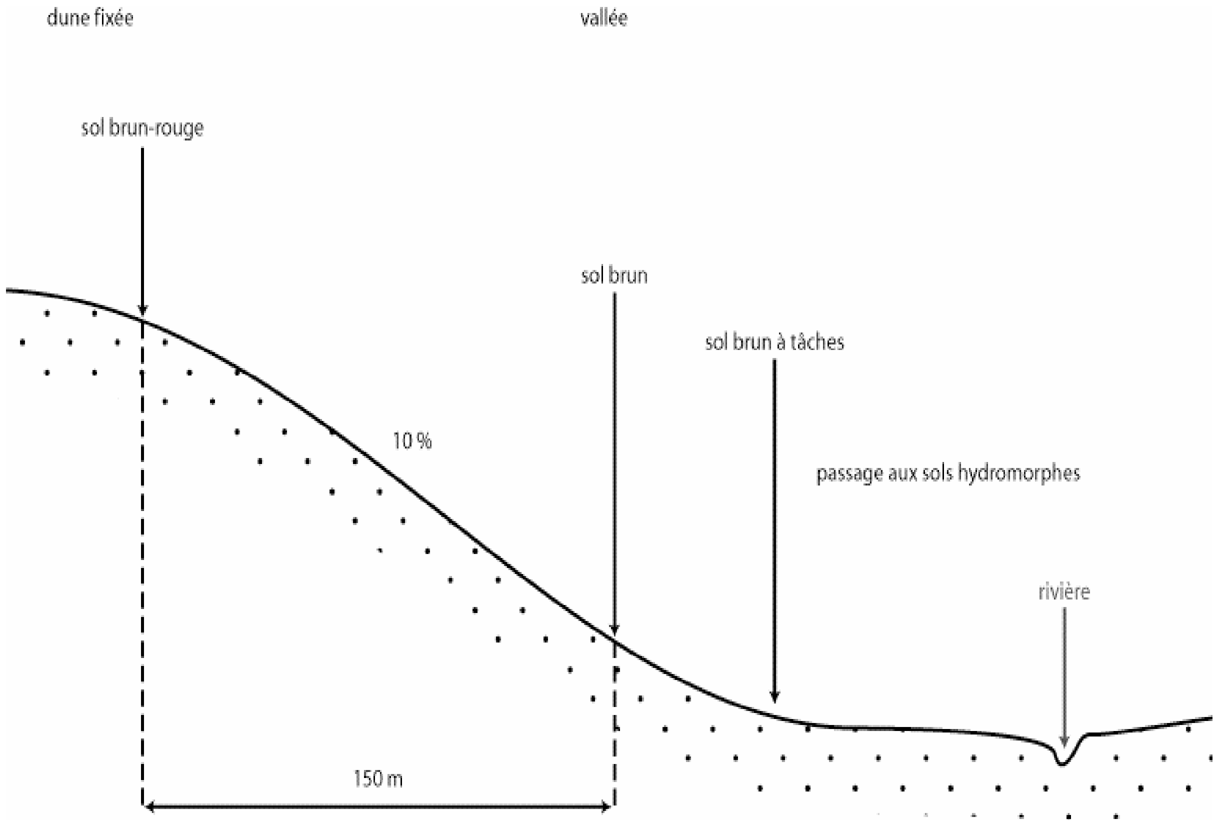


Figure 3.6- Soil distribution from dunes to the River bank (Loyer, 1969)

Two main soil associations with local names are identified in the Delta according to the level of water saturation (or inundation time period), texture, structure, and the degree of salinity:

- Diery soils or zonal soils occur on sandy and sandy clay sites and represent subarid soils (Isupova and Mikhailov, 2006); these generally poorer soils have never been inundated by river flood because of their location in higher topography.
- Walo soils found in the depressions, which are influenced by rises and falls in the water level of the river; sedimentation results in richer and more fertile hydromporphic and halomorphic soils.

The Walo soil association is composed primarily of Hollalde, false Hollalde, and Fonde soils. In addition to these three main soil types, there are the Falo and the Diacre soils (Fig.3.7 and Fig.3.8). These soils are classified by the UN FAO as Vertisols and Fluvisols, and belong to the hydromorphe class. In American soil taxonomy the hydromorphe class doesn't exist, and they are classified as Entisols.

Hollalde soils are Vertic Xerofluvents (Boivin *et al.,* 1998) and are very rich in clay (75 to 90%). They are composed of smectites (60 percent) and are interstratified with 30 percent kaolinite, 5 percent illite and 5 percent chlorite (Boivin *et al.,* 1998). Hollalde soils have a prismatic structure, and occupy about 75 percent of irrigated areas (SAED).

The false Hollalde soils are a silty-clay soil with 30 to 50 percent clay. These structureless soils can be found within irrigated areas. These soils become inundated during relative small to average river floods and are classified as Aquic Vertic Ustifluvents.

Fonde soils are rich in silt, have 10 to 30 percent of clay, and are classified as Typic Xeropsamments (Boivin *et al.,* 1998). These soils have a cubic structure and occupy 30 percent of the land with irrigation potential (SAED). Hollalde soils are denser, more impermeable, and are located in the floodplain. Fonde soils are loose and form in topographic locations that are either on the uplands or the side slopes. These clay soils constitute the best areas for irrigated rice cropping because of their adequate physical and chemical properties.

Falo soils, form in aquic condtion (halomorphe), undergo periodic saturation and reduction (psuedogley), and have a low amount of humus. They are composed of 60 percent of clay (from flood deposits). Falo soils are located on the banks of minor beds of the river.

Diacre soils are located on the levees and are sandy clay soils. These soils are inundated only during the period of high water (flood crest).

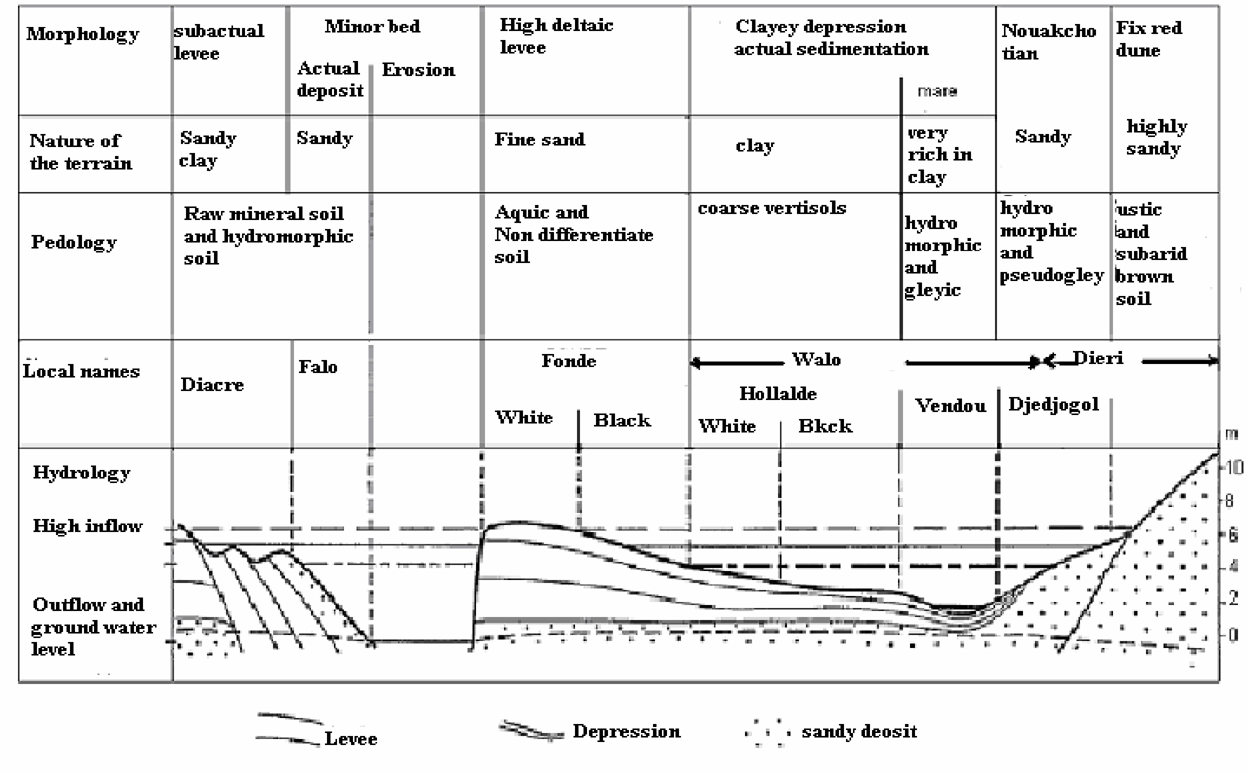


Figure 3.7- Soils characteristics and classification according to their local name and topography. (Michel, 1973)

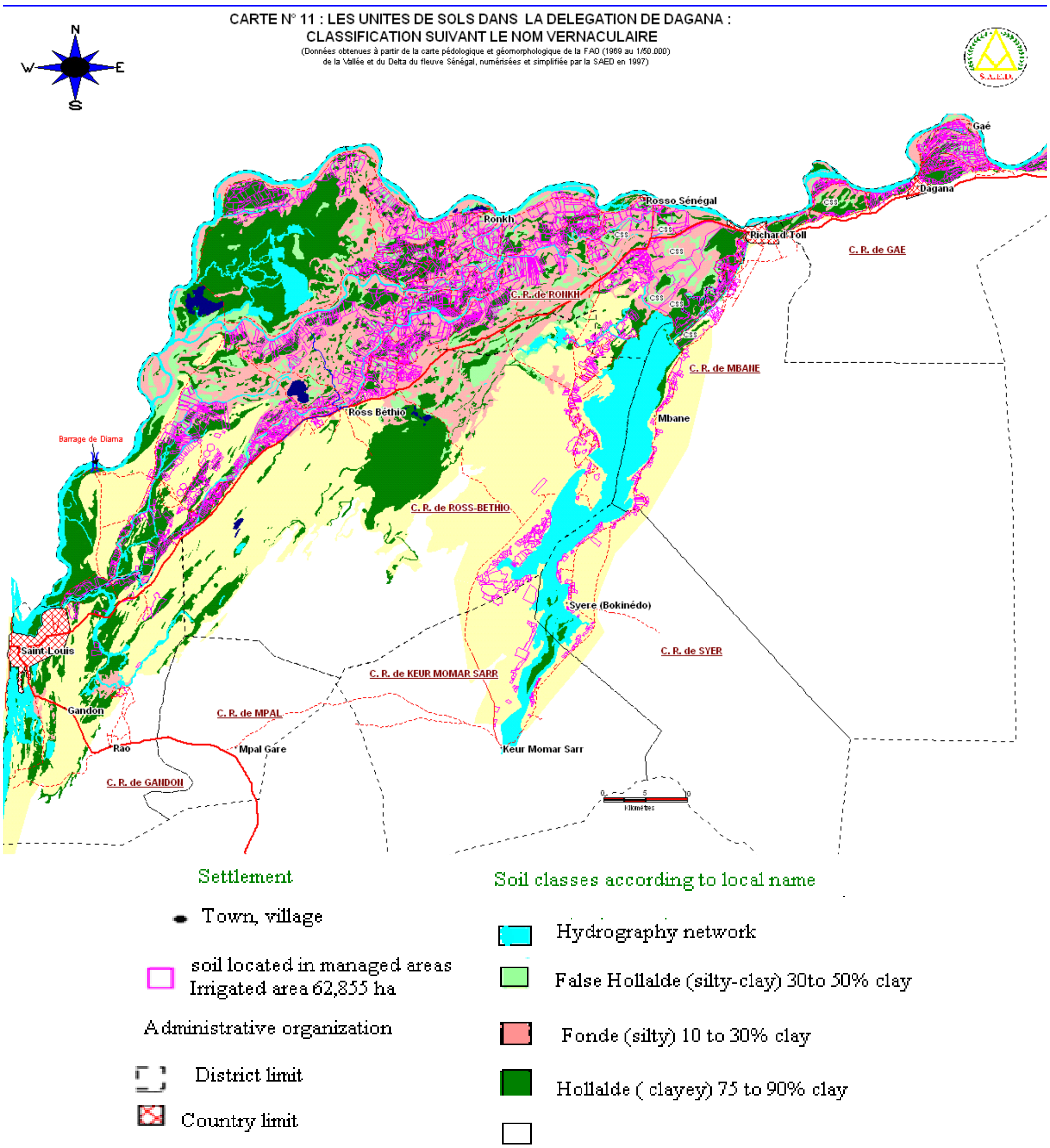


Figure 3.8- Map of soils class in the Senegal delta according to local names (SAED 1997)

There are several types of aquic or hydromorphic soils in the delta depressions and these soils are classified according to their degree/period of saturation. Hydromorphic soils are present under mangrove areas and undergo continuous saturation. These soils have black or black gray color and are the salty peat soils frequent in the intertropical regions (Sall, 2006) (Photo 3.4). Hydromorphe soils are saturated with water in all layers and they are influenced by capillary action from the water table which lies close to the surface. These soils do not have a saline crust at the surface.

Photo 3.4- Hydromorphic soil rich in organic matter with salt crust (Ndiaye 2009)

Periodic endosaturated soils are inundated for part of the year and exhibit mud-cracks during the dry season. Water loss through evaporation triggers formation of saline crust on the soil top (Photo 3.5). Hydromorphic soils have temporary saturation and other soils exhibit episaturation (saturated in one or more layers within 200 cm of the surface); these soils have cracks on the soil surface.

Halomorphic soils (Photo 3.6) are well represented in the delta area. Solonchaks soils are formed when evaporation greatly exceeds precipitation for at least part of the year, and when salt is present in moderate to high amounts in the parent material (FAO, 1998). There are Solonchaks with the presence of saline efflorescence and Crypto-Solonchaks, which are free of saline efflorescence (Sall, 2006). These soils have high salt accumulation levels and cannot be used for normal cropping unless the salt is leached out. Solonetz (Photo 3.7) or soils in which the sodium content is present in excess over calcium are expanding in the delta. Clay content in the topsoil is decomposed in high pH conditions. This process results in a low salt concentration combined with high exchangeable sodium, leading to the columnar or prismatic structures (FAO, 1998).

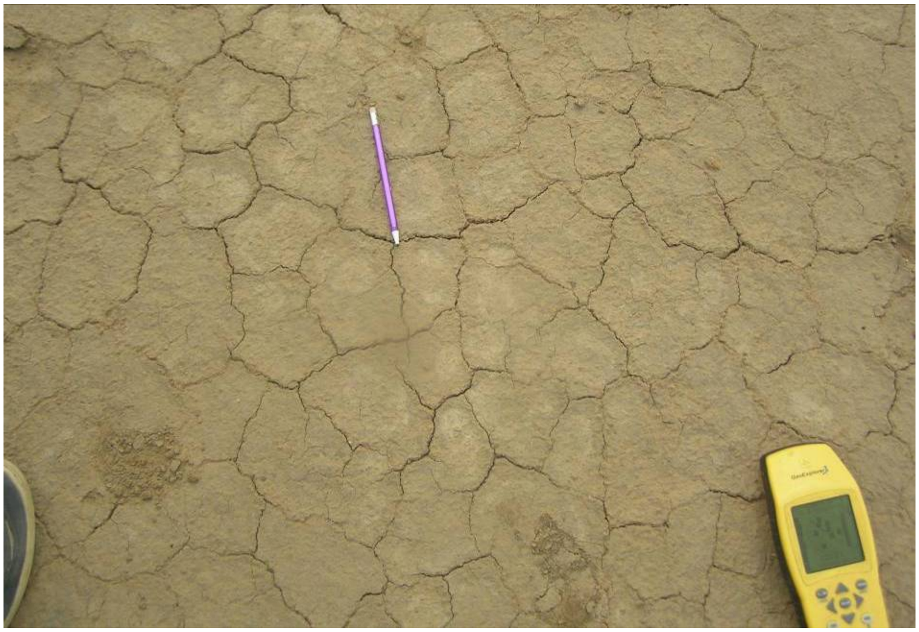


Photo 3.5- Halomorphic soil with cracks during the dry season (Ndiaye 2009)

Photo 3.6- Halomorphic soil with salt crust (Ndiaye 2009)

Photo 3.7- Solonetz (Sodic soil) (Ndiaye 2009)

3.1.2.1- Conclusion

Diverse soils have been identified in the Senegal River delta area. Geomorphological processes and rainfall variability (which affects flood size and fluctuations in river level) are the common environmental factors responsible for the soil pedogenesis and the proprieties of the major soil groups. Along the coastal zone sandy soils with the absence of a significant soil profile occur in the coastal dunes. Ferralsols or "sol Dior" are found behind dunes. The sandy soils present in the Dieri are never affected by river floods.

Lowland areas, corresponding to the Walo soils, are characterized by hydric and saline conditions. Different types of halomorphic soils are differentiated according to the length of time of their submersion and the saturation level. Sites can be permanently or temporarily inundated by flood waters. Salinization is a natural process occurring in the delta region due to capillary rise from the saline ground water table. Temporarily inundated soils, influenced by strong evaporative pressures, develop a salt crust. These soils are subdived into four groups according to their clay percentage: Hollalde, False Hollalde, Fonde, and Falo.

Soil properties provide reasonable information for soil resource management. Vegetation on Diery soils is predominantly used for nomadic grazing and perhaps a seasonal cereal crop (e.g., millet or sorghum). However under irrigation high yields can be obtained. The fertile Walo soils are use for horticulture, a seasonal rice crop, irrigated rice, and sugar cane. Soils with high salt accumulation limit plant growth because needed nutrients are less available. Moreover, these soils are more easily erodible, with both inorganic and organic particles mobilized by water movement and high winds. Geochemical soil characteristics, which are influenced by environmental position, are generally associated with the vegetation distribution. Along the river, water availability provides an environment where plants, birds, fish, reptiles and amphibians can flourish.

3.1.3-Vegetation and wildlife

3.1.3.1- Vegetation

The SRB is characterized by a Northwestern - Southeastern vegetation gradient related to the climatic gradients and soil pedogenesis. A large river part of the basin is located in the arid to semi-arid Sahel zone. Only the southern upper basin in Guinea belongs to the Soudanian climate zone characterized by annual rainfall higher than 1000 mm. Sahelian grassland and wooded grassland are the main vegetation types in the river valley and delta. The vegetation is mostly semi-desert types, with few perennial vegetative species. Notwithstanding, various edaphic plants occur in the depressions that hold water for several months after annual river flooding. These species are determined primary by soil salinity (halophytes) and the degree of water saturation (hydrophytes).

a)- Vegetation in the non flooding zone

According to Loyer (1989) the non flooding zone is dominated by *Acacia radiana*, *Balanites aegyptiaca*, and *Boscia senegalensis*. In the Diery area of sandy red stabilized dunes, the vegetation is characterized by grassland with annual species mostly dominated by Graminae (*Cenchrus biflorus, Shoenfeldia gracilis*, and *Aristida stipoides*) and some woody species (*Faidherbia albida, Comiphora Africana, Balanites aegyptiaca* and *Boscia senegalensis*) well adapted to drought (Photo-3-8).

Vegetation in yellow dune areas is characterized by the presence of *Aristida longiflora* and *Hyparrhenia dissolute* in the uphill slope facing the trade winds and downhill areas protected from winds are occupied by bushes composed of *Maytenus senegalensis, Parinari macrophylla* and *Chrysobalanus orbicularis* (Sall, 2006).

b)- Vegetation of the depressions

Along the coast, wetlands are occupied by mangroves growing in the intertidal zone around Gandiol, southwest of Saint-Louis. The large amount of silt deposited by the river has produced an environment suitable for mangrove growth. They are well adapted to large fluctuations in salinity and the main species are *Avicennia Africana, Rizhophora racemosa* and *Laguncularia racemosa*. Beside the littoral dunes, a series of marshy depressions are occupied by relic species generally characteristic of the wetter recent Quaternary climate: *Elais guineensis, Ficus congensis, Phoenix reclinata* (Sall, 2006).

Hygrophytic species, such as *Acacia nilotica,* colonize depression areas of clay and sandy hydromorphic soils. Lowlands, where the water table is close to the surface all the year, are generally occupied by herbaceous association: including *Vetiveria nigritana*, *Vossia cuspidata*, *Cyperus sp*., *Sporobolus robustus*, *Scirpus maririmus*, and *Borreria verticillata*. During the dry season when the water table goes down, several other vegetation groups colonize this area. When there is a consistent salinity, halophytes plants are well represented: *Tamarix senegalensis* (Photo 3.9), *Prosopis juliflora, and Accacia Senegal* which are relatively tolerant to salt (Loyer, 1989). The submerged marsh and fringe of large water bodies are invaded by *Typha australis* (Photo 3.10) and *Pistia stratiotes,* a floating plant. These invasive species limit water circulation.

Beside the natural vegetation, a rice crop, several other cereals and vegetables are cultivated in the area. Wetland and coastal areas in the delta have the richest biodiversity of all Sahelian ecosystems. Biodiversity is very important in agricultural landscapes because it can contribute to enhanced water quality. There are many wetland areas in the SRB which have been organized into protected areas. The species diversity and high production levels of wetland plants support even more diverse animal communities.

Photo 3.8- Vegetation type in the Dieri (Ndiaye 2009)

Photo 3.9- Tamarix sp (halophyte) (Ndiaye 2008)

Photo 3.10- *Thypha australis* bordering the river (Ndiaye 2009)

3.1.3.2- Wildlife

Wetlands temporary or permanently inundated by water provide important habitat for wildlife. The SRB is not especially rich in species however it does possess some endemics: small arid adapted rodents (*Gerbillus sp*); a variety of fish species, ten reptiles species (including Nile crocodiles, lizards and snakes); amphibians species, a few mammals (*Phacochoerus aethiopicus* (Photo 3.11), *Canis aureuss, Felix sylvestris)*; and several birds species (Dendrocygne veuf, l'ibis falcinelle, le flamant rose). Wetlands in the delta and valley play an important role for many migratory bird species coming from Europe and North Africa during the winter season. Several reserve areas and parks have been implemented in Senegal and Mauritania to protect these fragile and important ecosystems. Djoudj National Park and the Guembeul and Ndiael Wildlife Reserves exist on the Senegalese side of the river and in Mauritania the National park of Diawling and the Banc d'Arguin (Fig.3.9). All these reserves are classified as Ramsar sites (Table 3.1). Ramsar is an international convention on Wetlands adopted at Ramsar (Iran), in 1971. The definition of wetland in the first article of the Convention is:

> 'Wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.'

This definition encompasses coastal and shallow marine areas (including coral reefs), as well as river courses and temporary lakes or depressions in semi-arid zones (Hails, 1997). In addition, criteria exist for identifying wetlands of international importance: the wetland area should be occupied by high numbers of a range of species or 1% of the total numbers of one species during a definite time period. Djoudj National Bird Sanctuary, created in 1971, is a wetland of 16,000 ha, with a large lake surrounded by streams, ponds and backwaters. Djoudj ($16^{0}30^{'}$N / $16^{0}10^{'}$W) retains flood water longer than most other parts of the delta, is an important ornithological site, and was declared a UNESCO heritage site in 1981. It is one of the main habitats for migratory birds in West Africa; hosting about three million birds per year composed of 366 different species: including Garganey (*Anas querquedula);* Shoveler (*Anas clypeata)*; Pintail (*Anas acuta)*; Black-tailed Godwit (*Limosa limosa)*; Greater and Lesser Flamingo (*Phoenicopterus rubber* and *P. minor)*; Great White Pelican (*Pelecanus onocrotalus)* (Photo 3.12); and Avocet (*Recurvirostra avosetta)* (Hails, 1997). Djoudj is an important breeding site for Great White Pelican, Purple Heron (*Ardea purpurea)*; Egyptian Goose (*Alopochen aegyptiacus)*; and White-faced Tree Duck (*Dendrocygna viduata)* as well as many other species (Hails, 1997). There are at least 30 plant species with *Acacia nilotica* as an important nesting site for species such as the Great White Egret (*Egretta alba)*, Yellow-billed Egret (*Mesophoyx intermedia)*, Little Egret (*Egretta garzetta)*, Green-backed Heron (*Butorides striatus)*, Wood Ibis (*Mycteria ibis)*, Pink-backed Pelican (*Pelecanus rufescens)*, White-breasted Cormorant (*Phalacrocorax lucidus)*, and African Darter (*Anhinga rufa)* (Hails, 1997).

Photo 3.11- Warthog, *Phacochoerus aethiopicus,* is common in the delta (Ndiaye 2009)

Photo 3.12- Pelicans at Djoudj National Bird Sanctuary

http://en.wikipedia.org/wiki/Djoudj_National_Bird_Sanctuary

Table 3.1- Ramsar sites in SRB

Site	Statute	Date of creation	Areas (ha)
Ndiael	Special reserve for fauna	1965	46,550
	Ramsar site	1977	
Djoudj	National park	1971	16,000
	Ramsar site	1977	
	UNESCO heritage	1981	
Guembeul	Special reserve for fauna	1983	720
	Ramsar site	1986	
Diawling	Ramsar site	1991	16,000
Banc d'Arguin	National park	1970	

Another important reserve, Langue de Barbarie Park, situated on the sandy peninsula of the Langue de Barbarie is also home for a variety of migrated birds. In summary, wetland areas and ecosystems are threatened by human activities in the delta and by the climate variations characteristic of the Sahel zone (characterized in the 20th Century by a substantial rainfall deficit).

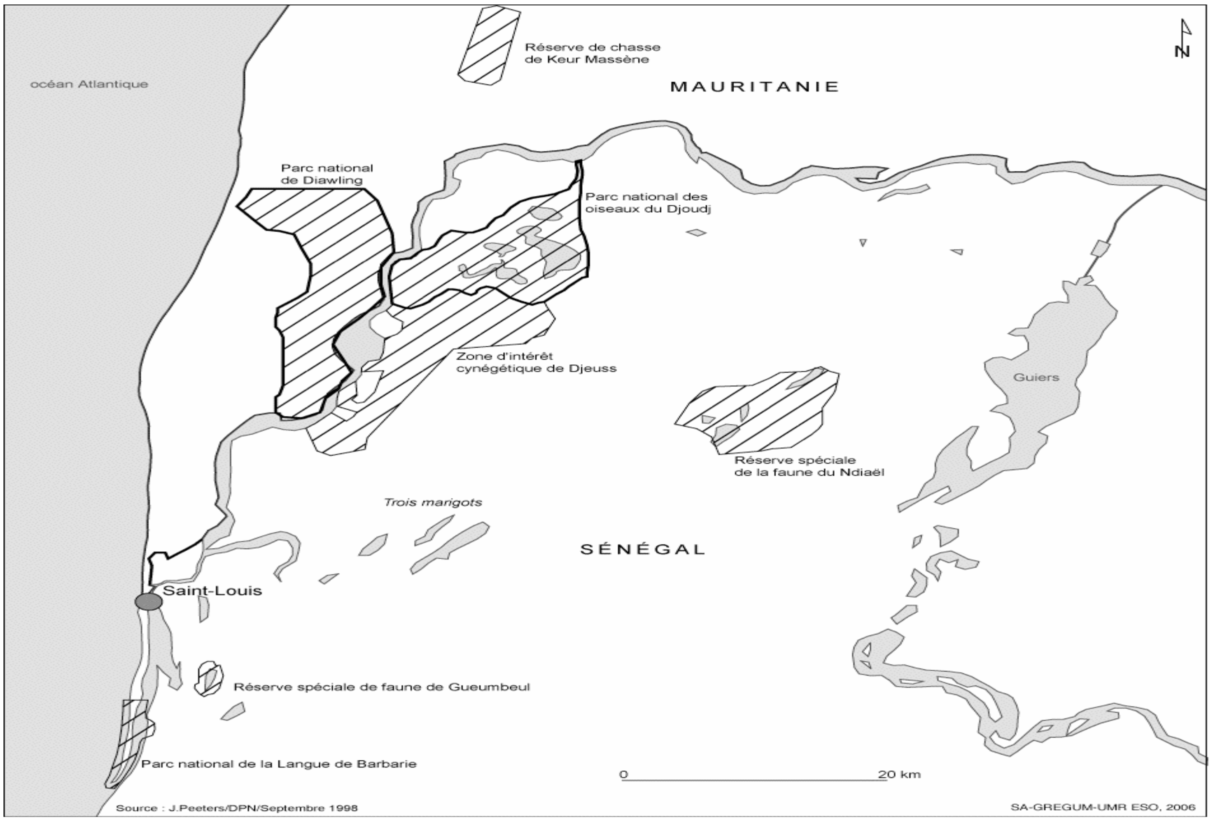


Figure 3.9- Geographic location of some protected wetland areas (Sall 2006)

3.1.4- Climate

Three climatic domains have been identified in the SRB following the geomorphologic subdivision: the Sahelian; the Soudanian and the Guinean climatic domain. The mean annual rainfall of the area is used to delimit the different climatic zones. The Sahelian domain corresponds to the north of the basin from the delta to Bakel (15^{0}N-17^{0}N) and has a mean annual rainfall lower than 200 mm. The Sahel zone has a semi-arid climate type. The Sudanian climatic zone is delimited between Bakel and the North of Fouta Djalon in Guinea Republic (12^{0}50$^'$-15^0) a range of mean annual rainfall of 300 – 500 mm. The Guinea climatic zone receives higher precipitation and coveres the entire Fouta Djallon area (Sall, 2006).

31.4.1- Precipitation and seasonal variability

The climate in the Sahelian zone is characterized by a cool dry season from October to February, a hot dry season from March to June and a hot wet season from June to September (Barbiero *et al.,* 1998). The average annual rainfall is 200 mm and 90% of the rainfall occurs during the wet season with a monthly maximum in August. Strong inter-annual and multi-decadal rainfall variability is observed in the delta and lower valley, and when they occur, rainfall deficits severely impact local water supplies. Niasse *et al.,* (2004) reported that since 1970, the mean annual rainfall has decreased by more than 30% in the Sahelian zone while the average discharge of the major river systems dropped by 40% to 60%.

Several wind types from different directions are associated with the climate. During the dry season two winds blow: 1) the Northwestern maritime Alize (trade winds) which originate from the Azores anticyclone and 2) the northeast continental trade wind or "Harmattan" which is hot, dry and frequently dust-laden (Fig. 3.10). A boundary or discontinuity in Western Senegal separates the two air streams (Fall *et al.* 2006). The wet season is characterized by a monsoon, with winds blowing from the south Atlantic. The southwesterlies are warm and humid and related to the meridional shift of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ boundary is associated with the leading edge of moisture laden, Atlantic air mass and is very distinct compared with the dry air mass over the Sahara. If the ITCZ is restricted in its annual northward migration, the magnitude and duration of the Sahelian rainy season is curtailed. Longer term change in the mid-summer location of the ITCZ can result in severe droughts or flooding in the SRB region. Declining Sahelian environmental conditions are also related to the intensification of the "Harmattan" or desert wind. According to Barbiero *et al.* (1998), dry and warm winds increase evaporative demand and create a plant–water imbalance. Average evapotranspiration is 7 mm per day and can reach 15 mm per day (Loyer, 1989).

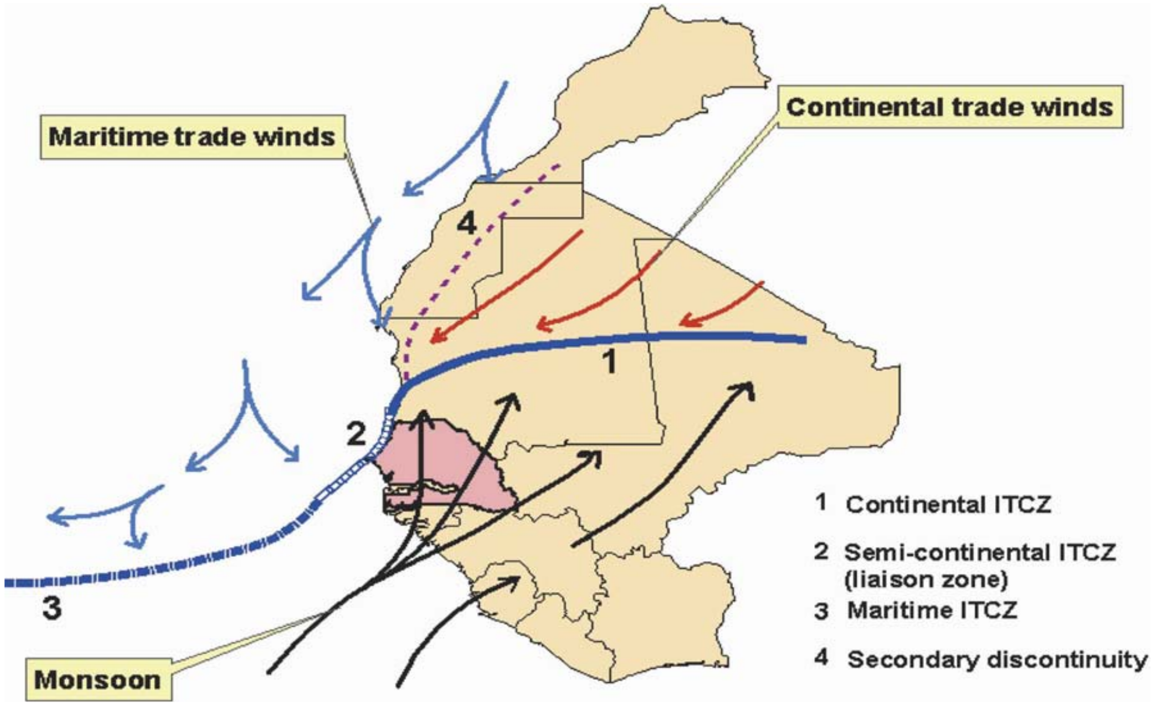


Figure 3.10- Mean position of ITCZ in western Africa during the summer season and related air streams (in Fall *et al.*, 2006)

3.1.4.2- Temperature

Average temperature varies in the range of 20^0 and 33^0 with a mean annual temperature of 26^0 in the Sahel climatic zone. Temporal and spatial variability of temperature are evident throughout the basin. Lower temperatures are observed in the western part and the highest temperatures take place in the East part of the SRB (Fig.3.11). The annual temperature range varies from 23^0C to 29^0C at Saint Louis and from 25^0C to 35^0C at Bakel (Fig.3.12). Temperature fluctuations are affected by oceanic factors, continental factors, and seasonal variability. Along the coast, temperatures are 5 to 6 ^{0}C lower than inland due to the proximity with the Atlantic Ocean, the cool and moist trade winds winds which blow over the cool Canaries current. In the middle valley temperatures are under the dry and hot "Harmattan" wind influence. At Saint Louis, temporal variation is related to the monsoon or seasonal shift with maximum temperatures in September or October and minimums in January or February (Fall *et al.*, 2006). Month-to-month temperature variation is minor in the delta, because of the Atlantic Ocean influence. Areas under maritime influence experience generally cooler summers and mild winters, with a smaller annual temperature variation. Inland temperatures reach a maximum during the late Spring with the dry conditions that occur prior to the arrival of the ITCZ

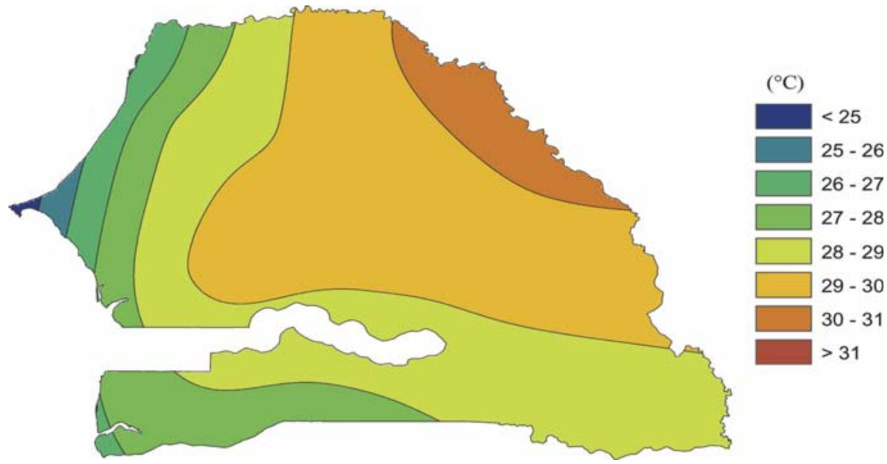


Figure 3.11- Mean annual temperature in Senegal. (Source: S.Fall *et al.*, 2006)

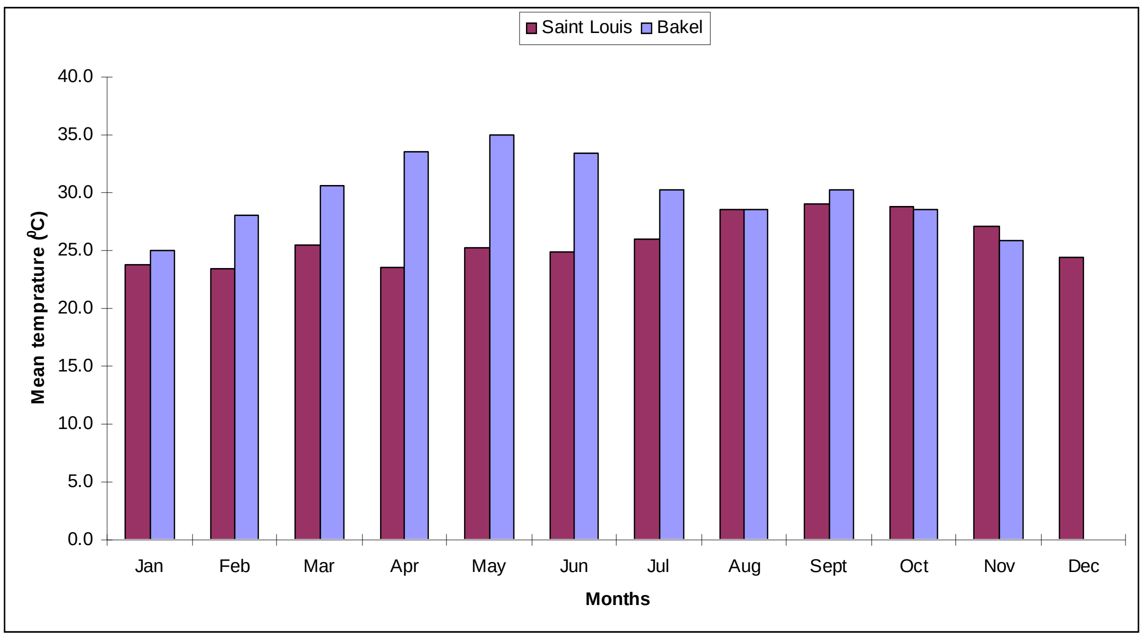


Figure 3.12- Mean monthly temperature at Saint Louis and Bakel (1985- 2003)

3.1.5- Water resource

West Africa is divided into two broad physiographic regions, with a boundary in an approximate east-west direction at roughly 12^0 N. In the north is a sedimentary plain and to the south is a series of highlands separated from each other and from the coast. These highlands consist of hills and plateaus that divide those rivers that flow south directly into the Gulf of Guinea from those that flow northwards for at least part of their course. Most of the regions' rivers are shared among several countries, for example Senegal, Mauritania, and Mali share the Senegal River Basin.

The principal water resource of the SRB is the Senegal River and its tributaries. Major tributaries include the Bafing, Bakoye, Baoule and Faleme, which all originate in Guinea in the Fouta Djallon Mountains. From their confluence near the Senegalese city of Bakel, the Senegal River flows 1,800 kilometers to the Atlantic Ocean. The Bafing is considered as the principal tributary and contributes 50 percent of the mean annual flow. In the middle valley, between Bakel and Dagana, the river extend 600 km with a SE- NW orientation from Bakel to Kaedi and is oriented E-W until it reaches the coastal zone. At the coast, the river flows south to its mouth (Sall 2006). Several Rivers' annual flow regime depends, for the most part, on rain that falls in the upper basin in Guinea; precipitation seasonality in the highlands of Guinea explains the high-water period or flood stage between July and October and a low-water period between November and May/June. Due to decadal changes in the climate system during the late 20th Century in the Sahel, ground water tables have decreased and several rivers and lakes have dried up dramatically.

3.1.5.1- Surface water

The natural hydrologic network system in the SRB delta region is influenced by the presence of Atlantic Ocean in the west coast and Senegal River flows coming from the east. During the dry season the action of the sea water is dominant but during the wet season the river flow is very powerful and blocks salty marine water at the mouth area. After the construction of Diama Dam, eastward movement of saline ocean waters has been blocked.

The river is connected with several tributaries: on the Senegalese side (Taouey, Gorom Ndiael, Khant, Nguine) and is linked to Lac de Guiers by the Taouey Canal (Fig. 3.13). It has seen its flow considerably reduced from 2,247 cubic meters per second (m^3/s) before 1970, to about 1000 m^3/s.

Lac de Guiers is the largest reserve of surface freshwater in Senegal with a maximum length of 70 km and a width of 8 km. Principal uses of the water in the lake are: irrigation and production of drinking water. Before the construction of the dam the volume of the lake fluctuated each year from 500-600 million m^3 during the flood season to 50-70 million m^3 towards the end of the dry season when sea water was entered the lake and caused a sharp increase in salinity (Varis *et* *al.,* 2006). Following construction of the Diama salt wedge dam, the Lake has undergone a significant increase of its water level (mean water level 2.5m) (Fig. 3.14) (Coly 2004). Varis *et al.,* (2006) reported a decrease of water salinity in it northern part of the lake however the southern part is still more saline due to a combination of dry season evaporation and the source of fresh water entering from the north.

Several other small temporary and permanent water points are observed within wetlands. Djoudj Wetland situated between the Senegal River and "Djeuss" is composed of three lakes (Lamantin Lake 1000 ha, Grand Lake, 5500 ha and Khar Lake, 1500 ha) that are linked with the Senegal River . The hydrologic connection includes the Djoudj River to the north and Gorom River to the south; Crocodile canal, between the Senegal River and Lake Lamantin is used to inundate the wetland. Before the building of hydraulic works, this wetland area was replenished during the annual floods (Tricart, 1957).

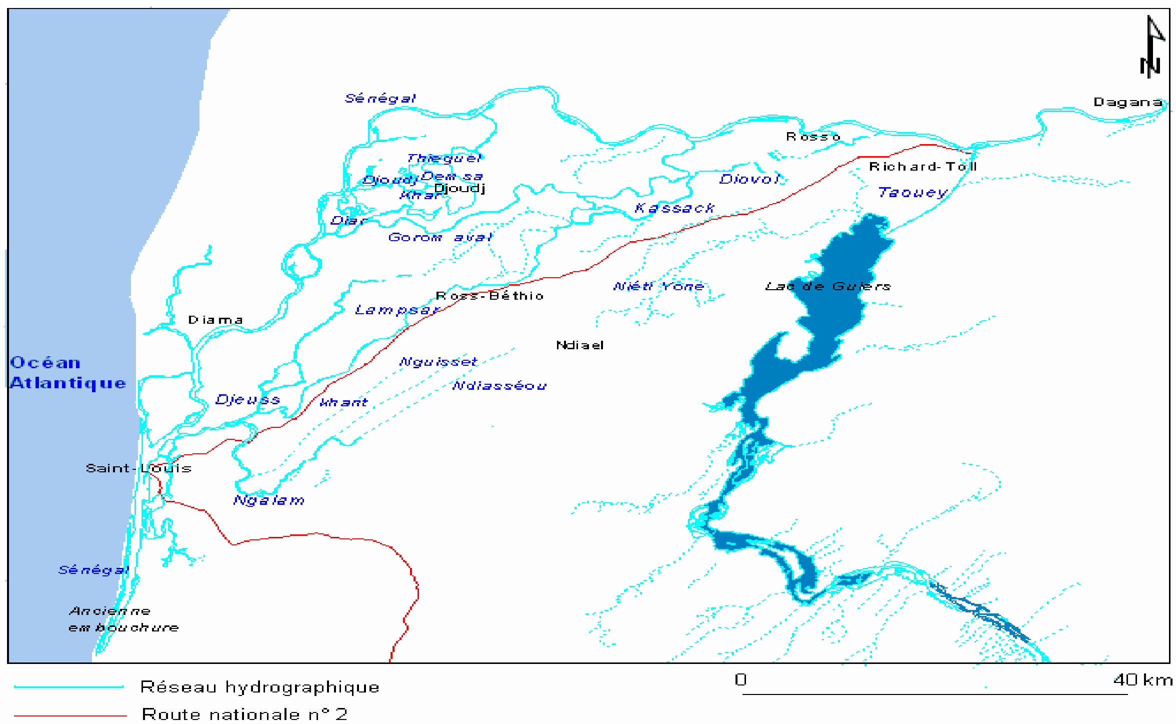


Figure 3.13- Hydrogrphic network of the delta (in Sall 2006)

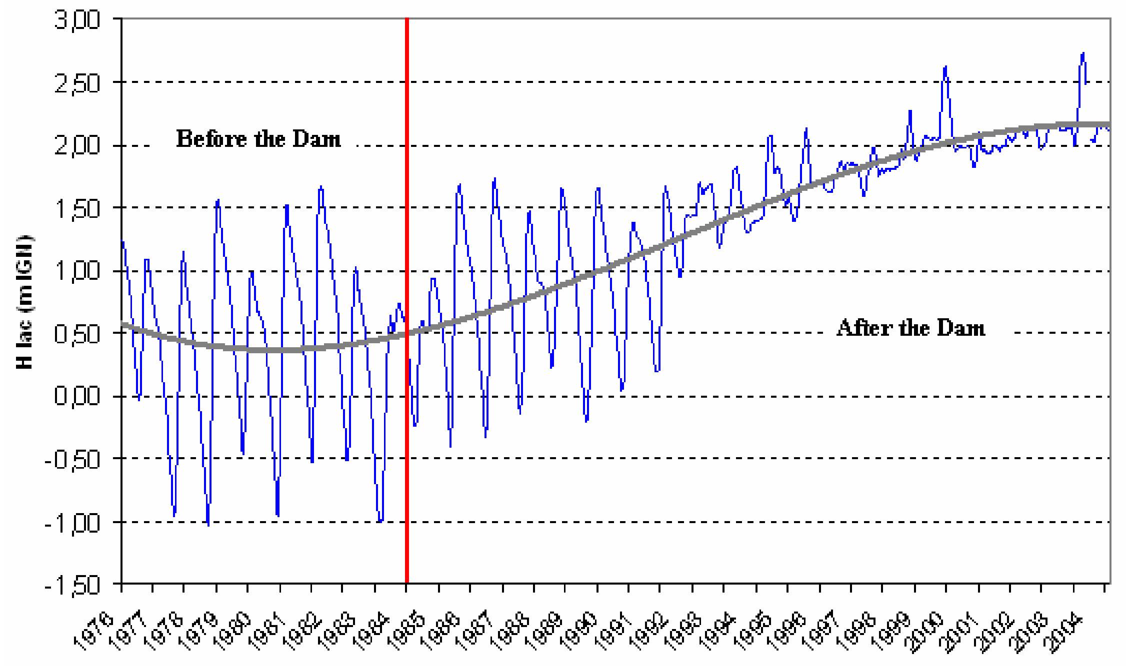


Figure 3.14- Mean monthly water level in the Lac de Guiers from 1976 to 2001 (in Coly 2004)

3.1.5.2- Ground Water

The principal ground water acquifer in the Senegal River delta area is in the Eocene Maestrichian strata of the Continental Terminal formation. The Maestrichian acquifer is found at -50 m at the junction Lac de Guiers- Taouey canal and at a depth of -500 m in Western Rosso (Sall, 2006). Depth to this Eocene aquifer is localized function of the shape and depth of Lac de Guier anticline. The alluvial aquifer is the principal near surface aquifer. This aquifer extends throughout the flood plain and is present to various depths which are generally less than 2m (OMVS). This aquifer is subdivided into several independent ground water domains. The main Continental Terminal aquifer is located in Nouachotian layer sediments (Sall, 2006) and is thicker from N-E to S-E (Fig. 3.15).

The water level in the alluvial aquifer varies with the seasons along with the general hydrological regime in the valley. Since the dam was built, groundwater recharge and the water table have been significantly modified. Reducing the volume of the floods and building dikes significantly reduced the area of natural recharge. On the other hand, flow regulation during low water periods and irrigation increases groundwater recharge during the dry season in some areas. Alluvial ground water is salty. This salinity is explained by the geological history of a region affected by several marine transgressions during the Quaternary. The sea water was trapped in sediments. Sall (2006) reported that the ground water salinity can be higher than the sea water salinity in certain zones of the delta.

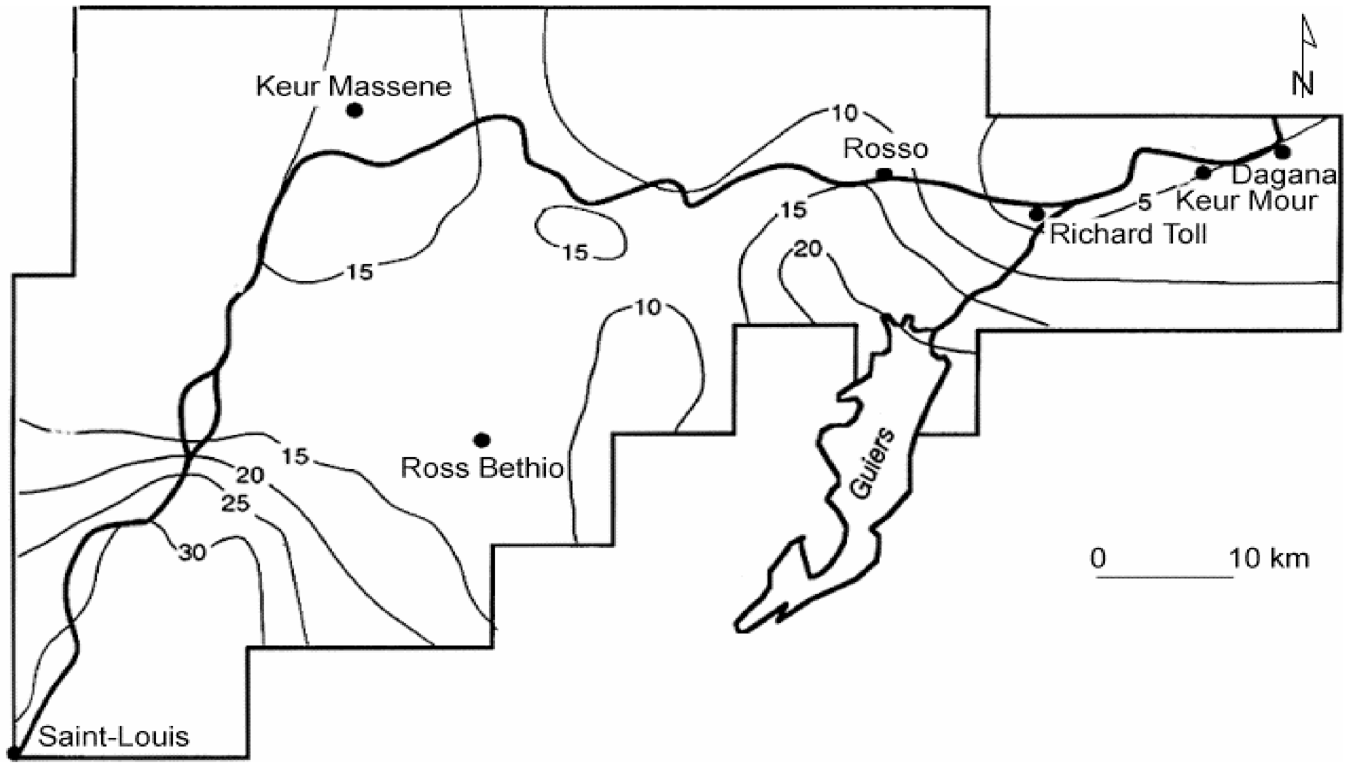


Figure 3.15- Thickness (m) of the alluvial aquifer the Senegal River delta (in Sall 2006)

3.2- Socio-Economic characteristics

3.2.1- Population

The population in West Africa was about 225 million people in 2000. The United Nation office for West Africa reported in 2005 that the population estimate for the year 2020 will be about 430 million people. The rural population consists of 145 million people. Warren *et al.* (2001) reported that "over fifty per cent of the population of the west African Sahel lives in rural areas, where they depend on agriculture and or on pastoralism." The demographic growth rate is higher (3.9%) in urban areas than the 1.4% in rural areas. The social system, religion, traditional customs, and the need for a labor force for agriculture, all favor the existence of a large family size.

The SRB was a center of the West-African empires and kingdoms (Mali or Ghana Empires, Waalo, Teknour Brakna Kingdoms) (Ndiaye, 2007). Today, the SRB has a total population of 3,500,000 inhabitants, 85% live near the river. Resources available because of the Senegal River attracted earlier local populations and French colonists to the area.

The Senegal River Delta and Lower Valley correspond to the Departments of Saint-Louis and Dagana. Togetehr, they cover an area of 6,087 km^2 with a population of 453 896 inhabitants. Saint-Louis occupies only 4.6% of the surface area but supports a population of 237,816 inhabitants with a density of 271 inhabitants/km^2 (Table 3.2). These two departments are subdivided into three counties: Saint-Louis, Richard Toll and Dagana. Saint Louis County located in the coastal area is bordered by the Atlantic Ocean and the Senegal River. It is more populated than the other two counties with 174,017 inhabitants (Sall, 2006). This is due to the exodus of rural people to coastal cities, to Central Africa, and to Europeans countries. In West Africa the movement of the rural population to urban areas is very important. An average annual urban growth rate of 4.8% was experienced in the region between 1980 and 1993; this was more rapid than in any other part of the world (Maconachie and Binns 2006). Uncontrolled population growth and subsequent environmental degradation, associated with chronic poverty and the lack of economic possibilities in the rural areas, have caused the rural exodus and also the seasonal migration phenomenon.

Saint-Louis Island saw its population increase subsequently from 48,800 in 1961 to 81,204 inhabitants in 1970 (Sall, 2006). And following the severe drought of 1970s and early 1980s, the population along the river on the Senegalese side increased by 107% from 1972 to 1988 (Ndiaye, 2007). Seasonal migration, occurring in the dry season when young people join the cities and the coastal zone to seek jobs, advanced by several months during the drought years because of the diminution of the rainy season period. Migration flows contribute to reduce the human resource base of the rural areas every year. Beside the depopulation of rural villages, the movement of people extends the urban areas leading to the creation of suburban zones. This typically unplanned development creates many problems in this area: overcrowding, food insecurity, water shortages, public health issues, and increasing unemployment. Rapid urban growth in City of Saint-Louis has led to a number of informal settlement which have experienced river flooding. These floods marked the return of summer rains after several decades of drought; Leona, Pikine, and Langue de Barbarie are the most affected areas.

Migration to European countries has greatly affected Senegal and other West African countries. Saint-Louis is an important departure point for illegal migration. The United Nations reported that in the year 2005 one hundred West African youth tried to reach European enclaves through Morocco. They risk their lives in several ways migrating to Europe, viewing the destination as the new Eldorado because of the lack of opportunities at home. The BBC has reported that since 2005 it was estimated at least 1,000 people a year are lost at sea attempting the perilous near coastal voyage in small Senegalese fishing boats.

Ethnically, the local population is composed of, in descending order of population numbers, the *Hal Pullar* group *(Peulh and Toucouleur)*, the *Wolof*, the *Mandingo* group *(Soninke, Malinkes, and Bambaras)* and the Arab/Berber. *Wolof* and *Toucouleur* are generally involved in farming and fishery while *Peulh* are specialized in raising livestock.

Table 3.2- Population in the Senegal River delta and lower valley

Department	**Population**		**Surface area**		
	number	Percentage	km^2	Percentage	Density (number/ km^2)
Dagana	216,080	33.5	5,208	27.4	41
Saint-Louis	237,816	36.9	879	4.6	271

3.2.2- Principal economic activities

Agriculture, fishery, and tourism are the main economic activities ongoing in the delta and lower valley region. Agriculture is the most important activity in SRB countries. In rural areas over 90% of the population are involved in traditional agriculture which is dependant on climate variability. Since the construction of Diama Dam, irrigated agriculture in the delta area has been improved considerably. Fishery has also played an important ruoe in the region because of proximity to the relatively cool and productive coastal Atlantic Ocean waters and due to presence or the river, lakes, and several ponds.

3.2.2.1- Agriculture

Water availability always impacts the success of agricultural activities. Before human modifications to the hydrologic system, farming was limited to areas near the Senegal River and generally only after the overflow period. Before the construction of Diama dam, saline waters penetrated far inland, regularly passing Richard Toll about 140 km upstream. Several dikes and small dam were constructed in the past in order to control the annual flood and the sea water invasion, in an attempt to improve local agriculture. Several dikes were constructed in the delta zone to block sea water intrustion and in the Lac de Guier area, the Taouey Canal was dug in 1974. The first dam was constructed at Richard Toll in 1947 in order to grow an irrigated rice crop and another small dam at Keur Momar Sarr was built in 1956 to isolate the Bounoum arm. After construction of Diama Dam in 1986, sea water are no longer invades areas located upstream of the dam. Irrigated agriculture expanded rapidly immediately after completion of the dam. About 80,000 hectares of land is now cultivated in the basin: 60,000 hectares during the rainy season (July - August) and 20,000 during the dry season (March - June) (UNESCO, 2009).

Rice is the principal crop targeted by SAED, a governmental development corporation, with a goal to reach food sufficiency in Senegal. By 1997, 100,000 ha had been equipped for irrigated agriculture, and only 44,000 ha were farmed because of loss of soil fertility and increased salinity (OMVS). The irrigated areas are located in the Walo soils specifically in the Hollalde and Fonde soils. Horticulture and orchards are also developed on the urban periphery and around Lac de Guiers. But, the production is still low. Despite these management efforts, farming is still traditional in most parts of rural areas because of the population's low income, the high rate of illiteracy, and the lack of new technologies. Few farmers can afford to use external inputs, like fertilizer to correct the overuse of their soils and increase their production (Breman *et al.* 2001). Most of the farmers use manure to enrich the soil and this addition contributes to nitrate contamination in ground and surface waters.

In many zones agriculture is largely dominated by small-scale production without mechanization and irrigation. However there are some agro-industrial units operating in the region. CSS, the sugar company, is the largest and is located in Richard Toll district at Rosso, Senegal. The company has a production potential of more than 8,000 ha of sugar cane using water from both the Senegal River and Lac de Guiers (OMVS). Other companies include SOCAS, a company specialized in tomato processing, and several smaller private rice paddy operations supervised by SAED (OMVS). In the Diery zone, farmers cultivate cereals (millet, sorghum, rice, maize) and a peanut crop during the dry season. Today, irrigation is the engine for development in the basin; not only with improved technology, but also with the wider variety of produce types grown (rice, onions, tomatoes, potatoes, sweet potatoes).

Livestock raising is also an important economic activity in the basin. Breeders are generally nomadic and they practice transhumance. Extensive livestock holding include cattle, sheep, and goats.

3.2.2.2- Fishery

Major factors influencing the fisheries sector are the quantity of fish and biodiversity. After agriculture, fishing is an important activity for populations living near the river or along the coasst. Artisanal fishing is much more developed than industrial and semi-industrial fishing and provides the urban areas with fish. However, this economic sector is threatened by a considerable decrease in tonnage caught throughout the region. Depletion in the number of fish and an increase in price have impacted the delta and valley region for at least a decade, due to an unsustainable use of the fisheries resource. Atta-Mills *et al.* (2004) reported that over fishing, overcapacity, habitat degradation, and inequitable access agreements have contributed to the declines in catches faced by regional fishermen. According to OMVS, some observers link this decline to the management projects (dams, dikes) and to their impacts on the local environment: a significant decrease in salinity; proliferation of floating water weeds (due to eutrophication of the aquatic ecosystem), and water pollution. In addition intensive fish harvesting by the large and extensive European Union fleet of ships (Atta-Mills *et al.* 2004) exacerbates the decrease in fish resources. Many West African countries have agreements which authorize European Union (EU) fishing fleets to operate in their territorial water territories without a quota allocation. According to Kaczynski and Fluharty (2002):

> "The fisheries agreements with Senegal illustrate the EU fishery policy in West Africa. Since 1979, the EU fishing industry benefited from profitable access to the fish-rich Senegalese waters, with few restrictions imposed by either the EU or Senegalese government. After over 15 years of EU-Senegalese "cooperation" the assessment is clearly negative, from both an environmental and social point of view: fish stocks are depleted and the Senegalese artisanal fishery is disrupted."

The declining catches have impacted the economic and social life of the local population pushing them to migrate or to change economic activities. Some Senegalese fishermen have changed activity and destination by transporting illegal immigration candidates northward along the coast with their insecure rickety fishing boats.

3.3- Environmental Problems in the Senegal River Valley

3.3.1- Climate change In the Senegal River Valley

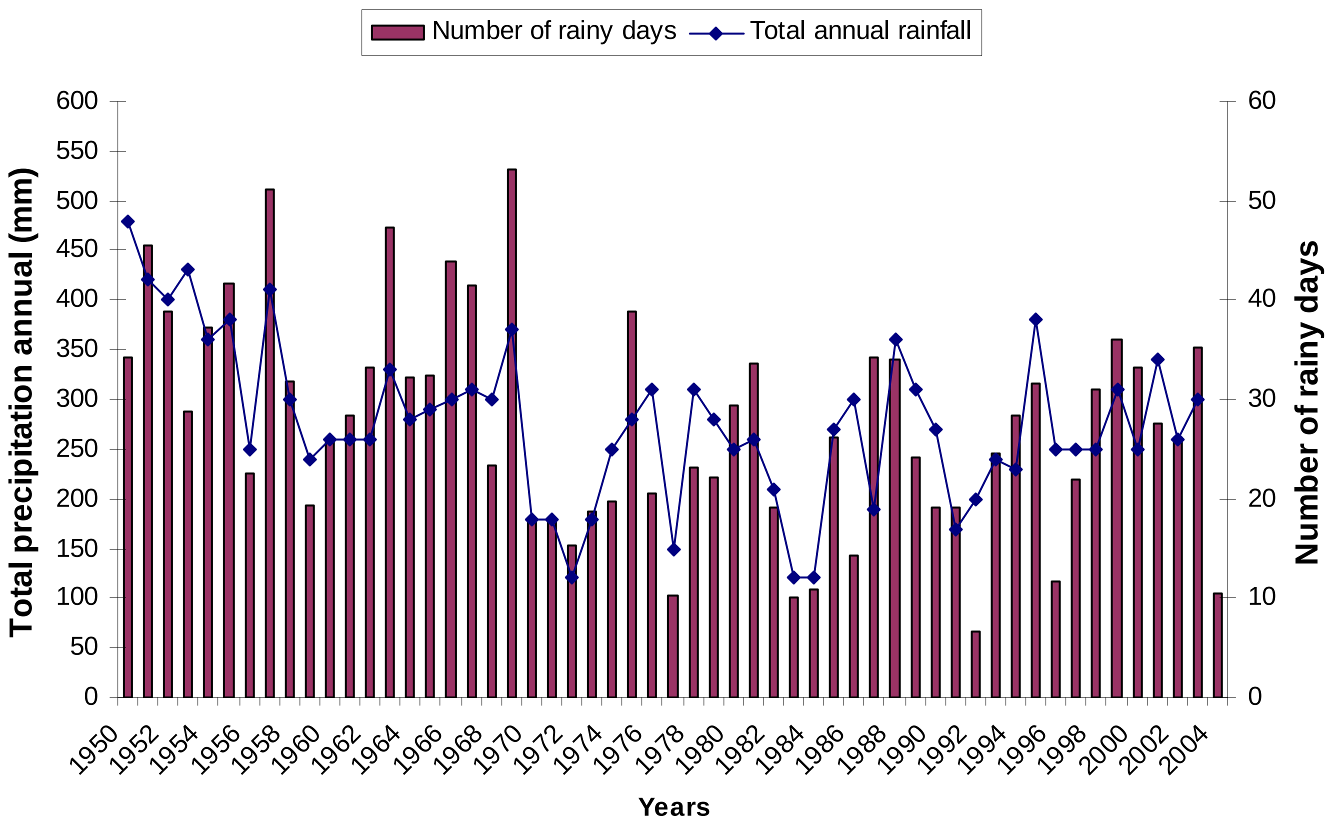
Variability and change are important charactistics of the Earth's climate system, with changes in radiative forcing and system feedbacks leading to temperature and precipitation fluctuations on both global and regional scales. Scientific studies show that the Earth's atmosphere is now warming due to human-induced changes, leading to different impacts from one region to the next. The increase of greenhouse gases (GHGs) since the industrial revolution, from the burning of fossil fuels for energy and transportation and from land cover change, have been strongly connected to global warming. The review of the Intergovernmental Panel on Climate Change (IPCC) assessment (Watson *et al.*, 2001) indicates that the concentration of carbon dioxide (CO_2) has risen at least 30% since the late 1800s. As the GHGs have increased in the atmosphere, the global average temperature has become warmer, increasing by over 0.6 ^{0}C during the 20th Century (Watson *et al.*, 2001). Warming has been linked to an increase of water surface evaporation, sea ice melting, mass loss from alpine glaciers, and sea level rise.

The Senegal River valley, located in the Sahel climatic zone, is highly vulnerable to climatic variability. Africa contributes only 4% of the atmospheric GHGs per year, a small amount compared to the 23% per year from the U.S. Africa has contributed the least to the global warming but is in line to be among the hardest hit by the resulting climate changes (Fields, 2005). If the trends continue, by 2050 sub-Saharan Africa will be warmer by 0.5 to 2^{0}C and drier with water loss exacerbated by higher evaporation rates (Nyong, 2005). According to Hulme *et al.*, (2000), understanding and predicting the inter-annual and inter-decadal variation in climate has become a major challenge facing African climate scientists in recent years.

In the Sahel, important variability has been noticed in the annual rainfall and temperature data. Hulme *et al.,* (2000) reported that in Global Climate Model (GCM) scenarios, which can stimulate change to African climate, and the role of human induced land cover change is an important driver of African climate variability. However, the dry conditions during the later decades of the 20th Century were most probably driven by changes in ocean surface temperature and specifically a warming in the Southern Hemisphere oceans (Brook 2004).

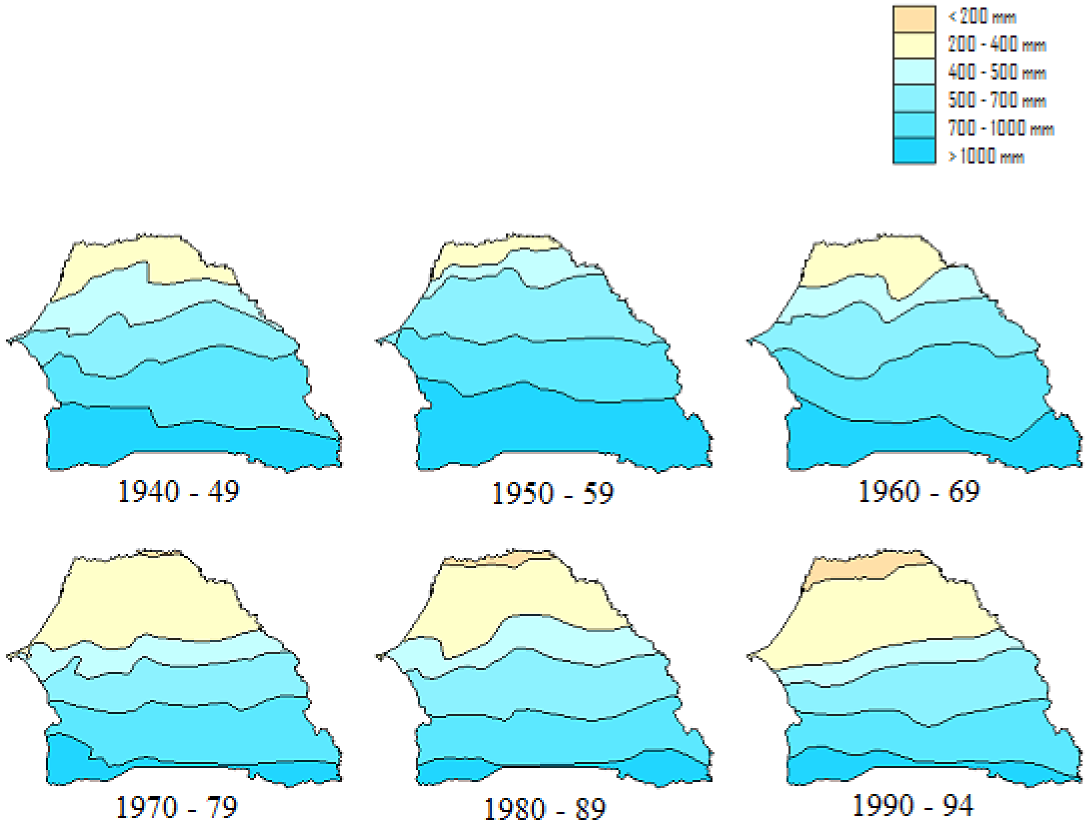
3.3.1.1- Rainfall variability

The vast majority of annual rainfall in Senegal occurs between May and October and this rainfall period is shorter in the northern part of the country. From June to September approximately 85 to 90% of the precipitation occurs. The number of days with rain averages between about 35 and 50 days per year. Mean annual rainfall for Saint Louis ranges from over 500 mm to less than 300 mm per year (Fig. 3.16). High interannual rainfall variability is evident in the plot of rainfall data for Saint Louis from 1950 to 2004. Decadal rainfall variability is noticed, with 1970-1974 and 1982-1984 registering some of the lowest precipitation amounts. The entire data record can be divided into a humid phase before 1970 and a dry phase thereafter.



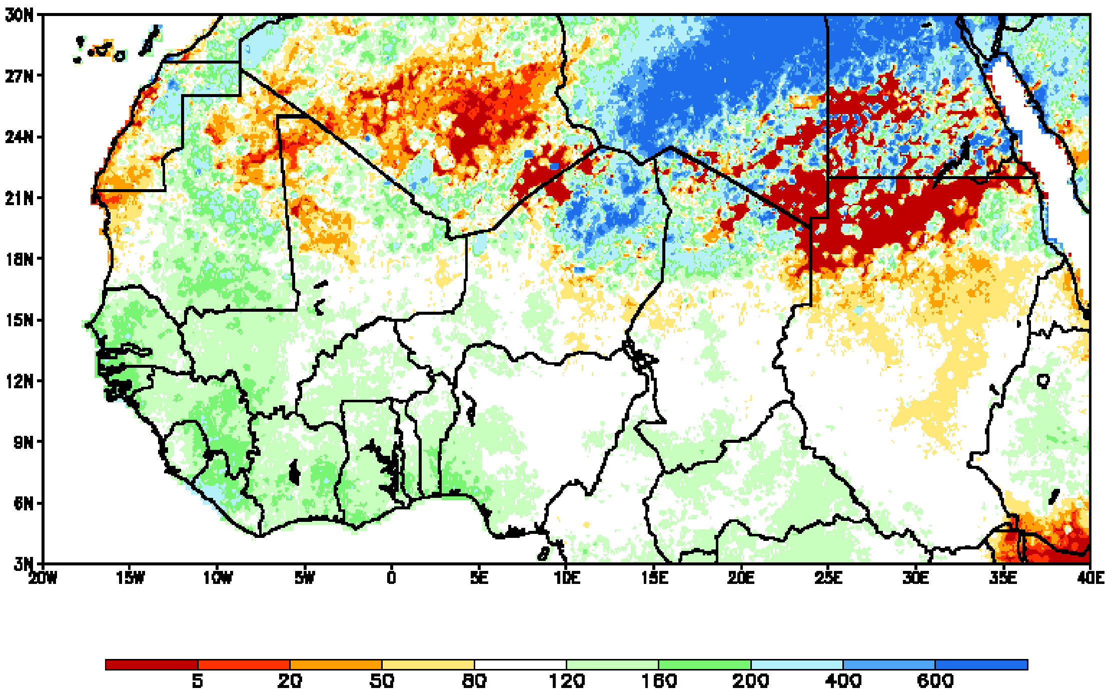
3.16- Time series of Saint Louis rainfall and the number of rainy days

Maps of average rainfall by decade (Fig. 3.17) show that from 1950 to 1960, the Saint Louis and Matam regions are situated between isohyets 200-500 mm and during years 1990 to 1994, 90% of the River valley and delta are located into the isohyets smaller than 200 mm (CSE). During 2003 and 2008, rainfall was particularly abundant throughout the region, causing flooding and landslides in certain areas. A review by USAID (2008) shows that above average rainfall was prominent across the Sahel region and many part of Senegal recorded more than 150% of normal rainfall (Fig. 3.18). Nonetheless dry conditions persisted in some areas and the 2003 rainfall total for the Sahel was considered unusual (Brooks, 2004).



3.17- Mean decadal rainfall in Senegal (1940-1994) (CSE)

Southward or northward migration of the ITCZ is related to the West African monsoon, which brings moisture into West Africa from the Atlantic Ocean. Evolution of the rainy phase of the West African monsoon during early summer controls the northward advance of seasonal rainfall into the Sahel. Intensification of the southeasterly winds favors the northward migration of the ITCZ and larger rainfall totals. Inter-annual rainfall declines also may be related to the intensification of the Harmattan or desert wind; possibility due to global warming and the loss of biomass in the region (desertification). Correlation between rainfall in Sahel and the El Niño Southern Oscillation index (ENSO) has been observed, but the strength of the relationship is not strong. Brook (2004) report that the shifting patterns of warming in the Pacific Ocean result in changes in the distribution of atmospheric deep convection, reorganizing atmospheric circulation, and shifting the position of areas of monsoon rainfall. ENSO has been linked to flooding, drought, and temperature extremes. Research done by several climatologists has demonstrated some predictability of Sahelian rainfall based on sea surface temperature departures from normal. However the impact of ENSO is more significant in eastern Africa.



3.18- Percent of Normal Rainfall (%) May 1 – Sep 30, 2008 (Source: FEWS/NOAA)

3.3.1.2- Temperature Variability

Temporal and spatial variability of temperature are evident throughout Senegal. Lower temperatures occur near the coast and the highest temperatures are found in the northeast. Mean monthly temperature varies from 23^0C to 29^0C at Saint Louis and from 25^0C to 35^0C at Bakel. Temperature fluctuations are affected by the oceanic/continental factor, and seasonal variability. For the SRB, places along the coast experience lower temperatures because of the moist marine winds coming from the Atlantic Ocean; drier and hotter air masses impact the middle valley and are associated with more frequent "Harmattan" winds.

Recent global temperature increases have been strongly linked to GHG emissions. Carbon dioxide emissions stem from the burning of fossil fuels and land use changes including deforestation. At the local to regional scale, land cover change has more influence on near-surface heating than GHG's forcing in West Africa (Crutzen and Meinrat, 1990)

Attempts have been made at estimating CO_2 emissions in the Sahel from biomass burning and soils, which may play an important role in atmospheric pollution and climate. Wildfire and burning of agricultural waste produces pyrogenic emissions which release GHGs into the atmosphere. This phenomenon might contribute to climatic deterioration and lead to the increase in terrestrial temperature. According to Crutzen and Meinrat (1990), biomass containing 2 to 5 petagrams of carbon is burned annually; in West African savannas, 227 million ha are burned (including 53 million ha in the Sahel) and 45 to 240 Tg of carbon are burned per year. Peatland fires, in the northwestern coastal area of Senegal around Lompoul during drought years, may contribute significantly to interannual GHG emission variability.

Soils are typically considered as an ecosystem component for carbon storage that helps to sequester atmospheric CO_2 rate. But several studies have shown that the soil organic matter is susceptible to conversion into CO_2 and return to the atmosphere (Tieszen *et al.,* 2004). During these periods, soils are no longer a sink of carbon dioxide.

3.3.2- The sea level rise flooding hazard

Warming during the 20th century contributed significantly to a rise in sea level. Global mean sea level increased at an average annual rate of 1.8 mm/yr and it is projected to rise by 0.09 to 0.88 m between 1990 and 2100 (IPCC, 2001). In Senegal, a 1 m rise in the sea level would inundate and/or erode over 6,000 km^2 of land. Under a 1 m sea level rise scenario, estimates suggest that at least 110,000 - 180,000 people (or 1.4 to 2.3% of the 1990 population of Senegal) would be at risk and inundation would be responsible for more than 95% of the land loss (IPCC, 2001). The coastal area near Saint Louis is very dynamic and a rise in sea level promotes land loss, increased flooding, and salinization. The impacts would vary from place to place and the magnitude of impact would depend on relative sea-level rise, coastal morphology/topography, and local human modifications (Nicholls and Mimura, 1998). An artificial new mouth for the Senegal River, which was dug at the Langue de Barbarie in 2003, has accelerated erosional dynamics. Creation of this artificial opening to the Atlantic has been accompanied by an increase in water salinity in the southern part of the estuary, especially near Gandiolais (15 km downstream of Saint-Louis) which is negatively affecting irrigation in the area (Isupova and Mikhailov, 2008). Strong wave action impacts the coastal zone on a seasonal basis with a maximum wave height > 5 m; in addition, an increase of mean level (with a rate of few millimeters per year) has been observed in the Senegal River delta area (Isupova and Mikhailov, 2008). During the wet season, the south equatorial current supplies warm water along the Senegal coast (Sall 2006). Isupova and Mikhailov (2008) reported that oceanic water temperature varies on average from 21^0 on February to 25^0 on July. At the same time, the increase in river volume results in a salinity fluctuation which reaches 35 ‰ during the wet season and rises to 37 ‰ during the dry season Isupova and Mikhailov (2008). A change in water density from 1023 to 1025 kg/m^3 (August to February respectively) has been noticed. Sediment accumulation at the river mouth contributes to an increase water flow transit time. The combination of anthropogenic and natural factors causes flooding in the community of Saint-Louis and surrounding areas.

3.3.3- Environmental degradation

3.3.3.1 -Environmental change

The Senegal River delta and valley are affected by long term climate variability and change; indicators of these climate shifts include a rainfall deficit, warmer temperatures, sea level rise, floods, and drought. These shifts have led to environmental degradation (e.g. land cover change, soil degradation, and loss in biodiversity), water deficits, and a profound effect on human life and activities. These negative aspects of climate variation affect the economy of the region and the country, which has experienced severe economic hardships since the 1970s. Major changes in this area link climate variability with changes in land management and resource exploitation. According to Dolman *et al.,* (2003), global change and climate change can only be understood when the major causes of land-use change are understood.

Grassland and wooded grassland are the main vegetation types in this geographical area. Changes in soil characteristics can be linked to spatial and temporal change in vegetation; with the expansion of soil salinization favoring halophytes (*Tamarix sp*). In addition to natural vegetation changes, the rice crop and other cereal and vegetable species cultivated in that area are affected by this blight, leading to a decrease in soil fertility and a progressive drop in crop yields.

Construction of the salt-wedge Diama dam (1986) changed the hydrological system of the SRB and influenced the evolution of soil characteristics. Invasive species, such as *Typha australis, Pistia stratiotes, Salvinia molesta are* now well established due to alkalization. The rapid proliferation of these invasice riparian species has had a dramatic effect on river discharge, with a decrease in water flow and sediments flux. Eutrophication of river water in the upstream delta area is aggravate by the increased of nutrient supplied to the water bodies. In most cases, runoff from agricultural activities is the source of of the increased nutrient flux (Dikinson and Murphy, 2007). Fertilizer consumption is increasing in the area since the implementation of management projects and increased nitrogen levels is one of the growing public health problems in the region. Areas situated downstream of the dam have seen an increased concentration of salt and a subsequent loss of biodiversity as the alteration of natural river flows has also lead to an increase of salt water intrusion into groundwater supplies.

3.3.3.2- Soil salinization

Salinization is the process by which water-soluble salts accumulate in the soil. It is a natural resource concern because excess salts hinder the growth of crops by limiting their ability to take up water. Salinization may occur naturally or because of conditions resulting from management practices. In semiarid areas, salinization often occurs on the rims of depressions and edges of drainageways, at the base of hillslopes, and in flat, low-lying areas surrounding sloughs and shallow bodies of water (USDA 1998). In coastal Senegal, the sodic and aquic or hydromorphic soils are located inside the interdunal depressions. Soil evolution is related to the ground water fluctuation, irrigation water use, and inundation. Following drainage, the soil pedogenic processes in the depression results in organic matter mineralization, oxidation, and gleyification. Soils in semiarid areas can receive additional water from below the surface, which evaporates, and the salts are left behind on the soil surface. During the dry season the evaporation rate/process is high and this leads to crystallization and accumulation of salt in the topsoil forming white or gray deposit. Salinity is becoming more and more of a limiting factor for irrigated agriculture and natural vegetation growth in delta area of the SRB.

Regional hydrogeology and land management are strongly related to the spatio-temporal distribution of the type of soil salinization. Irrigated soils without drainage have higher salinity and alkalinity than those which are irrigated and drained. Soil sodication varies according to the type of land management. Several studies have shown that soil quality in the valley is affected by a gradual decrease in natural salinization and a gradual increase in man made salinization.

3.3.3.2.1- Origin of soil salinity

The origin of soil salinity in the SRB is explained by geological and geomorphological processes and sea level fluctuations during the Quaternary era. Several alternating wet and dry periods have occurred, with wet periods corresponding to high transgressing sea levels and the dry phase being related to the sea regression. During the wet intervals, Atlantic Ocean water extended far inland, up to 100 km. A major transgression occurred between 7,000 Bp and 4,500 Bp with a peak at 5500 Bp (the Nouachottian transgression, when the sea level rose from 1 to 2.5m). Oceanic salts gradually move through the soil and enter the local ground water system.

During the 20^{th} Century, the northern part of Senegal experienced a severe drought that culminated in 1970s and early 1980s. Following this severe drought, two dams were constructed on the Senegal River to manage water resources: the Manantali hydropower dam in Mali and Diama in Senegal. Diama was constructed to block the seawater intrusion and preserve fresh river water for irrigation and drinking (Varis *et al.,* 2006). Since the construction of Diama Dam and the introduction of the rice irrigation projects, the Senegal River Valley ecosystem has undergone spectacular changes that were made worse by rainfall deficits, rapid population growth, agriculture expansion, and deforestation. Over two million people live in SRB, of whom 85% live near the river and rely on it for their livelihoods. Riparian communities in the Middle Valley (approximately 700,000 people) are particularly dependent on river environment.

Irrigation water management is closely tied to soil degradation. A major pedogenesis factor in the delta is the frequency and the length of the inundation by the river (Deckers *et al.,* 1996). Irrigation return flows, move salts from upstream areas. Under the impact of hydro-agricultural management these salts have different dynamics and represent a severe constraint for crop production (Diene, 1998). Management plans in poor drainage areas can increase ground water fluctuations and favor the transportation of salt to the topsoil by capillarity rise, from the saline and shallow water table. According to Wopereis *et al.,* (1998) about 72,000 ha have been developed for irrigated agriculture on the left or Senegalese bank of the Senegal River. During the irrigation season, the large quantity of irrigation water adds additional salt to the fields.

The negative impact on local soils of the rice production policy elicits grave environmental consequences, and thousands of hectares of rice production areas have already abandoned because of salinity (Venema *et al.,* 1997). Soil degradation through salinization is considered as one of the most important threats jeopardizing sustainable irrigated rice cropping in the Sahel (Van Asten *et al.*, 2003).

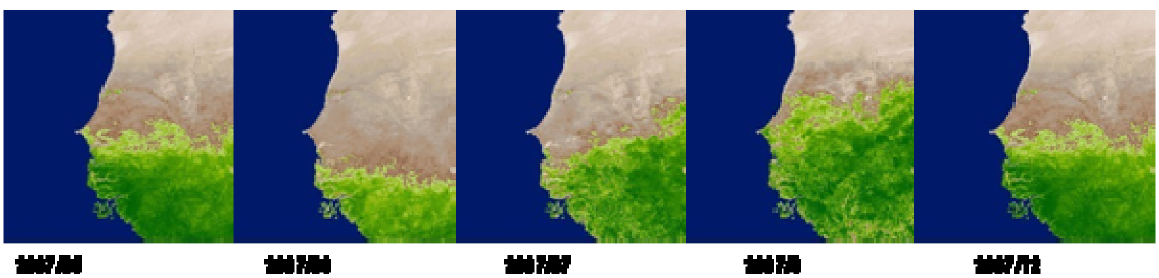
3.3.3.3- Deforestation

In the last half of the 20th century, analysis of original field data indicates that forest species diversity and tree density in the West African Sahel have declined. According to Gonzales (2001), average forest species diversity in Northwest Senegal fell from 64 ± 2 species in 1945 to 43 ± 2 species in 1993. Densities of trees of a height ≥ 3 m declined from 10 ± 0.3 trees/ha in 1954 to 7.8 ± 0.3 trees/ha in 1989. Standing wood biomass fell to 2.1 t/ha in the period 1956–1993, releasing CO_2 at a rate of 60 kgC /person/ yr. In has been suggested that these changes have shifted vegetation zones toward areas of higher rainfall at an average rate of 500 to 600 m/yr (Gonzales, 2001).

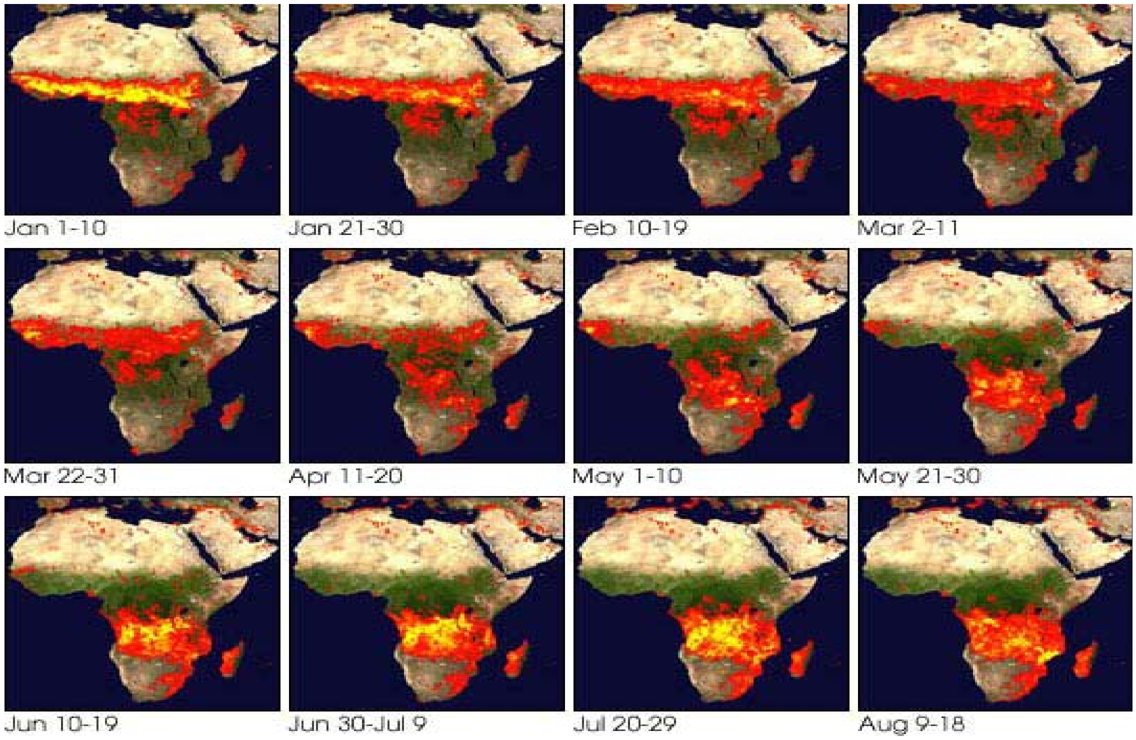
The distribution of vegetation across the country can be estimated using remote sensing data. According to Liang (2004), remotely sensed spectral bands provide information about vegetation structure and the state of vegetative cover such as leaf density, leaf water content, age, mineral deficiencies, and parasitic attacks and a good vegetation index should be sensitive to these factors. NDVI has been widely used in various applications (Liang, 2004). NDVI is also the most widely used numerical indicator for detecting live green plant canopy because the values are strongly related to the leaf chlorophyll content and absorbed photosynthetic radiation. Variation in NDVI value during 2000 and 2007 has shown that the highest NDVI value is observed in August and it covers the whole country from the south to the north (Fig.3.19 and 3.20). August and September have the highest mean precipitation and this is reflected the results obtain from NDVI analysis. Rainfall during the prior month is the major determinant of NDVI, which is considered to be a "greenness" index (Nicholson *et al.,* 1998). Vegetation distribution patterns in Senegal can be estimated from these satellite-based observations. During the dry season in the northern part of Senegal, the vegetation is dormant and there is no significant NDVI value. Vegetation in the north is strongly affected by the seasonal rainfall deficit, high rates of evapotranspiration, overgrazing, soil salinization, and land use change. There is a concern in the northern part of the country regarding potential "expansion" of the Sahara desert. Desertification, a combined cultural and climatic phenomenon, has a very strong negative effect on plant growth in the Sahel zone.

Seasonal fires are another cause of biomass loss. Each year in March and April thousands of fires smolder in the grasslands, scrub, and dry forests of the West African Sahel and Soudanian woodlands (Fig. 3.21). Fire has been used for centuries as a management tool in West African agricultural and pastoral systems and the loss of organic material has a negative aspect on soil fertility leading to long-term declines in soil productivity. There are several types of savanna plants that are well adapted to fire and these species will disappear if fire is removed from the ecosystem. Areas affected by the drought are invaded by woody plants. According to Frederiksen and Lawesson (1992), bushland has a woody density intermediate between that of grassland and wooded grasslands and a significantly higher woody cover.

3.19- NDVI data variability in 2000 (Source: Global Visualization Viewer)



3.20- NDVI data variability in 2007 (Source: Global Visualization Viewer)



3.21– Spatio-temporal fire cycle in Africa (www.wikipedia.com)

3.3.3.4- Desertification

Desertification is a spectacular manifestation of environmental change due to the coupled human and natural system. Desertification produces land and soil degradation in arid, semi-arid and dry sub-humid areas due to as the justaposition of dry climatic conditions and human demands on natural resources. It was found that desertification reduced both moisture flux convergence and rainfall in the Sahel region and produced amthospheric circulation changes and rainfall anomaly patterns (Nicholson *et al.,* 1998).

Feedbacks between land degradation and precipitation link desertification and climate change. Desertification aggravates climate change through the release of CO_2 from cleared and dead vegetation and through the reduction of the carbon sequestration potential of desertified areas. Conversely, climate change exacerbates desertification through the alteration of spatial and temporal patterns of temperature, precipitation, solar insolation, and winds (Gonzalez 2001). A major effect of the desertification in West Africa is a significant reduction in crop yield; Gonzalez (2001) reported that:

> "Desertification worsens the life of millions of people in the West African developing countries. It culminated in the Sahel drought of 1968 to 1973, a tragedy that witnessed famine and the death of up to a quarter of a million people."

Along the Senegal River basin, two decades of drought decimated arid agriculture, livestock, and drinking water supplies in areas inhabited by a semi-nomadic population. As a result this event, desertification became an important issue for the international community. The West African countries affected by desertification and drought are now grouped in an organization: The Permanent Interstate Committee for Drought Control in the Sahel (CILSS). The CILSS was created in 1973.

CHAPTER 4 - Assessing the spatial extent of saline and sodic soils using remote sensing and GIS techniques

Inductive research methods start with many observation of nature with the goal of finding a few, powerful statements or generalizations about how nature works. Repetitive satellite images of areas under environmental stress provide a potentially powerful way to assess conditions and changes over time. The imagery provides numerous observations and computer hardware combined with image-processing and GIS software make available valuable ways to analyze and visualize the data. GIScience techniques can enable accurate change detection in the distribution of salinity when combined with conventional methods of soil survey and mapping.

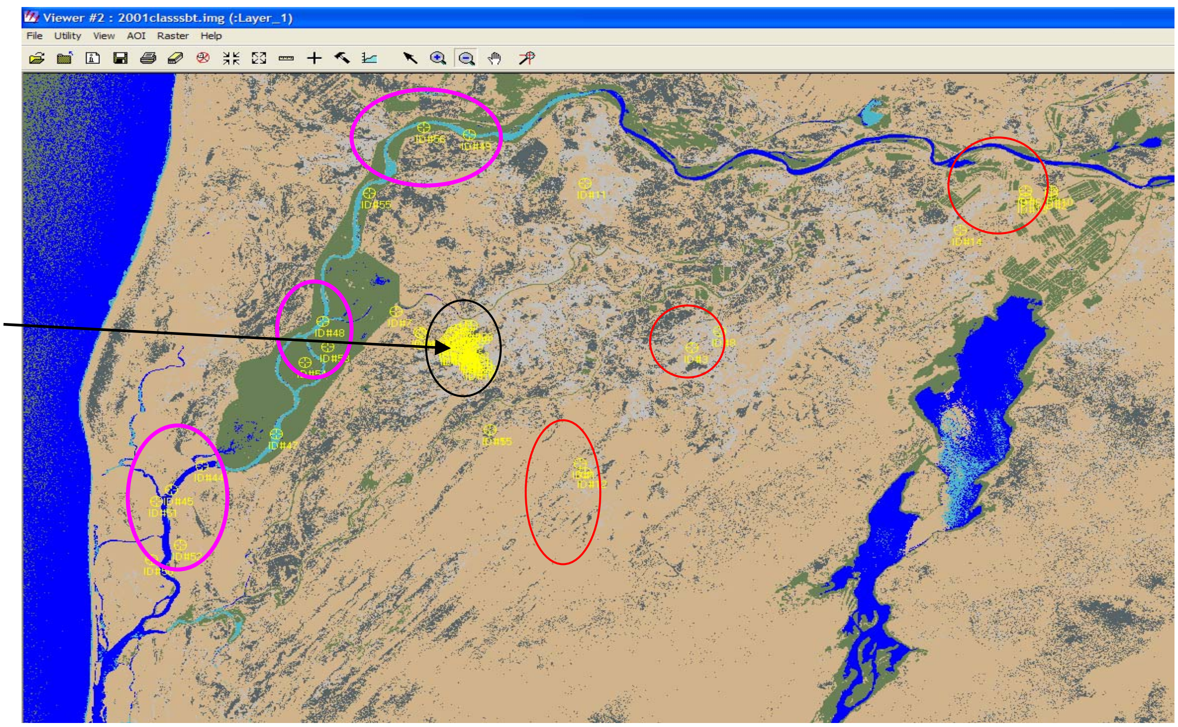
4-1. Data collection

4-1-1. Ground survey data

Soils were sampled during the period December 2008 – January 2009 at 20 locations in the study area. The soil samples collected were not very deep because the water table in the area is not deep. With a goal of using the samples to provide information about salinity and surface reflectance, the samples did not need to be deep. The choice of specific sampling locations was based on field observation of the topsoil and vegetation cover. Local topography was also considered, because the soil types are correlated with regional geomorphology. These ground-based observations of certain soil properties will assist in interpreting variations in the satellite images, which provide 'wall-to-wall' coverage of the study area. This approach allows the identification of the near surface soil character and facilitates comparison among the different types of soil impacted by salinity. The relationship between the soil and vegetation provides indirect information about chemical characteristic of the soil in this local ecosystem (*Tamrix sp* is a salt indicator and *Typha australis* is an alkaline, a non-salt and hydromorphology indicator). From this information, grounded theory is generated because of the strong connection to reality associated with the observations (Grunwald, 2006).

Presence of salt efflorescence and a salt crust can be detected either by ground survey or from remotely sensed data in visible wavebands. Before going to the field for data collection, an unsupervised classification of one Landsat image acquired during the dry season was completed to assess potential areas affected by the salinity. In the field, several points were selected and the coordinates (latitude/longitude) were obtained with a GPS receiver and recorded with a precision error of ± 13 m. Based on this method, surface soil samples were collected in the study area for laboratory analysis of chemical characteristics and for reflectance spectral analysis. Soil data collected in November 2008 from the Krankai, Senegal, region and analyzed by soil scientists from the SAED Institute on November 2008 (Fig. 4.1) were made available to increase the number of sites available for ground-truth in supervised Landsat image classification. This field work, followed by laboratory chemical analysis, enabled classification and change detection of salt-affected soils by use supervised classification of the satellite imagery.

Krankai site



___ Data collected on December 2008

___ Data collected on January 2009

___ Data collection based on observation

4.1- Location of data collection

4-1-2- Data acquired and sources

A major objective of this research was to detect spatial and temporal change in salt-affected soil in the Senegal River valley, using multi-temporal satellite data. A set of Landsat Multi Scanner Spectral (MSS) and Landsat TM and ETM+ images were obtained to assess salt affected soil (SAS) distribution in the SRB. The first priority in selecting Landsat images (ETM+ and TM) was to find data corresponding to the period of the year when salt-affected soil patterns are most evident. Images collected during the dry season are the most suitable for identifying salt distribution in the topsoil because of the high spectral reflectance (presence of salt crust). A number of Landsat TM, ETM+, and MSS images spanning 30 years was obtained from either the USGS, Global visualization (GLOVIS), the Global Land Cover Facility (GLCF), from scientists at CSE Senegal (Centre de Suivie Ecologique). Images (path 220 and row 49 for MSS images and path 205 row 49 for TM and ETM+) images from a number of years (1973, 1979, 1987, 1988, 1994, 2001 and 2003) will be used for detecting and mapping spatial and temporal change (Table 4.1).

Table 4.1- Landsat Data acquired and Sources

Image Types	Image Acquisition	Spatial Resolution	Sources
Landsat MSS	June1973	60 m	
	September 1979	60 m	GLCF/ESDI
Landsat TM	November 1987	30 m	GLOVIS
	March 1988	30 m	
Landsat ETM+	April 1994	30 m	USGS (CSE)
	May 2001	30 m	USGS (CSE)
	February 2002	30 m	
	March 2003	30 m	GLCF

MSS images have four spectral bands (0.5-0.6 µm, 0.6-0.7µm, 0.7-0.8 µm and 0.8-1.1 µm) while the TM and ETM+ images have seven spectral bands (0.45-0.52 µm, 0.52-0.6 µm, 0.63-0.69 µm, 0.76-0.9 µm, 1.55-1.75 µm, 10.4-12.5 µm and 2.08-2.35 µm). According to Ceuppens *et al.*, (1999) data collected at the end of the raining season may not be the best images for a change detection analysis in this area, as salts dissolve with high amounts of water. However, information about salt type, its spatial extension and abundance, and temporal changes can be obtained by combining field studies, laboratory analysis, and dry season satellite image interpretation. A map of areas under irrigation was also obtained to assist in interpreting the imagery.

Several studies have demonstrated the application of remote sensing in mapping and detecting SAS using a variety of methods (Howari, 2003) and many digital image processing and change detection approaches have been developed. to achieve the goals for this study, in particular detecting change in areal extent of salt types, it was necessary to select a suitable change detection technique in order to produce good quality results (Lu *et al.*, 2004). For this purpose, supervised classification, unsupervised classification, and change detection analysis techniques were performed. Prior to image processing, preprocessing of the data included registration and re-projection of the 1994 and 2003 Landsat images, layer stacking of the individual band images into a multilayer data file, and then Principal Component Analysis (PCA).

4-2. Methods to address local change

ERDAS and ESRI ArcGIS 9.3.1 software were used for scientific visualization, processing, and mapping the spatial data. Computer-assisted operations are categorized into seven types: image rectification and restoration; image enhancement; image classification; data merging and GIS integration; hyperspectral image analysis; biophysical modeling; and image transmission and compression (Lillesand and Kieffer, 1994). Various image transformation techniques have been used in soil salinity studies including registration and re-projection, principal component analysis, supervised classification, unsupervised classification, change detection and analysis of zonal statistics. In this research, all four bands of the MSS and six bands of the TM and ETM+ data have been stacked together (the TM thermal band was not used).

4-2-1. Data preprocessing

Satellite images acquired for the same region but at different times have differences because of varying factors in the acquisition process. Studies have shown that these factors can be divided into two categories: remote sensing system factors (the impact of temporal resolution, spatial resolution, spectral resolution, and radiation resolution) and environmental factors (the impact of atmospheric conditions, soil moisture, and phenological characteristics). To avoid or decrease error processing in the data and increase the quality of the results, preprocessing has been performed on the data prior to classifying and detecting change.

4-2-1-1. Image Registration

Before performing classification and change detection, image registration was done on the images acquired in 1994 and 2003; the other images were already registered to each other. Image registration improves change detection accuracy. Image-to-image registration was selected and the May 2001 image, which had been geo-referenced to UTM (Universal Transverse Mercator) WGS 84, Zone 28 North was used as the reference image. Eighteen GCP (ground control points), a second-order polynomial transformation, and nearest neighbor re-sampling methods were used. The nearest neighbor re-sampling method uses the value of the closest pixel to assign a value to the output pixel and thus transfers original data values without mathematically transforming them as happens with other re-sampling methods. Therefore, the extremes and subtleties of the original data values are not lost. Nearest neighbor re-sampling also has the benefit of having a faster computer processing time as compared to other interpolation methods.

4-2-1-2. Principal component analysis

Principal component analysis (PCA) is a method used to reduce data dimensionality by performing a covariance analysis between factors. The principal goal of the PCA is to filter out noise and reveal hidden structure within the data. PCA uses statistical methods to de-correlate the data and reduce data redundancy. It is a technique to compress multidimensional data in such a way that the transformed data or ‘bands’ are uncorrelated. The objective is to create new image data layers that reveal spectral differences that otherwise will be hard to detect in original data (Adams and Guillespie 2006). The output is a new set of digital numbers for each pixel for each derived component (or transformed band). If multiple dates of data are layer stacked together, then PCA can be used to detect temporal change.

With PCA analysis, visual interpretation can be performed using the first few principal component bands rather than using all the original data. Ceupens *et al.* (1999) reported that change elements tend to appear in the minor components. In this study, PCA was performed with all bands for the three types of Landsat images (with the Landsat TM thermal band omitted).

4-2-2-Data processing

4-2-2-1. Supervised classification

Classification is the process by which each pixel in the image is assigned to a class or information category on the basis of its statistical data attributes (Adams and Guillespie, 2006). Supervised classification develops rules for assigning reflectance measurement into classes using selected areas for building training signatures. Areas within the image are selected that correspond with desired information or land cover class. The spectral values present within the selected area are used as numerical basis for categorization of other pixels within the whole image area based on statistical similarity. Sites visited in the field for soil sampling were used to provide training sites for the thematic classes. In this study, seven information classes have been defined: Fresh water, Brackish water (which also included water rich in sediment), Water impoundment (including wetlands), Non saline soil, Saline soil, Saline-sodic soil, and Sodic soil.

Fresh water, Brackish water and Water impoundment/wetland were classified based on the selection of large and homogeneous areas within the image. Areas of Non saline, Saline, Saline-sodic and Sodic soil classes were selected based on the chemical analysis of the soil collected during field studies (Fig. 4.2.) and the corresponding field locations. Laboratory analysis of the soil samples yielded measures of electrical conductivity (CE), cation exchange capacity (CEC) and the exchangeable sodium percentage (ESP) (Table 4.2). Based on these results, the soil class was determined (Table 4.3).

Table 4.2- Classification of Salt-affected Soils

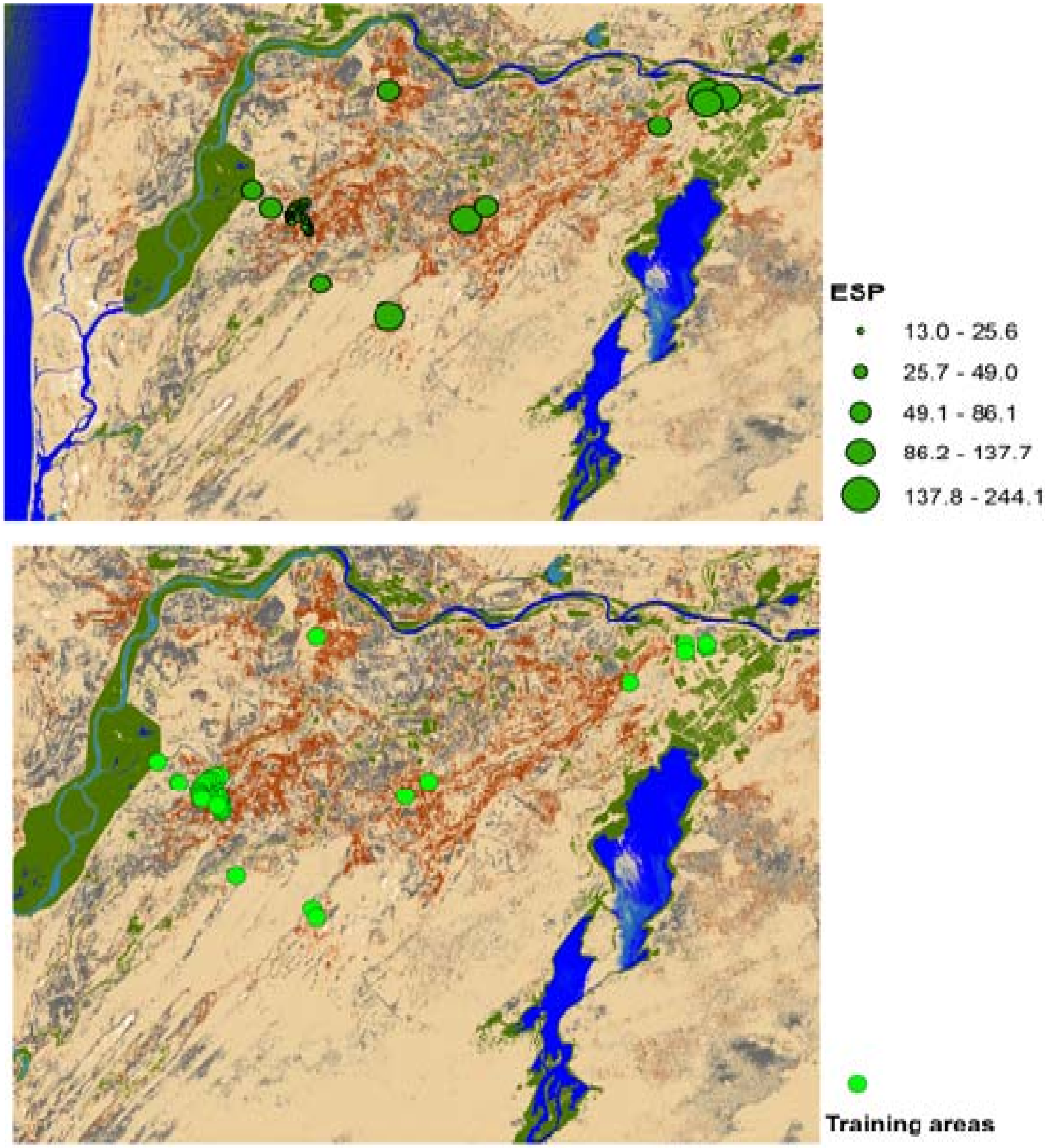
Soil classes	**EC (µS/m)**	**ESP (%)**
Saline	>4000	<15
Sodic	<4000	>15
Saline-sodic	>4000	>15

ESP provides information of the percent of the exchange sites are occupied by basic cations. The acceptable base saturation limit for sodium is 15%. Sodium levels higher than 15% result in soil dispersion, poor water infiltration, and Na toxicity to plants.

$$ESP = \frac{\text{Exchangable Sodium, meq/100g soil}}{\text{Soil CEC meq/100g soil}} * 100$$

For the Saline class, none of the samples fit the classification criteria. Training locations for this class were determined base on the assumption that, it is most probable to have these soils present in the area situated downstream from Diama Dam. Areas for statistical training were chosen based on visual image interpretation. According to Matternicht and Zinck (1997), these soils have high reflectance values in visible wavelengths and especially the blue region of the spectrum. For the other SAS classes, the field data collection locations were identified in the imagery (Fig. 4.3) and those locations were used to build statistical training data for the relevant SAS classes. The dry season Landsat images data acquired on May 2001 and March 2003 were classified using the supervised approach. Follow completion of building the training data, a maximum likelihood (MLC) and a parallelepiped classifier were used to assign each pixel to one of the information classes.

MLC is a statistical decision rule that examines the probability function of a pixel for each of the classes, and assigns that pixel to the class with the highest probability based on Bayes' Rule. This classification procedure calculates for each pixel p (with feature vector X_p) the a posteriori probability $P(C_i|X_p)$ for each class C_i. If $P(C_i|X_p)$ is known for every class, then class X can be determined (Stein *et al.*, 1999). MLC has a high computational requirement, due to the large number of calculations needed to classify each pixel, but also usually provides the highest classification accuracies.



4.2- Location of training areas

Table 4.3 - Salt-affected soil classification base on chemical characteristics. Sample IDs 1-27 were obtained from SAED whereas sample IDs 28-35 are from field data collection in support of this research effort.

ID	Sample Name	Longitude	Latitude	CE (µS/m)	Na+ (meq/100g soil)	CEC (meq/100g soil)	ESP(%)	Soil Class
1	S1	369977	1803395	9500	2.54	12.5	20.3	Saline-sodic
2	S2	370034	1803608	1500	2.27	11.75	19.3	Sodic
3	S3	3700348	1804084	1410	2.19	11.01	19.9	Sodic
4	S4	369871	1804385	2900	2.24	11.45	19.6	Sodic
5	S5	369766	1804714	3700	2.33	12.5	18.6	Sodic
6	S6	369671	1804995	5700	2.56	13.25	19.3	Saline-sodic
7	S7	369515	1805423	5200	2.48	12.3	20.2	Saline-sodic
8	S8	369190	1805268	550	2.71	13.15	20.6	Sodic
9	S9	368745	1805271	2500	2.12	9.75	21.7	Sodic
10	S10	368786	1805949	7900	2.69	15.5	17.4	Saline-sodic
11	S11	369019	1806352	5500	2.44	13.42	18.2	Saline-sodic
12	S12	369252	1806595	5800	2.56	14.25	18.0	Saline-sodic
13	S13	369564	1806935	820	2.01	8.7	23.1	Sodic
14	S14	369798	1807334	180	1.99	8.4	23.7	Sodic
15	S15	369318	1807298	2920	2.33	9.1	25.6	Sodic
16	S16	368921	1806945	115	1.89	8.5	22.2	Sodic
17	S17	368604	1806852	1500	2.14	11.2	19.1	Sodic
18	S18	368306	1806652	5590	2.71	16.3	16.6	Saline-sodic
19	S19	368096	1806307	5400	2.58	15.75	16.4	Saline-sodic
20	S20	367790	1805811	4400	2.36	15.1	15.6	Saline-sodic
21	S21	367823	1805554	3500	2.11	16.2	13.0	Normal
22	S22	367852	1805317	3600	2.31	15.89	14.5	Normal
23	S23	367870	1805157	6300	3.01	17.15	17.6	Saline-sodic
24	S24	367942	1804870	8300	2.54	15.45	16.4	Saline-sodic
25	S25	368102	1804718	3400	2.14	14.25	15.0	Normal
26	S26	369785	1803762	1300	1.86	11.1	16.8	Sodic
27	S27	369591	1804089	4500	2.39	13.2	18.1	Saline-sodic
28	Ndl1	378813	1793532	17300	4.3	8.8	49	Saline-sodic
29	RT3	417729	1820382	445000	4.9	5.7	86.1	Saline-sodic
30	ND1	388053	1805054	76000	6.7	5.3	126.1	Saline-sodic
31	DJ2	365602	1806637	37200	4.9	13.1	37.2	Saline-sodic
32	RN2	371421	1796901	65000	5.8	15.9	36.2	Saline-sodic
33	RT1	415663	1820708	137500	5.2	2.1	244.1	Saline-sodic
34	DJ3	363601	1808719	464000	5	7.9	63.3	Saline-sodic
35	RT6	390335	1806685	17930	7.4	10.1	73.4	Saline-sodic
36	DJ1	365772	1806502	447000	4.9	7.4	66.8	Saline-sodic
37	RT4	417729	1820708	302000	5	5.3	92.9	Saline-sodic
38	Del3	379247	1821469	50000	7.1	12.5	56.6	Saline-sodic
39	Ndl2	379247	1792662	11510	4.9	3.6	137.7	Saline-sodic
40	RT2	415663	1819947	129700	7.1	7.3	96.6	Saline-sodic
41	RT5	410228	1816794	59400	4.9	7.6	64.4	Saline-sodic
42	RN1	371421	1796901	417000	5.5	8.2	66.9	Saline-sodic

c) Accuracy Assessment

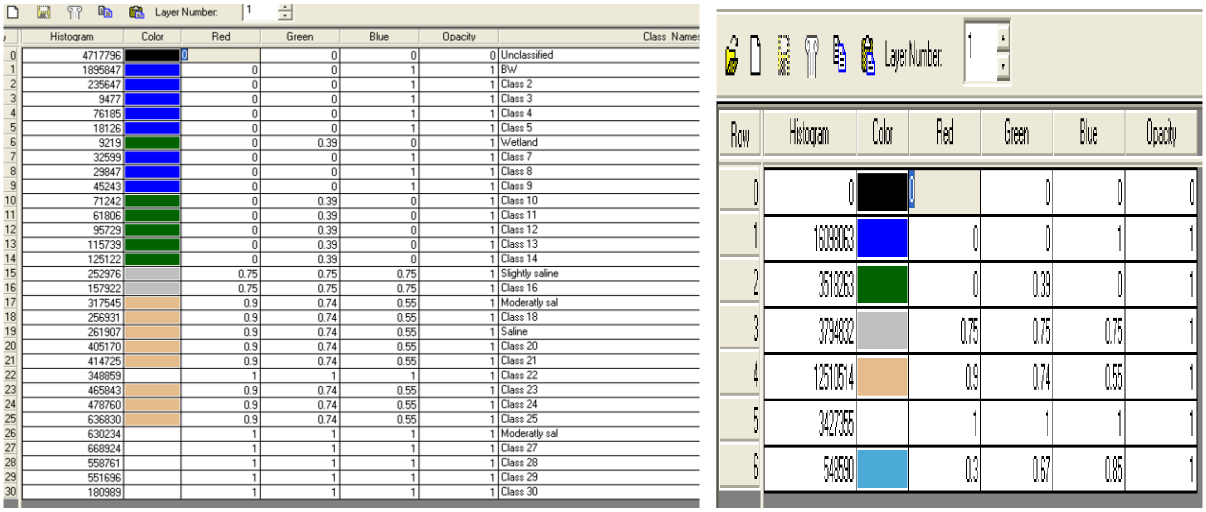
Assessment of classification accuracy is done to determine the agreement between selected reference materials and the classified data. Various types of errors can diminish the accuracy of feature identification. Three error types are possible: data acquisition errors; data processing errors; and scene-dependent errors. An error matrix can be created to highlight two categories of accuracy: 1) user's accuracy, which is concerned with the percent of each image class that has been correctly classified, and 2) producer's accuracy, which identifies how well the reference samples are classified.

A Kappa statistic can be calculated; this statistic expresses the proportionate reduction in error generated by the classification process compared with the error of a completely random classification. A Kappa statistic with a value of 0.90 implies that the classification process is avoiding 90% of the errors.

4-2-2-2.Unsupervised classification

Unsupervised classification is also called statistical clustering. This classification procedure doesn't need the analyst to define training areas/data sets. The computer algorithm finds classes by selecting and organizing data into groupings of similar pixels based on their statistical/spectral properties. ISODATA (the Iterative Self-Organizing Data Analysis technique), is the most common unsupervised classification scheme. This classification approach has been developed with empirical knowledge gained through experimentation and requires relatively little in the way of initial human interaction. However, results from an unsupervised classification algorithm still requires user decision-making, because after the classification has been performed the analyst needs to assign information classes to the spectral classes the computer algorithm has created.

In performing an unsupervised classification for this study, thirty statistical classes were used to categorize land cover features. After the automated classification process, decisions were made to assign a land cover type to each statistical class. Scientific visualization of the pixels that were grouped in each class and knowledge of the area are used to make information category assignments for each class. Using the unsupervised approach, four to six land cover types, depending to the year being analyzed, were identified from the original 30 statistical categories (Fig. 4.3). The 30 spectral classes were manually recoded to a number that represents one of the information classes.



Layer Number: 1

Row	Histogram	Color	Red	Green	Blue	Opacity	Class Names
0	4717796		0	0	0	0	Unclassified
1	1895847		0	0	1	1	BW
2	235647		0	0	1	1	Class 2
3	9477		0	0	1	1	Class 3
4	76185		0	0	1	1	Class 4
5	18126		0	0	1	1	Class 5
6	9219		0	0.39	0	1	Wetland
7	32599		0	0	1	1	Class 7
8	29847		0	0	1	1	Class 8
9	45243		0	0	1	1	Class 9
10	71242		0	0.39	0	1	Class 10
11	61806		0	0.39	0	1	Class 11
12	95729		0	0.39	0	1	Class 12
13	115739		0	0.39	0	1	Class 13
14	125122		0	0.39	0	1	Class 14
15	252976		0.75	0.75	0.75	1	Slightly saline
16	157922		0.75	0.75	0.75	1	Class 16
17	317545		0.9	0.74	0.55	1	Moderatly sal
18	256931		0.9	0.74	0.55	1	Class 18
19	261907		0.9	0.74	0.55	1	Saline
20	405170		0.9	0.74	0.55	1	Class 20
21	414725		0.9	0.74	0.55	1	Class 21
22	348859		1	1	1	1	Class 22
23	465843		0.9	0.74	0.55	1	Class 23
24	478760		0.9	0.74	0.55	1	Class 24
25	636830		0.9	0.74	0.55	1	Class 25
26	630234		1	1	1	1	Moderatly sal
27	668924		1	1	1	1	Class 27
28	558761		1	1	1	1	Class 28
29	551696		1	1	1	1	Class 29
30	180989		1	1	1	1	Class 30

Layer Number: 1

Row	Histogram	Color	Red	Green	Blue	Opacity
0	0		0	0	0	0
1	16098063		0	0	1	1
2	3518263		0	0.39	0	1
3	3794832		0.75	0.75	0.75	1
4	12510514		0.9	0.74	0.55	1
5	3427355		1	1	1	1
6	548590		0.3	0.67	0.85	1

Figure 4.3- Land cover categories after unsupervised classification and recoding.

4-2-2-3. Change detection analysis

Image differencing, principal components analysis and post-classification comparison are the most common methods used for change detection. Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Lu *et al.*, 2004). Different image analysis operations allow the software user to detect relevant patterns in Earth surface spectral response and with multiple dates, assess change in surface reflectance. In this study, the post-classification method of change detection was used. Some consider this to be the most simple of change detection analysis techniques. Each image in the time series is classified separately and then the areas of each class are compared to determine land cover change.

Supervised classification was used for the more recent images (2001 and 2003) and unsupervised classification was used for all images. A classification comparison method was used to assess changes among the classified images from 1973 to 2003. Results of the analysis provide a way to calculate the areal extent of change and to identify the locations of change. Trends in change over time can be obtained by comparison of change statistics from one time period to the next.

Image differencing, which gives change/no-change information, was performed for the following image pairs:

- April 1973 and February 2002 (to detect long term change over 30 years);
- April 1973 and November 1987 (to detect change before Diama Dam);
- November 1987 and February 2002 (to detect change after the dam was built);
- May 2001 to March 2003 (to detect change for the supervised classifications);

4-2-2-4. Zonal statistics

ArcGIS spatial analyst tools were used to process zonal statistics. Zonal Statistics tools can calculate a statistic for each class in a dataset. The algorithm takes a raster or gridded data layer of an independently obtained region as input. For example, this tool allowed quantification of the area of each remotely sensed land cover class that occurs in the irrigated rice crop zone managed by SAED. The SAED irrigated managed zone is used as feature data set and the input raster data set for this analysis is the supervised classification data layer (Fig. 4.4).

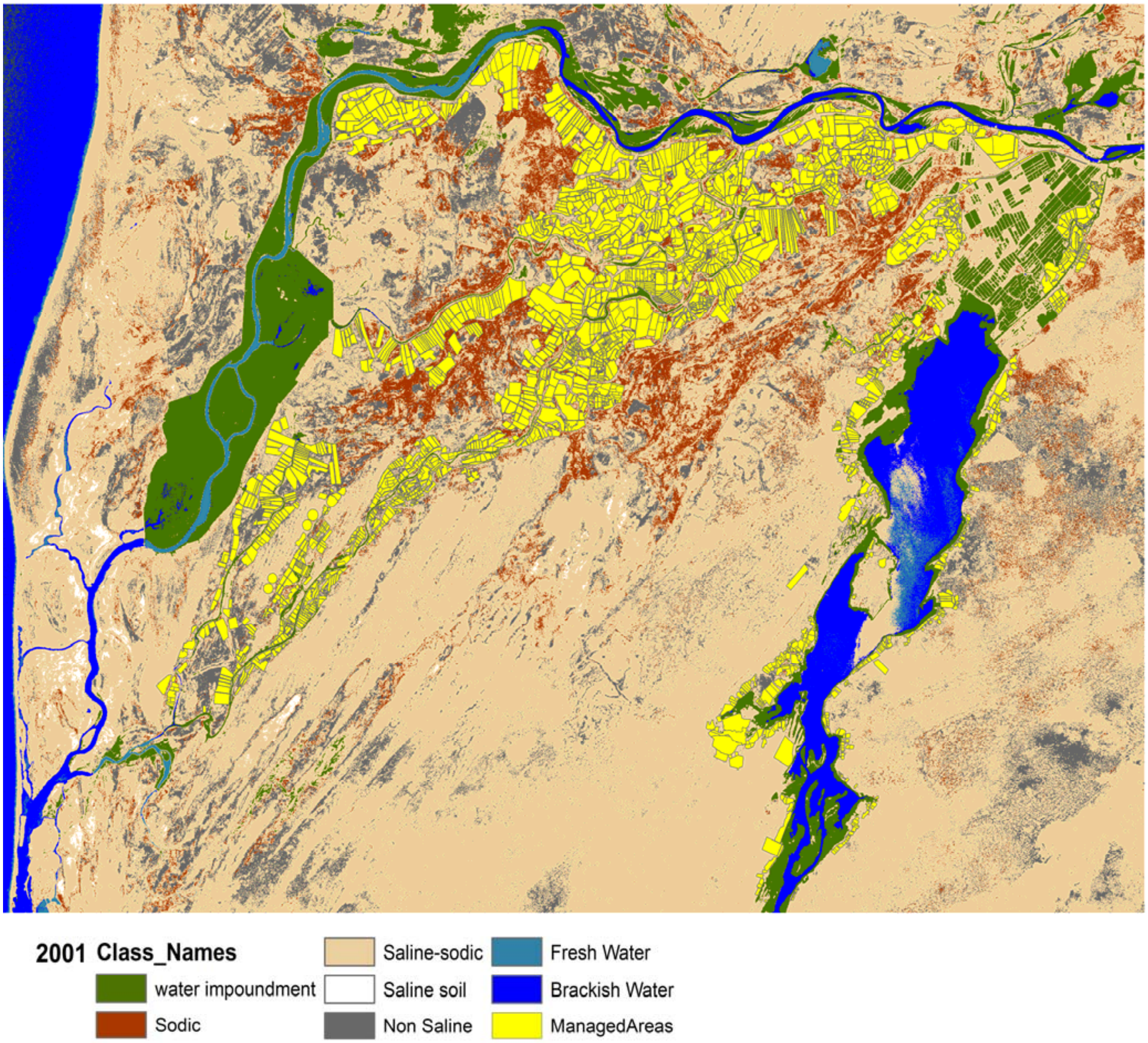


Figure 4.4- 2001 supervised classification with irrigated rice crop managed areas.

CHAPTER 5 - Results and discussion: Relationships between land use and land cover and salinity-sodicity extent in the Senegal River Valley

5.1- Spatio-temporal distribution of land cover classes

5.1.1-Results from digital classification

This analysis was designed to determine the spatio-temporal distribution of patterns and trends of land cover classes in the delta portion of the Senegal River valley with an emphasis in saline and sodic soils. Supervised and unsupervised classification and the post-classification change detection results have been mapped and analyzed.

5.1.1.1- Results from Supervised classification

This study assesses the utility of supervised classification for delineating land cover features and ArcGIS 9.1 has been used to map out classified images and performed zonal statistics on the managed areas. Pixel-based classification has been performed on Landsat ETM+ images acquired May 2001 and March 2003. Six land cover classes were identified to select training areas for the classification based on soil data collected from Krankai site in December 2008. For the March 2003 classification, seven classes were used based on data we collected in the field in January 2009, combined with the data collected from the Krankai site, and with areas corresponding to impounded water (generally occupied by invasive species) classified as wetland (Fig. 5.1). Accuracy assessment of classification results allowed selection of a best process that minimized classification error.

5.1.1.1.1- Accuracy of classification results

Classification accuracy was assessed for the 2001 data set based on the two different supervised classification training sets. The classification based solely on training from the Krankai area has an overall accuracy of 56 % with a Kappa statistic of 0.38 (Table 5.1), while the map classified by using more training areas has a higher overall accuracy (91 %) and a

Kappa statistic of 0.87 (Table 5.2). Only 38% of errors were avoided for the first classification process and 87% for the second. The quality of the classification is related to the amount of information gathered from the field and related evidence within the image data. There is a considerable decrease in area representing non saline soil, after areas corresponding to water impoundments have been classified as wetland. A Landsat TM image acquired in March 2003 has also been classified using the same training sites (Fig. 5.2). The overall classification accuracy is 73.2 % and the Kappa statistic is 0.63 (Table 5.3).

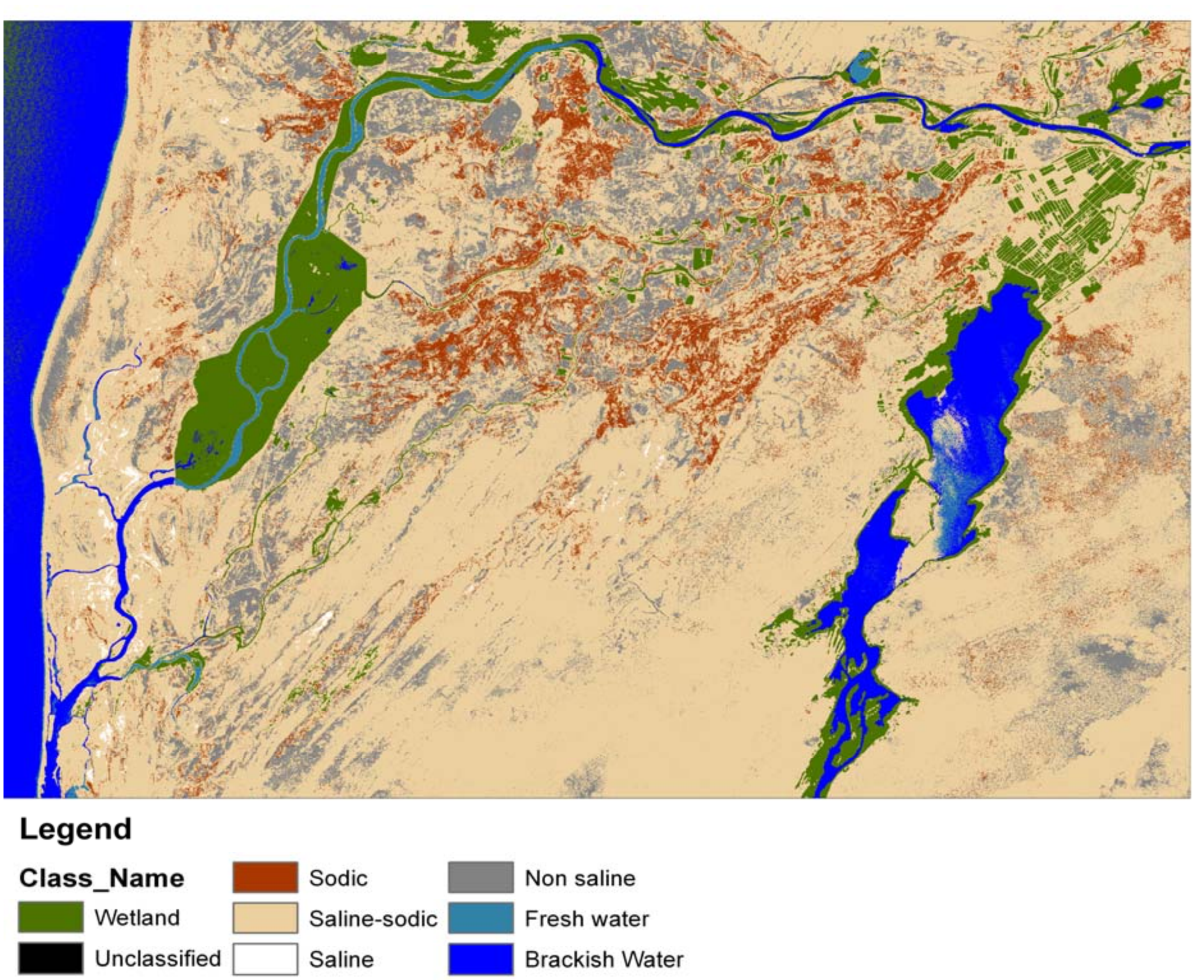


Figure 5.1- Supervised classification of the Landsat image acquired in May 2001.

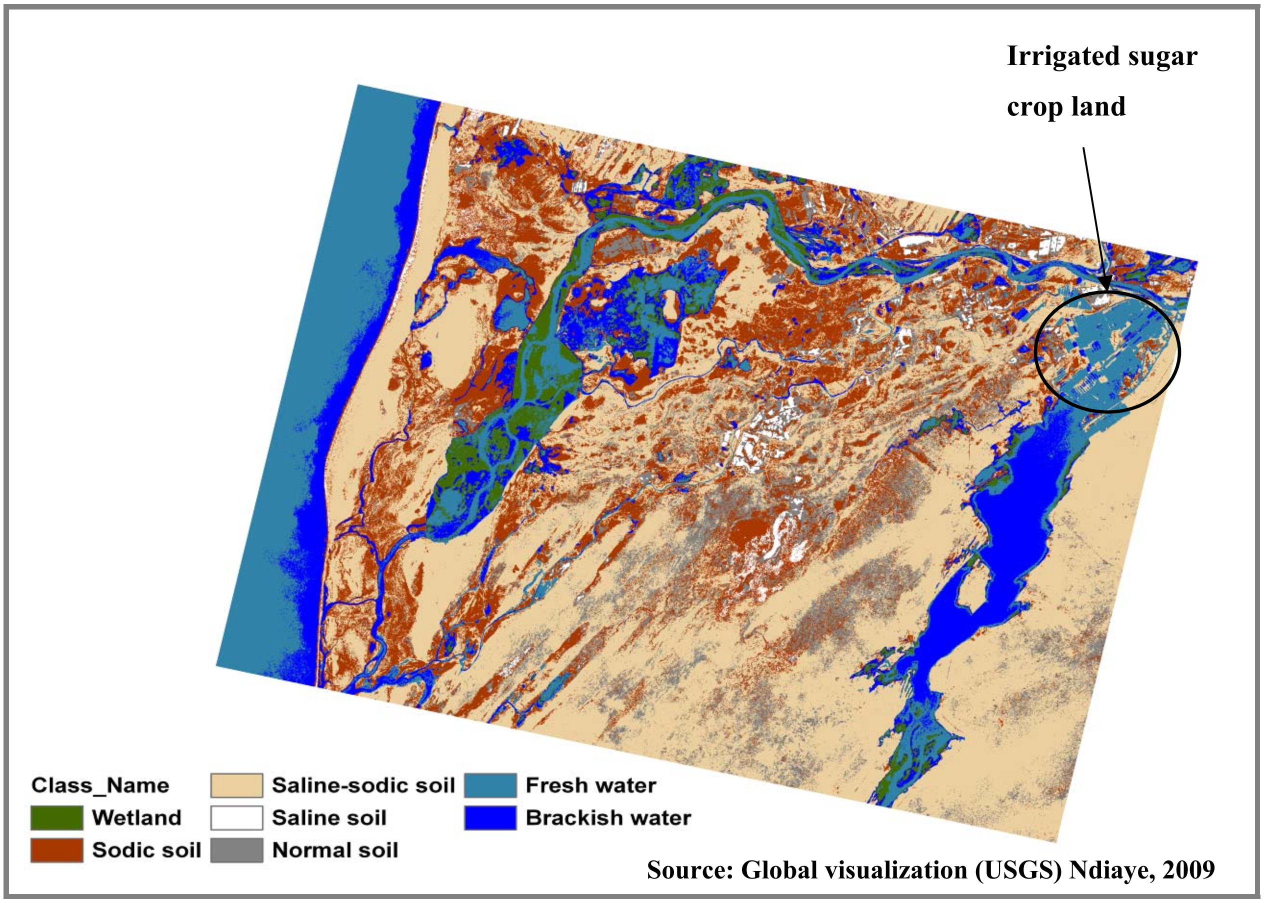


Figure 5.2- Supervised classification of the Landsat image acquired in March 2003

Table 5.1- Accuracy assessment of the supervised classification of the 2001 Landsat image (based only on ground truth data form Krankai site)

Class name	Reference total	Classified totals	Number correct	Producers accuracy	Users accuracy	Kappa statistics
Fresh water	1	1	1	100%	100%	1
Brackish water	1	1	1	100%	100%	1
Non-saline soil	3	6	2	66%	33.33%	0.26
Saline soil	1	1	1	100%	100%	1
Saline-sodic soil	12	8	5	41.67%	62.50%	0.38
Sodic soil	12	13	7	58.33%	53.85%	0.23

Overall Classification accuracy = 56.7%   Overall Kappa statistics = 0.38

Table 5.2- Accuracy assessment of the supervised classification of the 2001 Landsat image (based on more extensive training set data)

Class name	Reference total	Classified totals	Number correct	Producers accuracy	Users accuracy	Kappa statistics
Fresh water	3	3	3	100%	100%	1
Brackish water	3	3	3	100%	100%	1
Non-saline soil	3	4	2	66.67%	50%	0.47
Saline soil	3	1	1	100%	100%	1
Saline-sodic soil	22	20	19	86.36%	95%	0.92
Sodic soil	18	19	17	94.44%	89.47%	0.84
Wetland	4	4	4	100%	100%	1

Overall Classification accuracy = 91.1%   Overall Kappa statistics = 0.88

Table 5.3- Accuracy assessment of the supervised classification of the 2003 Landsat image

Class name	Reference total	Classified totals	Number correct	Producers accuracy	Users accuracy	Kappa statistics
Fresh water	3	3	3	100%	100%	1
Brackish water	3	2	2	66.67%	100%	1
Non-saline soil	3	7	2	66.67%	28.57%	0.25
Saline soil	4	1	1	25%	100%	1
Saline-sodic soil	27	22	19	70.37%	86.36%	0.74
Sodic soil	12	16	10	83.33%	62.50%	0.52
Wetland	4	4	4	100%	100%	1

Overall Classification accuracy = 73.2%   Overall Kappa Statistics = 0.63

Comparison of classification accuracy for the 2001 and 2003 images suggests that the 2001 image classification was better (91.1 % versus 73.2 %). Satellite images acquired for the same region, but at different times, exhibit different surface characteristics and these differences are reflected in the classification accuracy.

The land cover maps prepared from the 2003 and 2001 supervised classification images have seven land cover classes: saline-sodic; sodic; non-saline; saline; wetland; brackish water; and fresh water. The water, wetland, and saline soil class were established using arbitrarily selected training sites that were not related to any field measurement. However, these classes have the highest accuracy of 100%. Areas occupied by water and wetland can be relatively easily identified while observing the satellite image; but this is not the case for the different types of SAS. Issues encountered for the two images came from:

- the irrigated areas occupied by sugar cane crop in Richard Toll which have the same reflectance as wetland in the 2001 image but have a reflectance similar with the fresh water for the 2003 image;
- the ocean water, water situated downstream of the dam (enriched in salt) and some parts of water bodies situated upstream of the dam (enriched in sediment) have been classified as brackish water. It was not possible to distinguish the saline water and fresh water rich in sediment;
- for the 2003 image, part of the ocean has been classified as fresh water.

Generally, an incorrect land cover class might be assigned to a mixed pixel [an area with a mix of cover types]; mixed pixel classification is one of the great challenges associated with digital image processing of remotely sensing images. Each pixel must is classified into only one of many land cover types; but in some cases, ground data suggest that the pixel area is not homogenous.

5.1.1.1.2- Spatial distribution of land covers classes

Surface areas occupied by each class were calculating by using the number of pixels in a class multiplied by pixel area (Fig. 5.3). In 2001, most of the area is occupied by the saline-sodic soil class. These soils represent 63% of the area in 2001 and only 43% in 2003. The second largest area extent of a land cover class depends on the year; for 2001, it the non-saline soil (12%) and for 2003 it the sodic soil class (19%). Non saline soil class is mostly observed, for the 2001 image, in the area occupied by irrigation activity, around water impoundments and in a few patches in wetland areas. In 2003, non saline soils form longitudinal band with a north-east to southwest orientation, parallel to the Lac de Guiers, in the mid-south and southeastern areas of the delta. Land cover types and their extent during the year 2001 show allocation of the sodic soil to areas around the irrigated rice crop zone that is managed by SAED. For the 2003, the pattern of the sodic soil class is different; the spatial extent is both inside the rice crop area and it also occurs in other areas throughout the delta region. Water and wetland class areas also show differences between the two years that were assessed.

The saline land cover class takes up the smallest percentage area for both the 2001 and 2003 images. However, in 2001 the saline class is more concentrated downstream of the dam in the coastal zone where small patches can be observed; this class is insignificant in percentage but has an area extent of 1825.5 hectares. In 2003, the saline class occurs inland far away from the coast in the east and northeast parts of the delta.

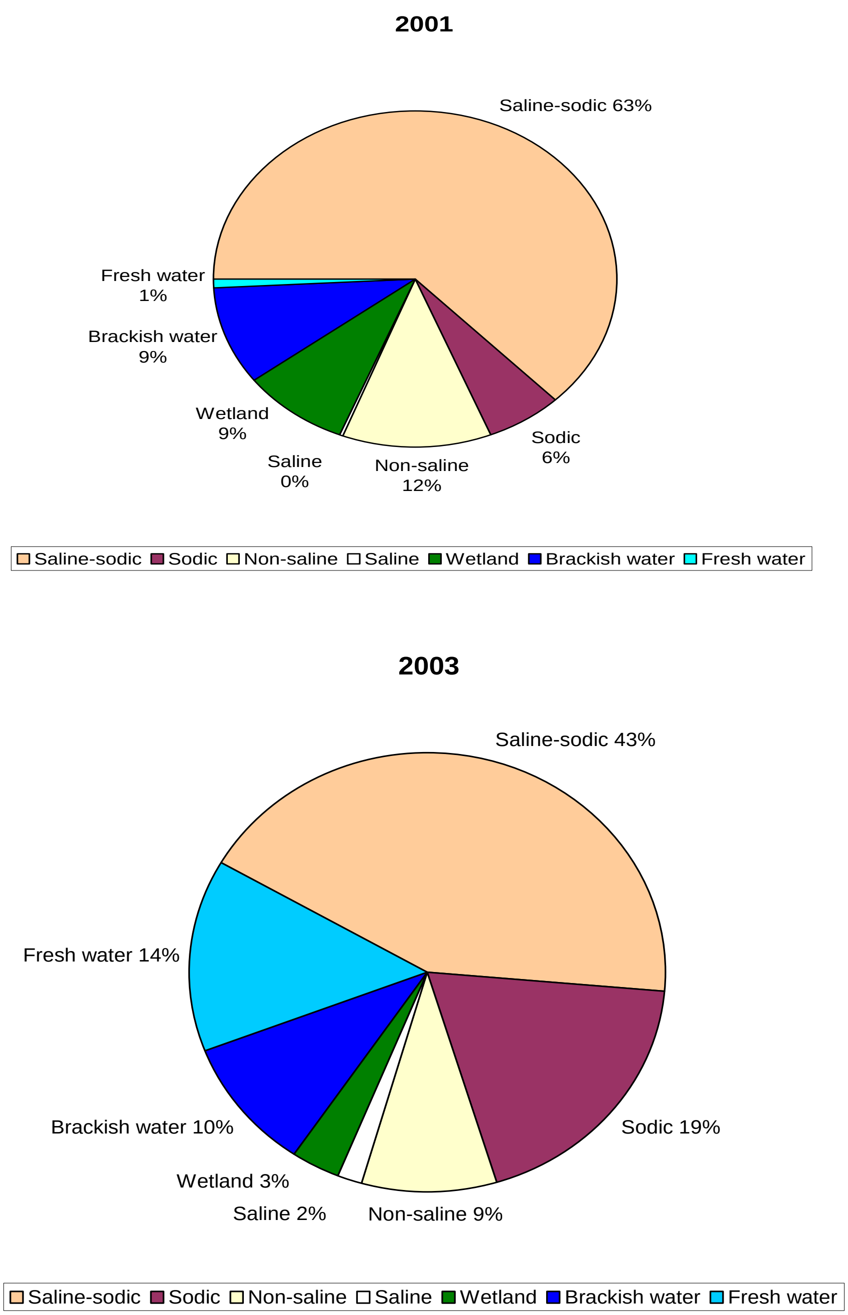


Figure 5.3- Area percentages of cover classes for supervised classification (2001 and 2003)

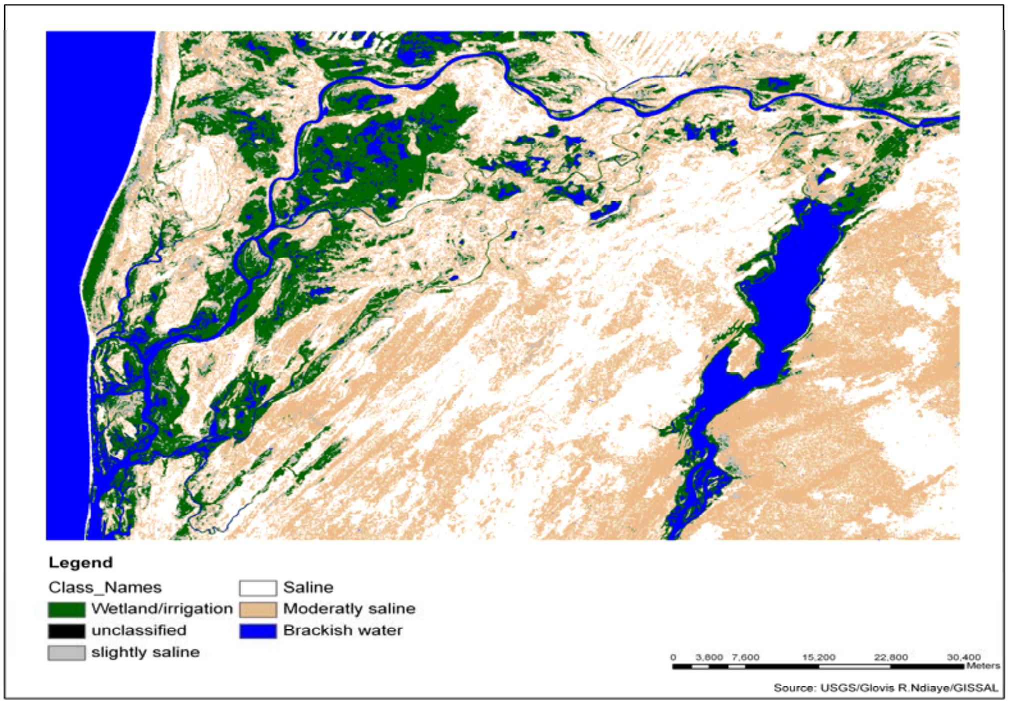
5.1.1.2- Results from Unsupervised classification

Unsupervised classification has been performed on all the images that were selected for this study. Results show that the number of land cover classes identified varies according to the image date.

5.1.1.2.1-Spatial distribution of land covers classes

a)- June 1973 image

The 1973 Landsat MSS image was differentiated into five land cover classes: Brackish water; Wetland and irrigated area; Saline, Slightly saline; and Moderately saline soil (Fig. 5.4). The class represented by brackish water occurs in low elevation areas all around the delta, throughout the entire river, and the waters of Lac de Guiers also were placed into this class. The Saline soil class has the greatest extent with 604,813 ha. Saline soil areas tend to be concentrated toward the east of the delta region with some spots noticed along the north coast. Wetland and irrigated areas are localized around the river, the lake, and flooded areas.



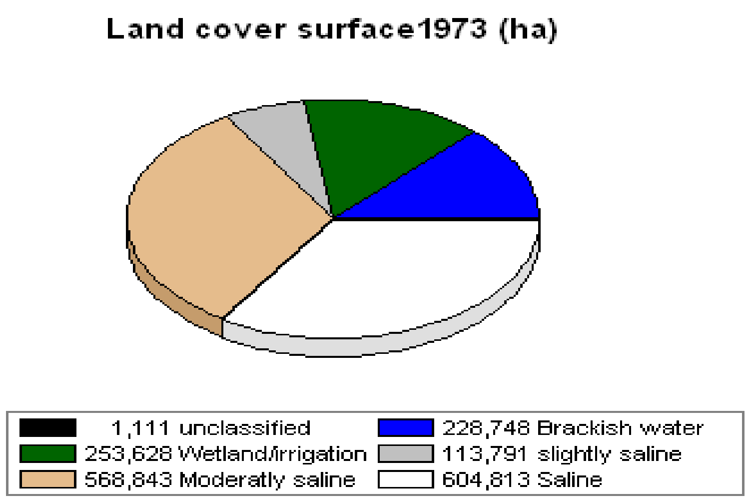


Figure 5.4- Unsupervised classification of 1973 image

b)- September 1979 image

Six land cover classes were identified for the 1979 image: Wetland and irrigation, Brackish water, Fresh water, Slightly saline, Moderately saline, and saline soil (Fig. 5.5). The Wetland and irrigated class has an areal extent with 560,105 ha and all water bodies are classified as Fresh water. Salt-affected soils are classified into the Moderately saline soil class (with an areal extent of 809,538 ha), the Saline soil class (which is present both inland and along the coast, but with greater areal coverage inland), and the Slightly saline land cover class (which is located around Lac de Guiers, in the Richard Toll area, and in southern parts of the delta).

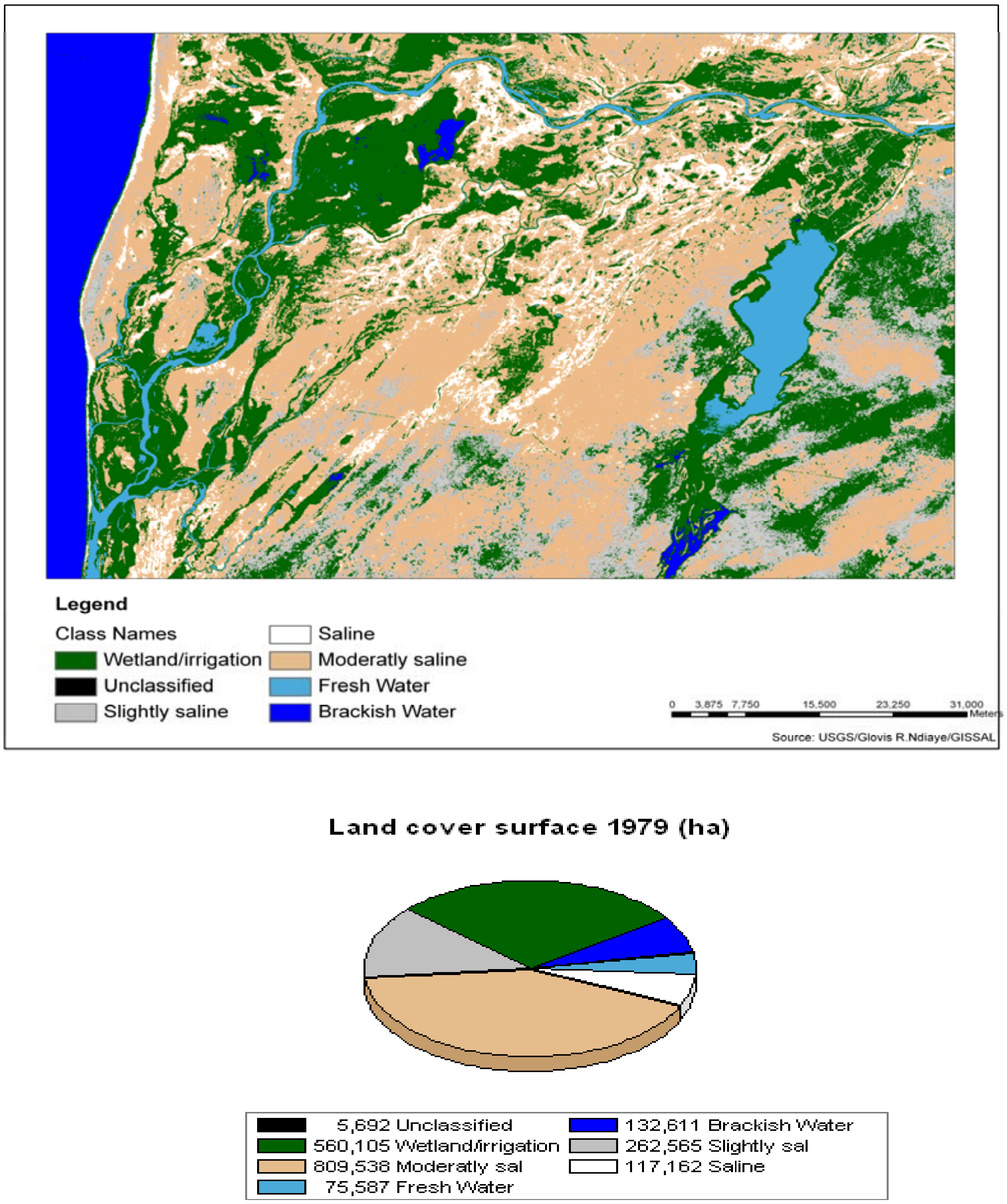


Figure 5.5- Unsupervised classification of the 1979 image

c)- November 1987 image

The 1987 image (Fig. 5.6) corresponds to the time of construction of Diama Dam which has had the effect of blocking the upstream movement of saline sea water. At the time of the November 1987 image, all inland water bodies were occupied by fresh water with an areal extent of 1,489,246 ha. Image interpretation suggests that even the river areas situated downstream from the dam were fresh water. Salty or brackish water is present in the Atlantic Ocean and a few small locations inland. The Saline soil class is observed in the area between the river and the Lac de Guiers. The Moderately saline class occupies most of the area with 2,798,106 ha. The Saline class soil is mostly present in coastal and farmland areas. The Wetland and irrigation class is also well delineated with an areal extent of 1,497,995 ha.

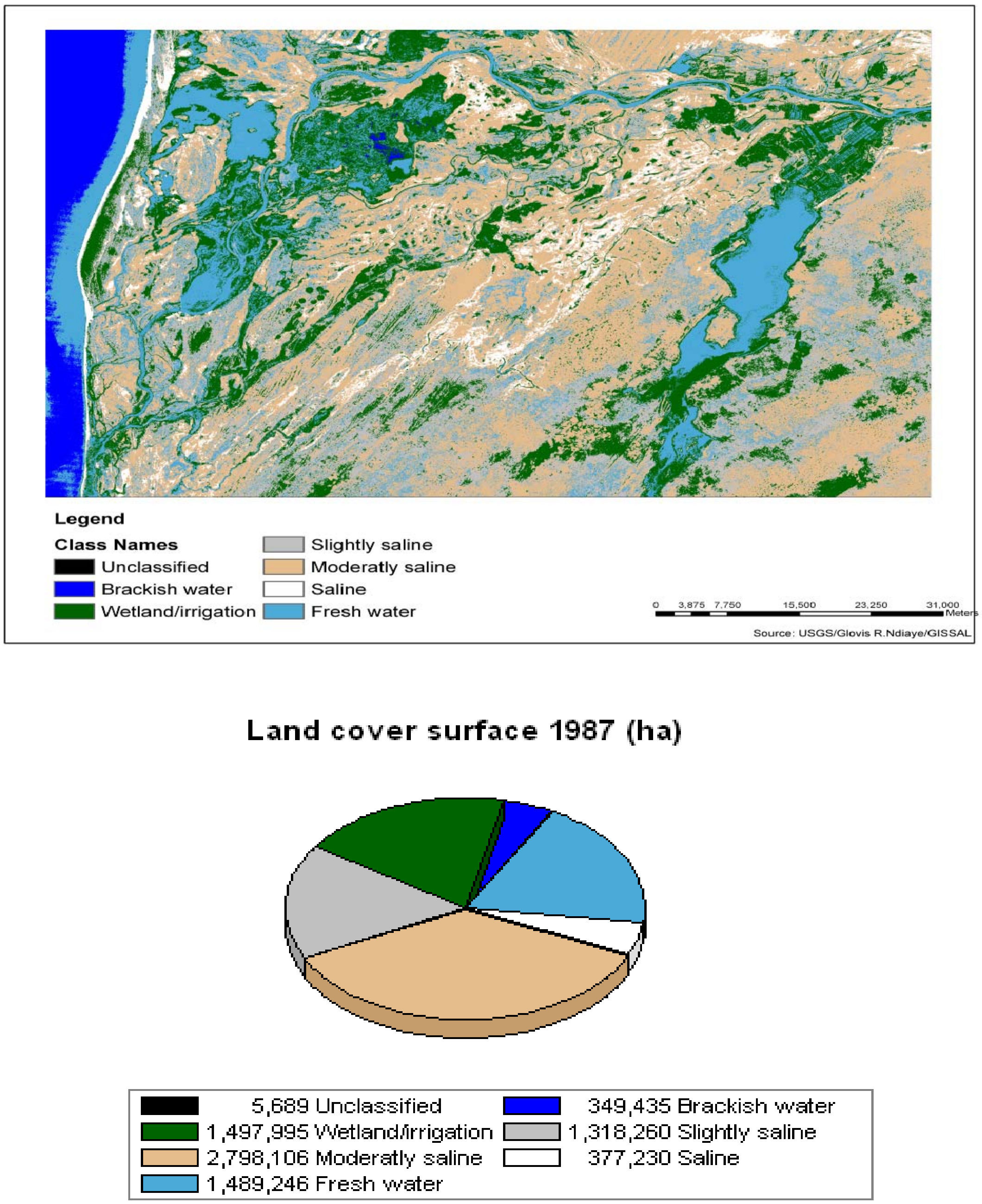


Figure 5.6- Unsupervised classification of the 1987 image

d)- March 1988 image

Classification of the 1988 image data provided a marked differentiation of water bodies into fresh and brackish water categories upstream and downstream from the dam (Fig. 5.7). The Brackish water class is also evident in the southern part of Lac de Guiers with some small patches within the wetland area. The Saline soil class is clearly evident in the area between Lac de Guiers and the river.

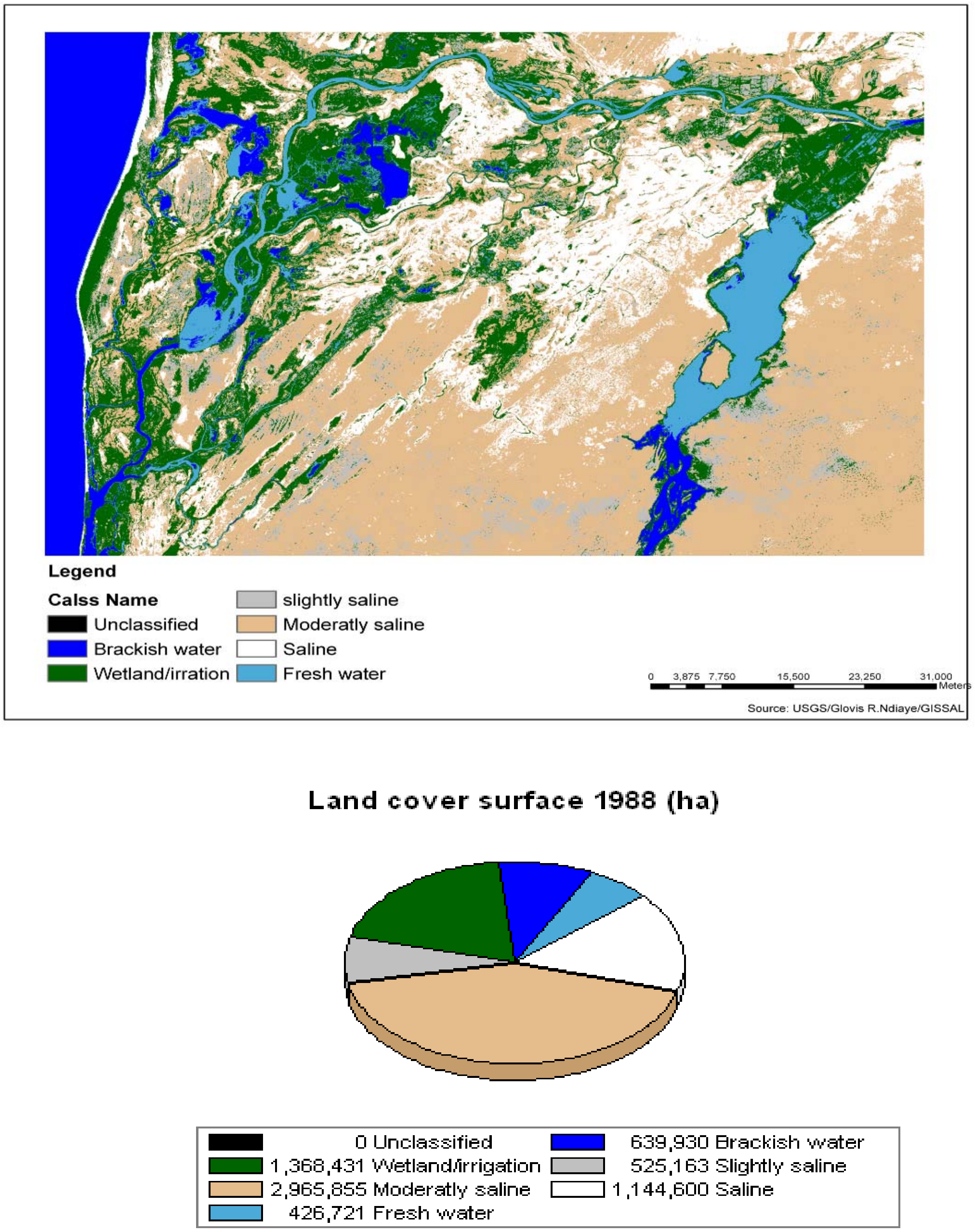
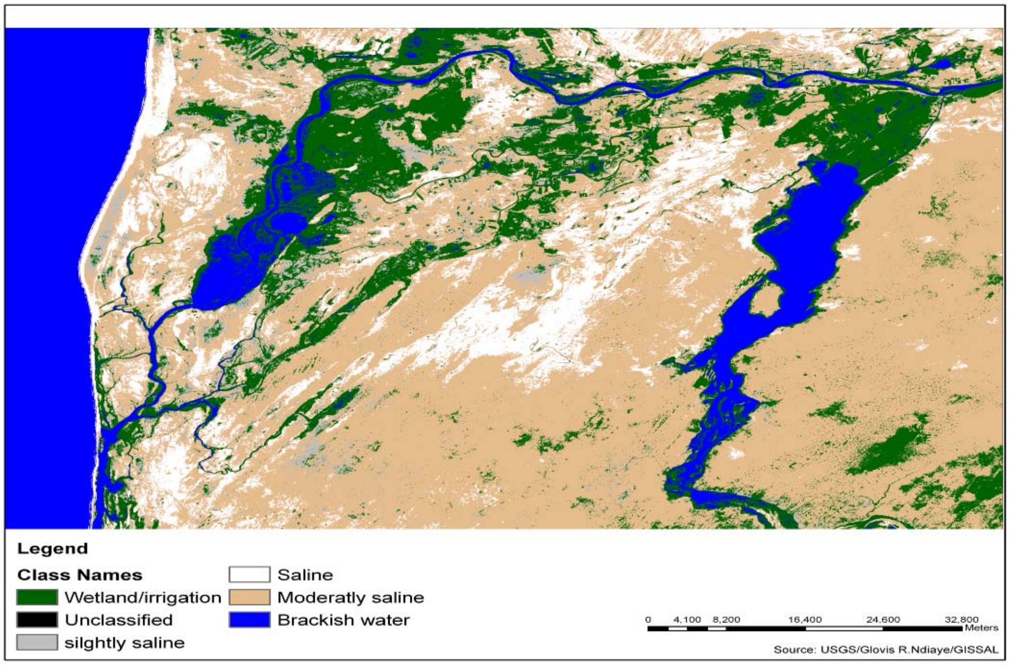


Figure 5.7- Unsupervised classification of the 1988 image

e)- April 1994 image

Classification of the April 1994 resulted in differentiation into five land cover classes (Fig. 5-8). As was the case in the classifications from other years, the Moderately saline soil class had the largest areal extent with 4,020,031 ha. All the water bodies were classified as brackish water; yhis might be related to a high concentration of sediment in some areas instead of saline water or a classification process that was not able to differentiate multiple water classes. The Saline soil was recognized in coastal areas, around the wetlands, and near farmlands.



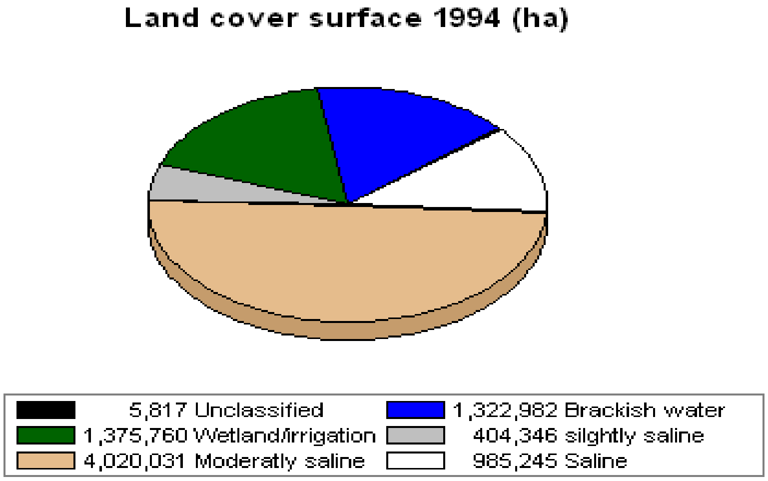
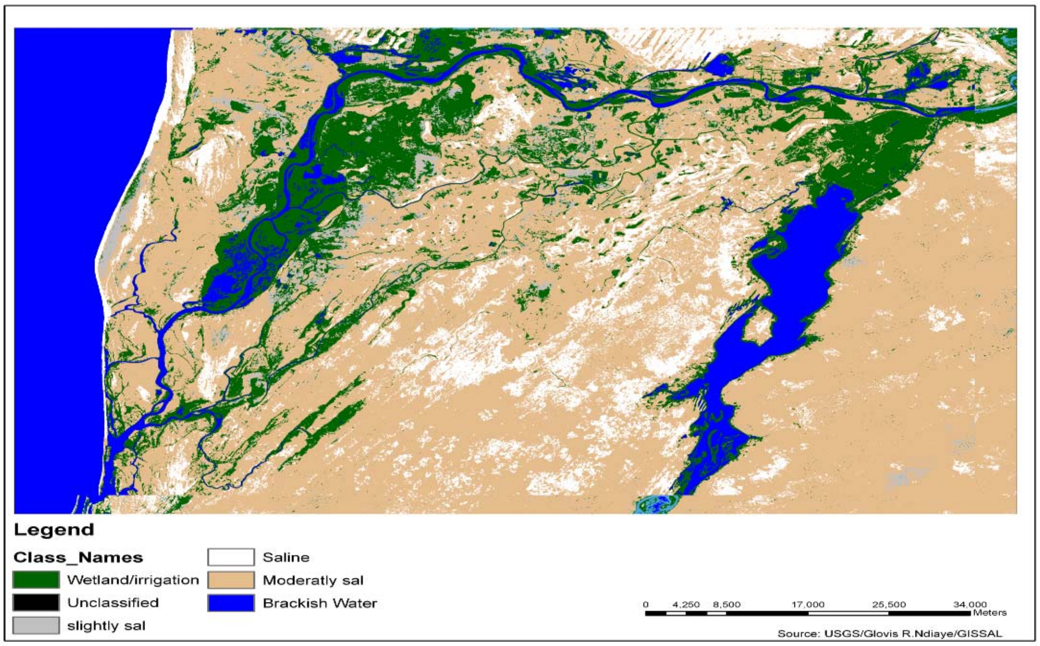


Figure 5.8- Unsupervised classification of the 1994 image

f)- May 2001 image

Unsupervised classification of the May 2001 image produced six land cover classes. The inland water bodies were classified into the Brackish water class. The Wetland and irrigation class was well differentiated and had an areal extent of 1,197,327 ha. The Moderately saline class occupied over 50% of the areal extent with 3,914,915 ha and the Saline class was present in small patches along the coastal zone, in farm areas, and to the southwest of Lac de Guiers (Fig. 5.9).



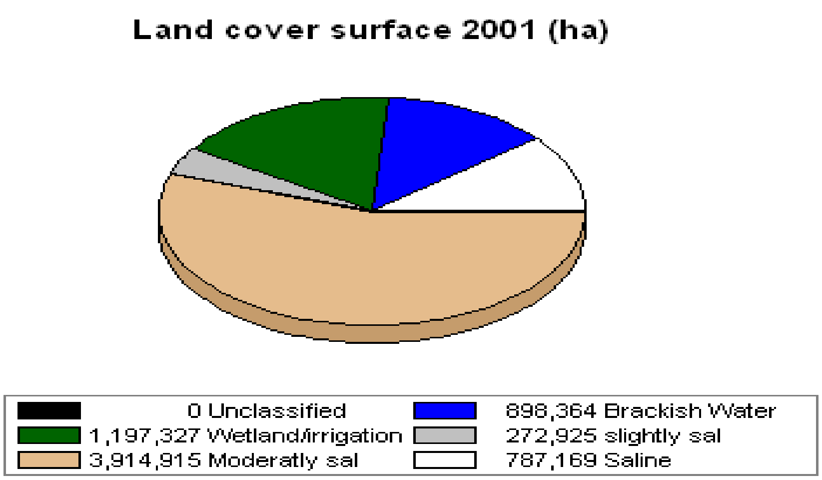


Figure 5.9- Unsupervised classification of the 2001 image

g)- March 2003 image

Unsupervised classification generated six classes for the March 2003 image data (Fig. 5-10). Fresh water is widespread all along the river upstream of the dam. The Brackish water class is found in the Atlantic Ocean, in Lac de Guiers, and some parts of the Senegal River particularly downstream of the dam. The Wetland and irrigation class is present along the river and it tributaries and in the Richard Toll area. The salt-affected soil classes are represented by the Slightly saline, Moderately saline, and Saline cover types. Moderately saline has the greatestest extent with 3,495,487 ha.

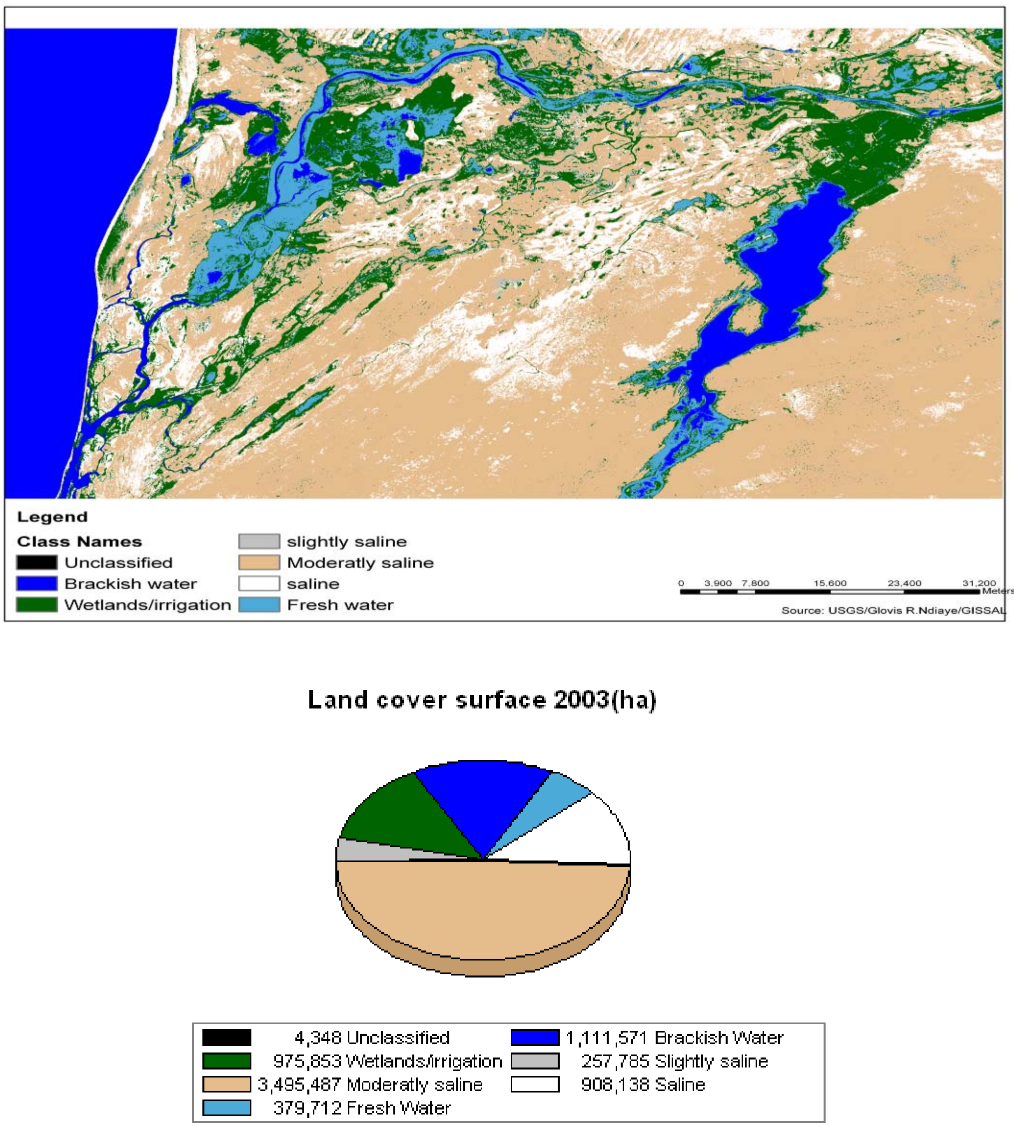


Figure 5.10- Unsupervised classification of the 2003 image

5.1.2- Assessment of the visual analysis

Following visual analysis of the unsupervised classification images, a summary of the changes observed includes considerable differences from before and after construction of Diama Dam. Areas occupied by rice crop irrigation before 1987 were identified in the Saline soil class and after that date these areas were more commonly in the Moderately saline soil or Wetland and irrigation class. An exception is in 1988 when the Saline soil class is widespread in that area. However, the supervised classification process suggests that in 2001 this zone is occupied by Non saline soil, Saline-sodic soil, and surrounded by Sodic soil and in 2003 the area is occupied by Sodic, Saline-sodic and Non saline soil classes. Natural hydrologic processes of the Senegal River delta region helps in understanding the mechanisms associated with water movement in the area (Figure 5-11). Seasonal water level variation in the delta region is strongly related to the interplay of the river and ocean dynamics. The action of the sea is predominated during the dry season, but river discharge increases during the wet season corresponding to annual flood period; the stronger river discharge pushes the saline sea water back to near the mouth (Sall, 2006).

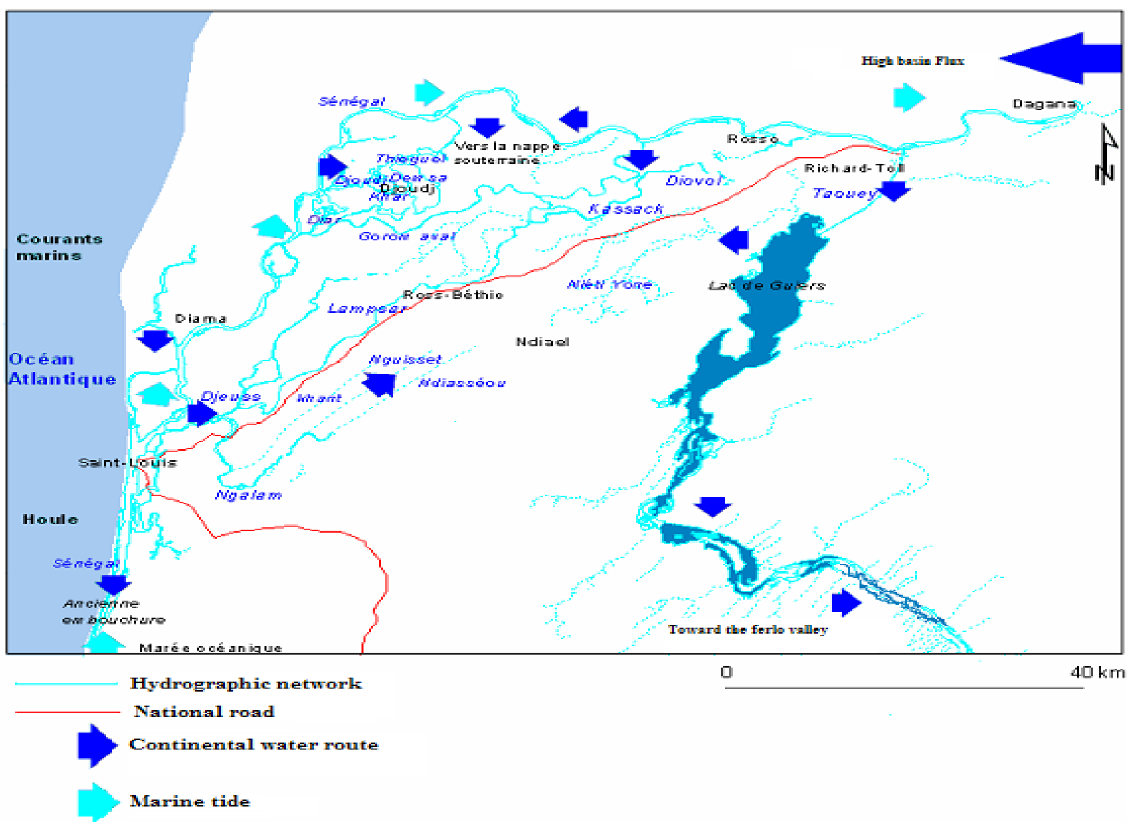


Figure 5.11- The natural hydrologic system of the Senegal River delta (Sall, 2006)

Before the construction of the Diama dam, when the Senegal River discharge was lower than 400 m^2 /s, marine tides propagated up the river a distance of over 400 km, causing a considerable intrusion of saline water into the region (Isupova and Mikhailov, 2006). River water discharge was low from December to July (Table 5-4).

Table 5.4- Annual distribution of Senegal River discharge (top number is m^3/s, bottom number is a %; the hydrological year: from May to April) In Isupova and Mikhailovitch (2001)

Gauge	Observation Period	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr Mar	Hydro-logical Year
Dagana	1903-1983		10 43	00 .21	100 4.3	000 6.1	200 8.7	200 5.6	55 .93	00 .61	00 .30	10 .30		640 — 100.0
Diama	1986-1994	0 .28	0 .56	50 .18	80 3.4	200 3.4	000 7.9	00 1.1	00 .57	00 .79	0 .84	0		300 — 100.0

Unsupervised classification did not perform well in differentiating water bodies contaminated by saline sea water and fresh water rich in suspended sediment. After construction of Diama dam in 1986, saline ocean waters do not intrude upstream of the dam (with the inland saline water progression blocked at a distance of 54 km from the mouth of the river). Therefore sea water delivered by tides predominates in the estuary and in the river only downstream of the dam. Additional studies are needed to see if the satellite image data can be analyzed to differentiate the categories of sediment laden, saline, and fresh water. It is clear from visual interpretation of the multiple image dates that an interesting interplay among these water types happens and was altered with the construction of Diama dam. In addition, the lower flows during the drought years of the 1970s and 1980s added an additional dynamic.

In the Richard Toll area, irrigation for intensive sugar cultivation started in the early 1980s by the Compagnie Sucrière du Senegal (CSS). Classification of the image data from after the completion of Diama dam indicates that this area is in the Wetland and irrigation class. In the supervised classification results this area is classified as Wetland and irrigation in 2001 and Fresh water in 2003. Presence of the fresh water class in 2003 might be a result of water being released by the irrigation system. Water is typically released on the fields each 12 to 14 days and remains on the fields for 1 to 2 days. There is also the possibility that an excess of water was applied (which persists longer) to leach out unwanted salts during an effort at reclamation of saline land (Sturrock *et al.*, 2001).

5.2- Change detection results

While landscapes tend to exhibit only small areas of change, an important aspect of image-based change detection is to determine which land cover classes are in flux. Post classification change detection is used in this analysis to investigate and understand the types of change in the Senegal River delta area from 1973 to 2003. In addition, other change detection analyses were done to assess changes that may have occurred in the time interval prior to dam building or in the time interval after the dam was completed. Finally, a separate change detection analysis was done for the two dates of supervised classification.

5.2.1- Comparison of land cover features and area extent

Quantification of the areal extent of land cover features gives us a general idea about the amount of surface area for each land cover classes and the changes from time to time. Charts and plots are very good for displaying one variable as a function of another. In our studies we use surface areas of land cover classes differentiated after classification, which we calculate by multiplying number of pixels by the spatial resolution of the image. This allowed us to do comparison between land feature extents, evaluate long term change and describe the trend. In this way it is possible to detect change and to understand the kinds of transition that have taken place.

5.2.1.1- Supervised classified images

Figure 5.12 presents a graphic representation of the differences between the 2001 and 2003 image classifications. Observed differences in the land cover between the two dates can be correlated with climate variation and human activities. Quantification of the land cover features suggests a decrease in Saline-sodic and Non saline soil and an increase in Sodic soil coverage. The area occupied by Wetland decreased between the two time periods whereas Brackish water decreased slightly while Fresh water surface area increased. Sodic soil area increased at the expense of Wetland and Saline-sodic soils. In addition, the areal extent of saline soil is much lower than the other salt-affected soil classes. As was discussed in Chapter 2, the geologichistory of the area has shown that the delta is already naturally affected by salinization. Sodic soils are a new type of salinity class, with secondary salinization taking place. A hybrid Saline-sodic class is progressively replacing the primary salinization which built up in the delta area since the early Quaternary. The saline-sodic transition is evident with a land cover class that has a much greater extent than the other land cover types.

Bui *et al.,* (1998) reported that among the environmental conditions that promote the genesis of sodic soils are the presences of shallow saline groundwater and the occurrence of perched water table within one meter of the surface. In the delta area, these conditions that favor the build up of sodic soil have already been observed. The salty ground water table has risen under irrigation management and this transition now facilitates the transportation of salt to the topsoil by capillarity rise. Irrigation without proper drainage can increase the sodium absorbed ratio (SAR) of the soil solution exacerbating Sodic soil class formation (Bui *et al.*, 1998).

The drainage system in the delta irrigated rice crop field is considered as poor, but SAED irrigated areas have several drainage canals surrounding their managed area (Photos 5-1). It was reported that lateral water movement can spread sodium (Na^+) from its original source to soils in a lower slope position where it can accumulate by evaporation. According to Mane (1998) there is a strong relationship between topography and salinity in the valley. Visual analysis suggests that Sodic soils occur around the managed areas and Non saline soils are mostly present in areas corresponding tofields of rice. However, after quantifying areal extent of each class within the managed area by using a GIS-based zonal statistic technique, Saline-sodic soil have the highest areal extent and that amount has increased considerably from May 2001 to March 2003 (Fig. 5.13). The Sodic soil extent also has increased during the same period inside the managed area, with a corresponding decrease in Non-saline soils.

An irrigation system based on leaching and drainage is probably the reason for the spatial changes in salinity. More fresh water in March 2003 is related to an increase in rainfall during the 2003 (Fig. 5-14). The total rainfall increased from 261.1 mm in 2001 to 351.4 mm in 2003 and this was accompanied by an increase in river discharge. During dry periods, most of wetland areas are affected by salinization (Photo 5.2).

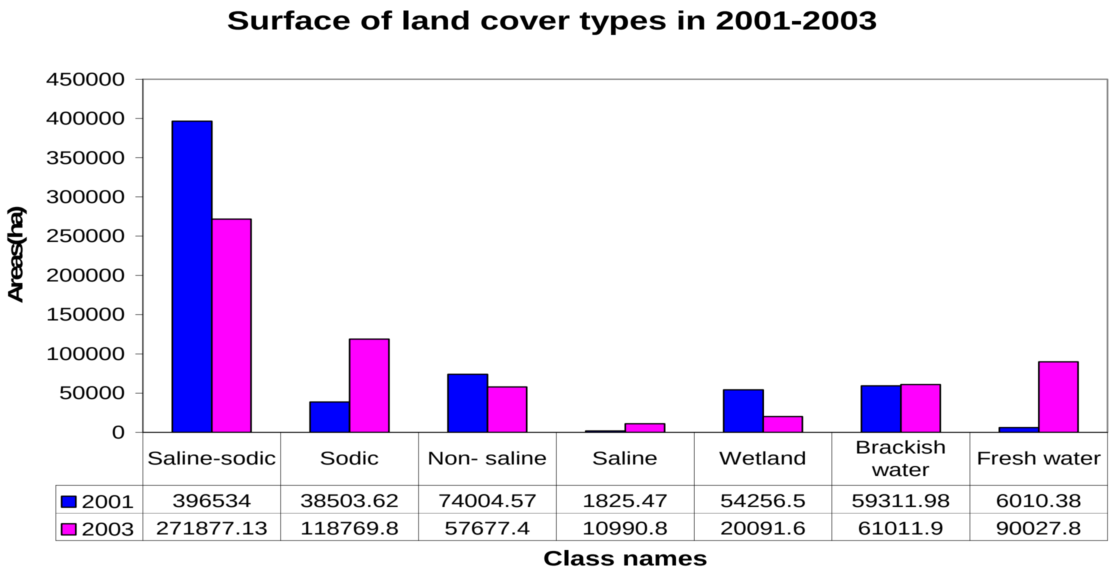


Figure 5.12- Land cover class areaa extent for 2001-2003

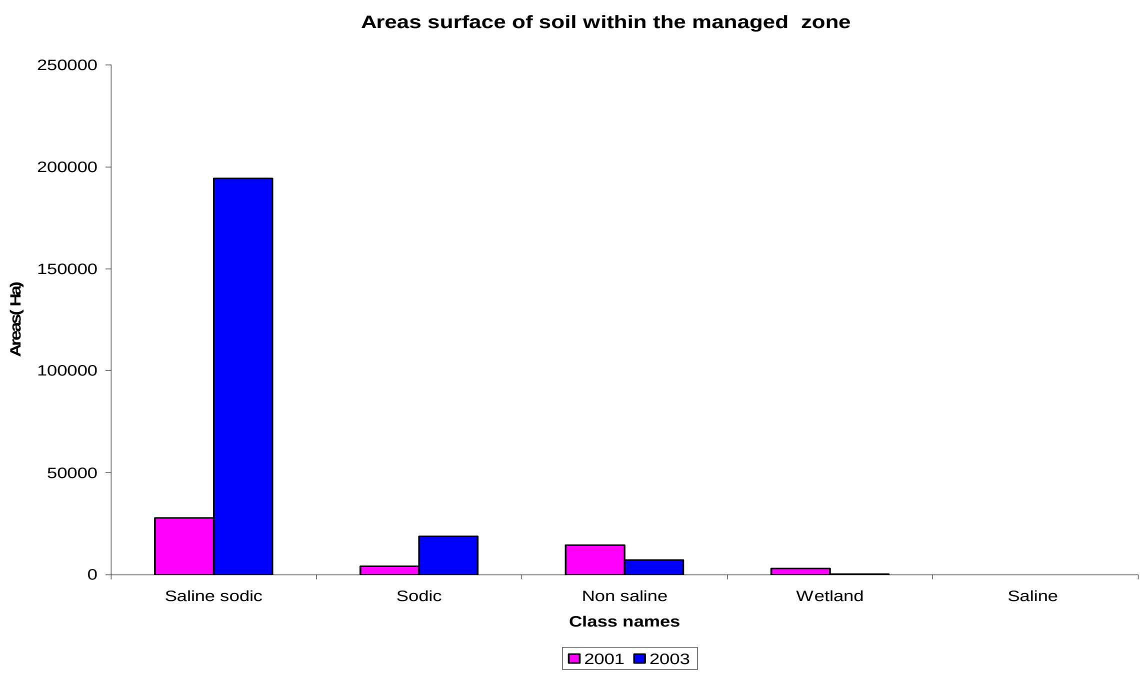


Figure 5.13- Area extent of land cover classes within SAED rice crop managed fields

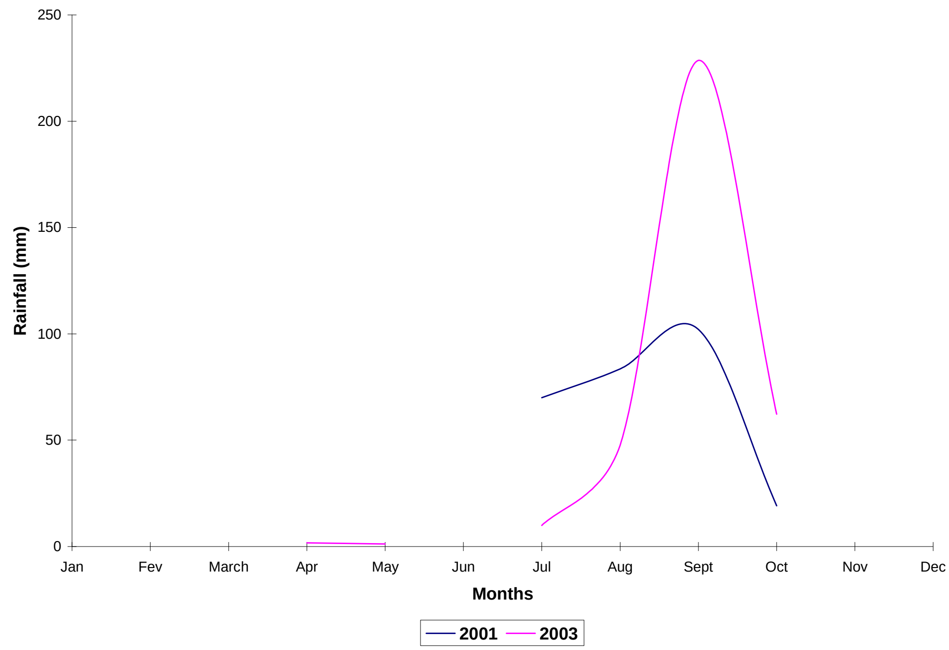


Figure 5.14- Summer rainfall variability in 2001 and 2003.

Photo 5.1- Drainage canal bordering a rice field in the delta (Ndiaye 2008)

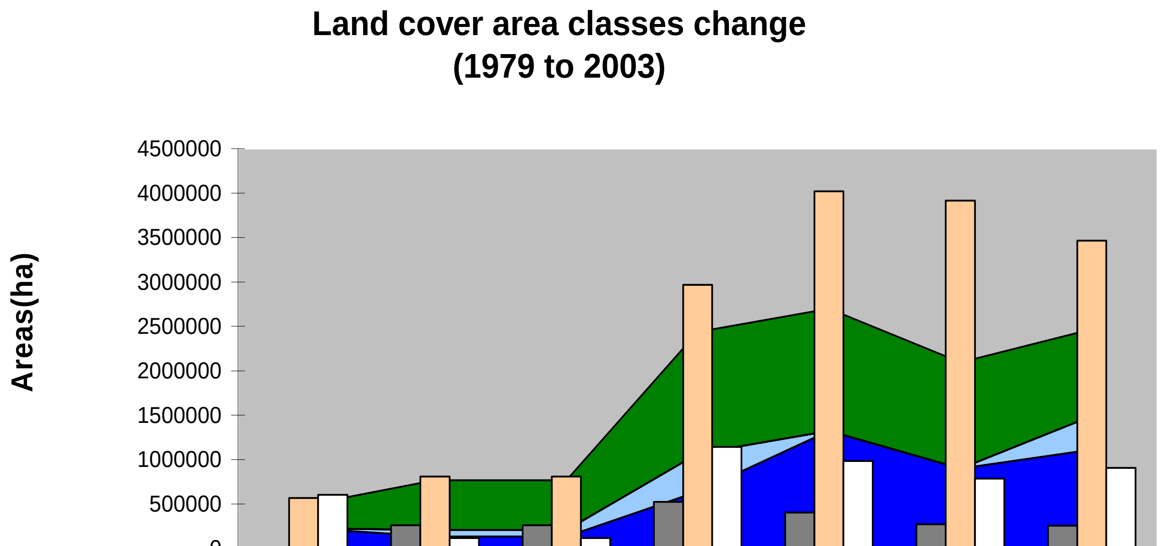
Photo 5.2- Salinity in the wetland (Djoudj Reserve) (Ndiaye 2009)

5.2.1.2- Unsupervised classification images

After performing unsupervised classification on all the images, land cover class extents for each year have been calculated and plotted to detect spatiotemporal variation (Fig. 5.15). The land cover types with obvious change are the Saline class, the Moderately saline class and Water. Image analysis suggests that management of river waters by the operation of Daima Dam is resulting in more water in the landscape. The combined total of the Fresh and Brackish water classes is more than double in the images from 1988 onward.

In addition, the Moderately saline soil class extent increased from June 1973 to March 2003 with a maximum in April 1994. Changes in SAS over time are illustrated in Figure 5-16; which shows the inverse relationship between Moderately saline soils compared with the other two land cover class from time to time. A close interaction between water and salinity variability is noticeable. Moderately saline soils are much more common in the area following the construction of the dam and the increase in water across the region. The wetland class areal extent has fluctuated over the years; decreasing from 1973 to 1987 and then increasing until

2003. Wetland extent has a similar trend with water in the area and is very likely affected by the presence of the dam.



	1973	1979	1987	1988	1994	2001	2003
Wetland/irrigation	253628	560105	560105	1368431	1375760	1197327	975853
Fresh Water	0	75587	75587	426721			379712
Brackish Water	228748	132611	132611	639930	1322982	898364	1111571
Saline	604813	117162	117162	1144600	985245	787169	908138
Moderatly saline	568843	809538	809538	2965855	4020031	3914915	3465487
Sligthly saline	0	262565	262565	525163	404346	272925	257785

Figure 5.15- Area statistics for land cover classes in the Senegal River delta from 1973 to 2003

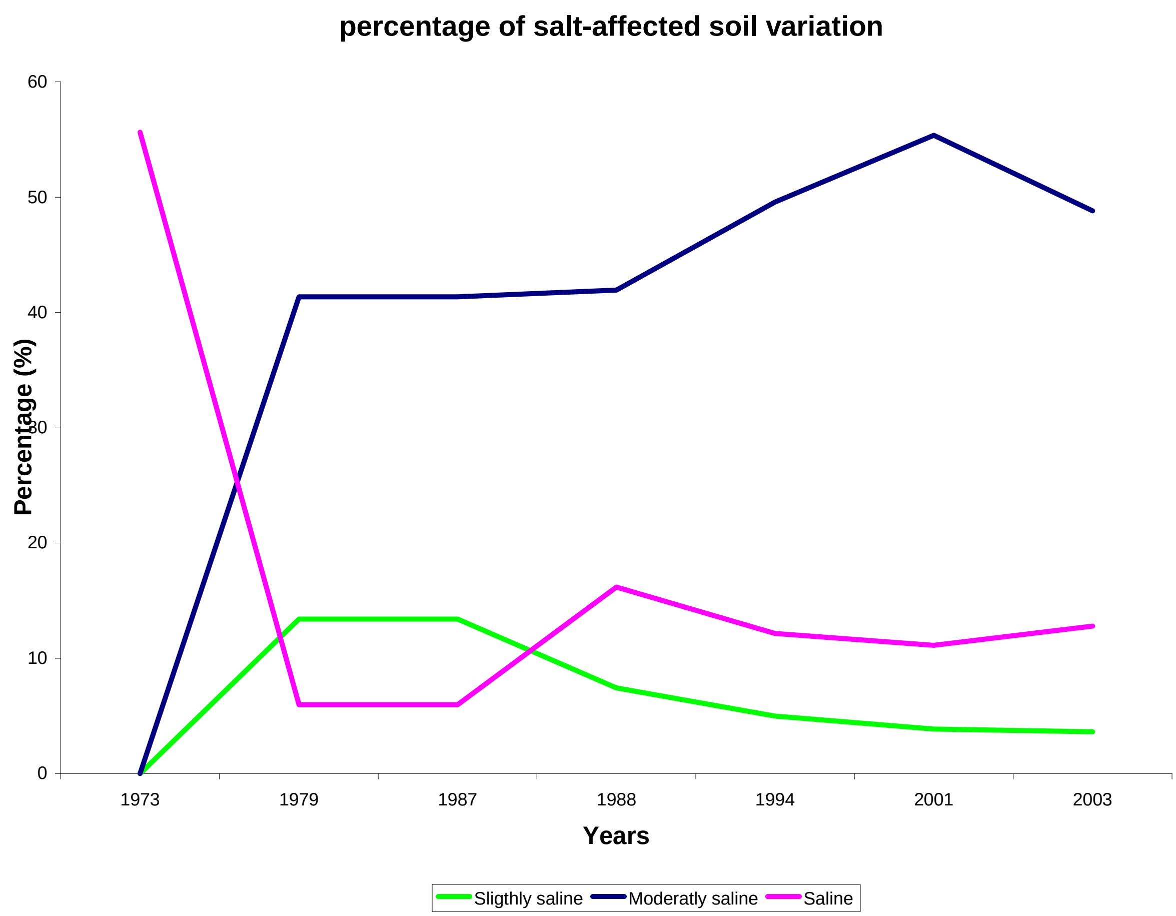


Figure 5.16- Temporal variation in salt affected soil classes

5-2-1-3- Conclusion

Important differences have been noticed between the results obtained from the supervised and unsupervised classification methods. One difference between these two methods is in the ability to diffenentiate SAS. With the supervised classification method, the procedures were able to differentiate land cover affected by sodicity based on ground truth data, which was analyzed in the laboratory to measure the ESP. Unfortunately, the unsupervised classification method could only separate salinity by degree classes and not the type of salinity.

However, these two techniques rely on interpretation of the same set of digital numbers and, as a result, have a number of similarities in the resultant land cover classifications. This similarity is illustrated by the line chart showing the variation in land cover class extent for both methods for May 2001 (Fig. 5.17). For this comparison, it was assumed that Saline-sodic class and the Moderately saline class can be correlated, because they seem to have the same spatial extent.

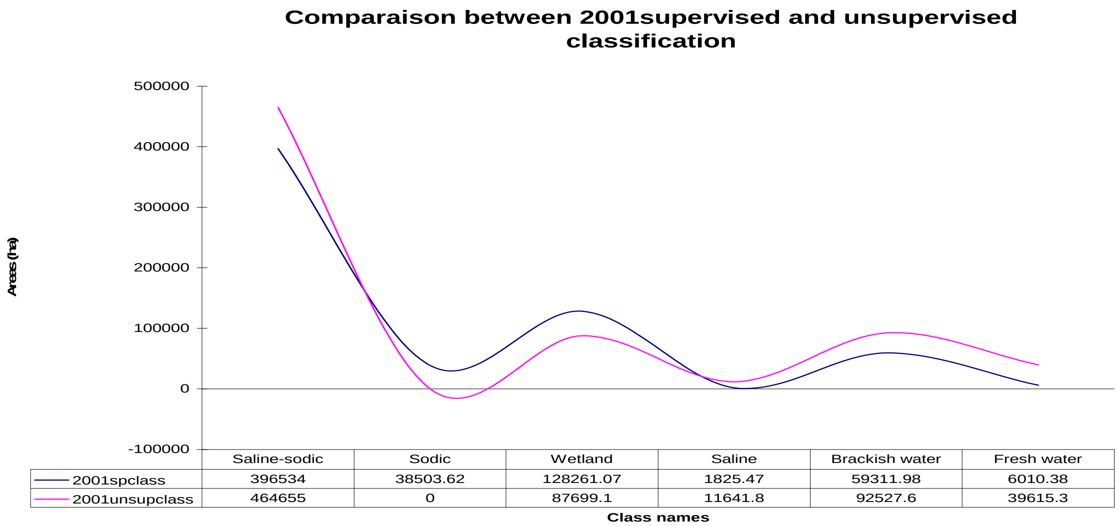


Figure 5.17- Comparison of supervised and unsupervised classifications for March 2001.

5.2.2- Image differencing results

Land cover types can be compared for two time periods to determine the magnitude of change by using the GIS Matrix tool. This analysis was performed for several pairs of images. Post-classification image differencing of the unsupervised classifications was done for June1973 and February 2002 (Fig. 5-18), June 1973 and November 1987 (Fig. 5.19), November 1987 and February 2002(Fig. 5.20).

In terms of the location of change, for the June1973 and February 2002 classification comparison, the emphasis is a salinity increase in areas occupied by rice cultivation and in the northern coastal area.

Comparatively, more of the area seems to have changed changed during the period, June 1973 and November 1987. The character of water in the river and in Lac de Guiers has changed from Brackish to Fresh water. Areas that have been shifted from the Moderately saline class to the Wetland class are located in sugar crop area near Richard Toll

For the November 1987 and February 2002 comparison, change has occurred only in the coastal area, in the rice crop irrigated area, and there is a shift from Moderately saline to Saline soils.

5.2.2.1-Conclusion

Spectral and spatial resolutions differences between the Landsat MSS image of 1973 and the 1987 TM image might affect the results obtained. However and according to Lu *et al.,* (2004) GIS techniques are helpful when multi-source data are use for change detection.

Post-classification change detection method enables knowledge of where change has occurred over time and also provides information about the type of change. This method of change detection using unsupervised classified images has some difficulty, since the procedure works best if both image dates have the exact same cover types. Nevertheless, combining visual interpretation and change detection results can help an analyst follow trends in cover types over time. Based on the results obtained through this research, it is suggested that these methods should be further tested using ground truth data in order to assess accuracy of the change detection. Lu *et al.,* (2004) reported that post-classification comparison underestimates the area of land cover change but overestimates the magnitude of the change being detected.

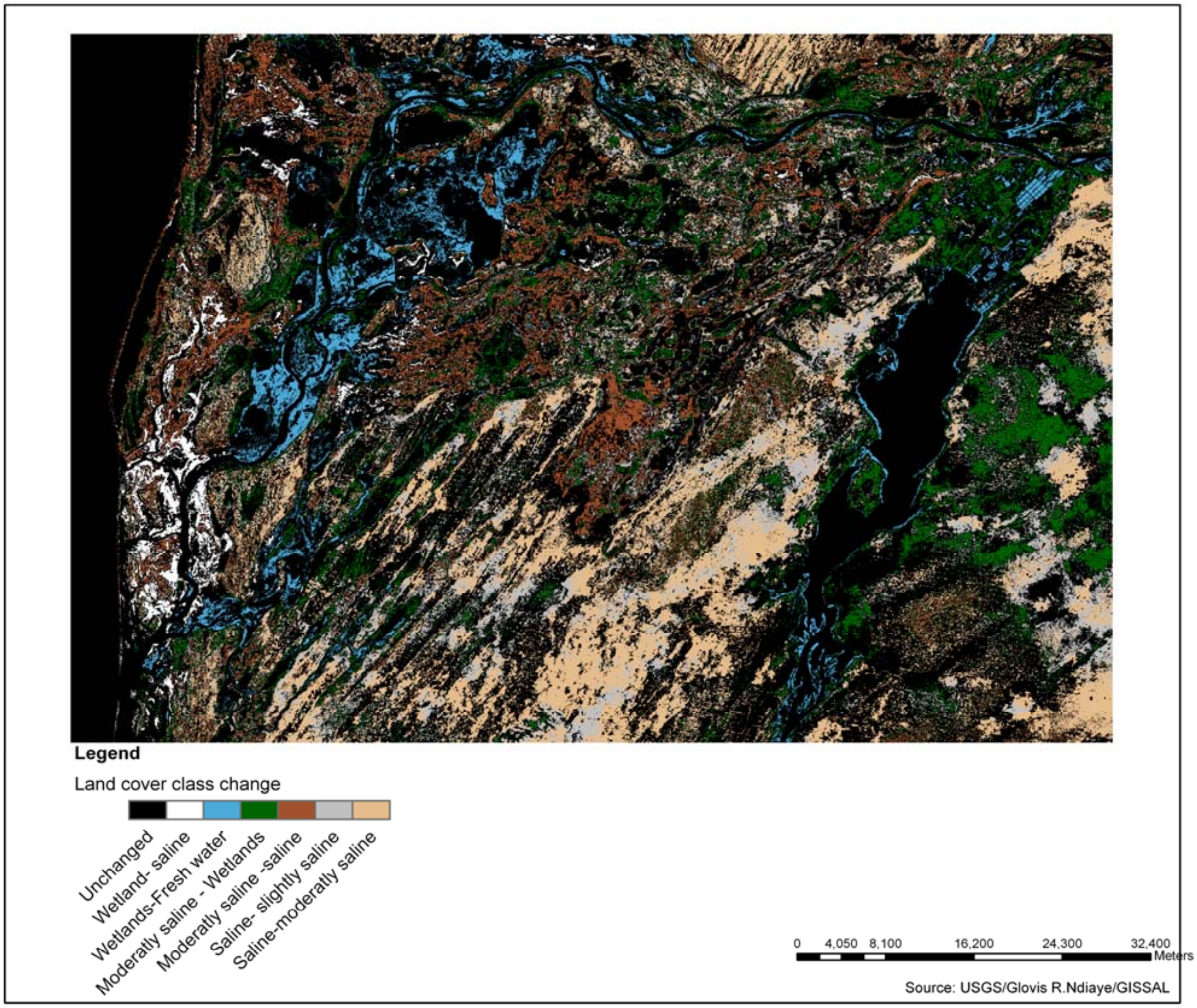


Figure 5.18- June 1973-February 2002 change detection map

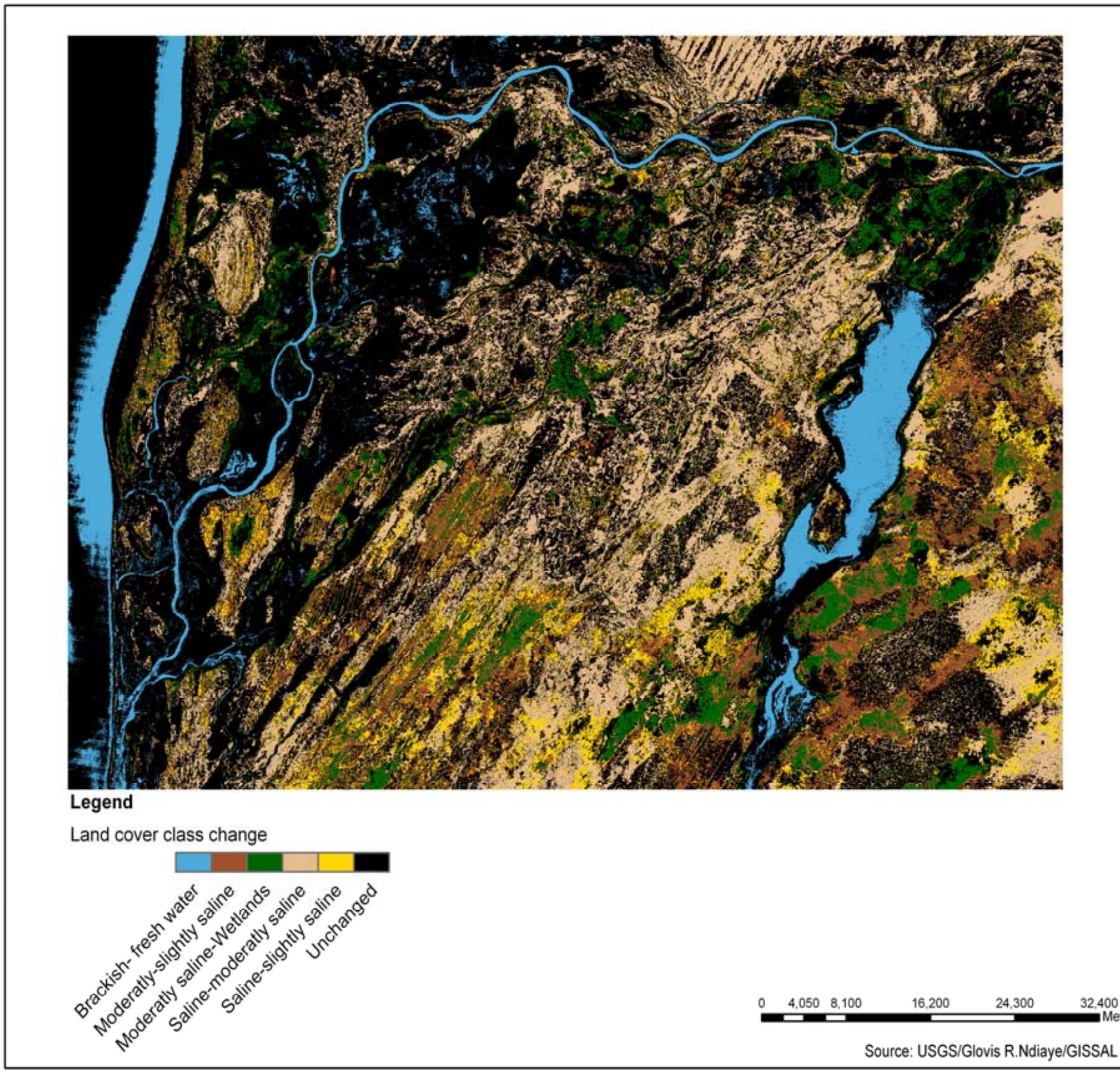


Figure 5.19- June 1973 - November 1987 change detection map

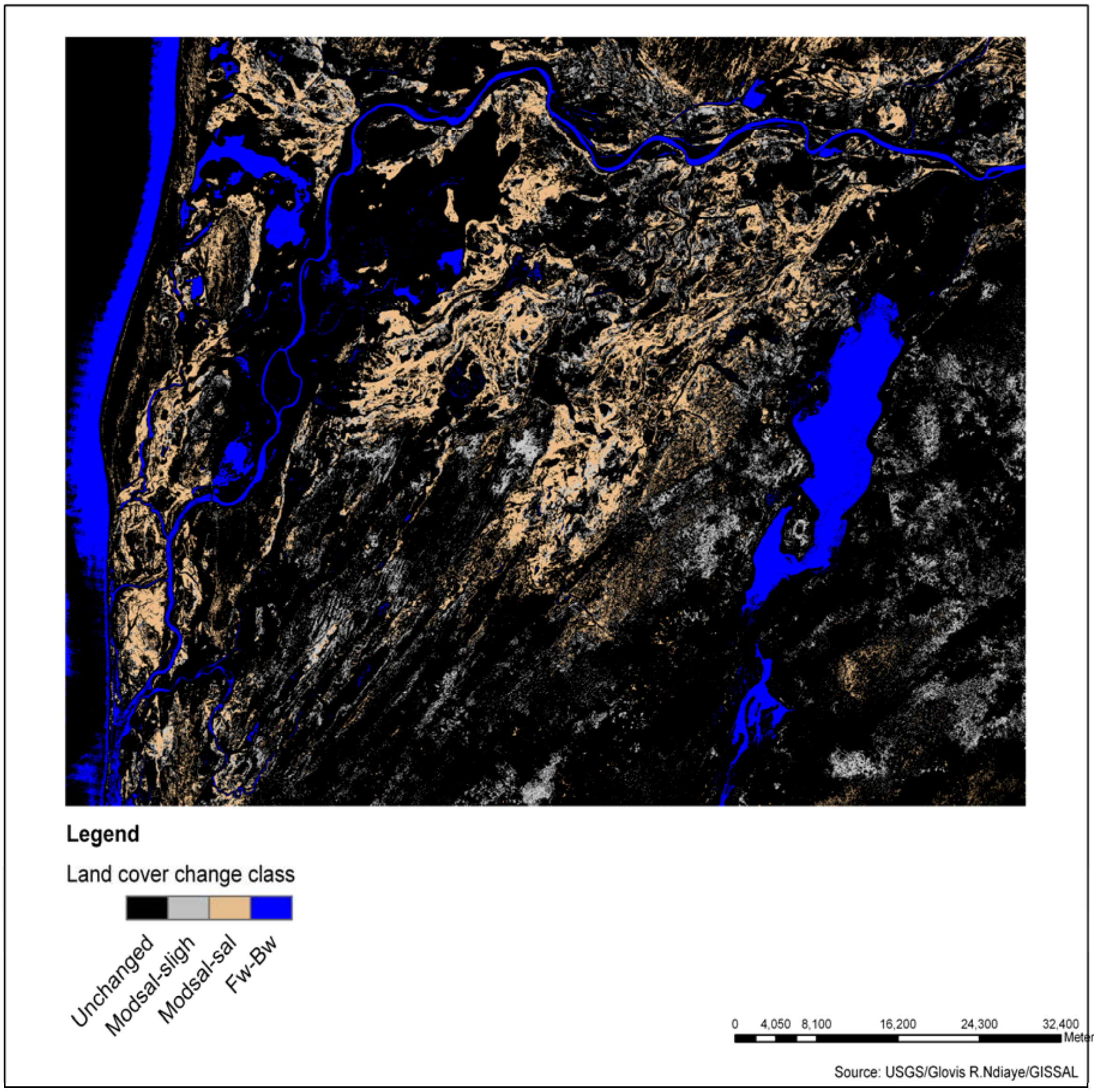


Figure 5.20- November 1987-February 2002 change detection map

5.3- Relationships between cover change and salinity-sodicity extent

Salinization is an acute problem in the Senegal River valley and delta. It reduces crop productivity and leads to environmental degradation. Chapter Two discussed how this salinity has built up in the delta, related primarily to climate variation and sea level fluctuation. Several management techniques have been implemented in order to address this problem and increase crop yields in the region. The construction of Diama dam formed an obstacle for the upstream propagation of saline ocean waters. A major goal of this water management program was irrigation. The aim was to bring 300,000 to 400,000 ha of land under irrigation, with two crops a year. Today only about 100,000 hectares of land are now under cultivation. Several irrigated areas have been abandoned over the years because of salinization. Irrigated agriculture has been frequently linked to salinity issues, particularly in the semi-arid Sahel where the use of large amount of irrigation water is coupled with poor drainage and high evaporation rates. Several studies have reported that irrigation without proper drainage can increase the sodium absorbed ratio of the soil solution resulting in a sodium concentration in the soil. This process is at the origin of sodic soil formation. The expansion of sodic soils is related to water management and thus to human action. For a number of years, it has been reported that the Senegal River valley and delta area are experiencing an increase in saline sodic soils. A purpose of this study was to monitor, map, and measure the spatiotemporal extent of sodic soil, so it is important to recognize the relationship between soil transformation, land cover change, and local natural resource management decisions.

According to the results obtained with supervised classification, there is a strong relationship between land cover with sodic and saline sodic soils and land use in the study region. Spatial patterns of sodic soils in the results of the supervised classification exhibitedd a strong relationship with the irrigated rice crop area implemented by SAED. In addition, the region has most of the environmental characteristic favorable to sodic soil formation. According to Bui *et al.* (1998) sodic soil can occur over a wide range of climates, but areas with a strong seasonal contrast have are greater likelihood for sodic soil formation.

Among the environmental conditions that promote the genesis of sodic soils are the presence of shallow saline ground water and the occurrence of a perched water table within 1 m of the surface (Bui *et al.* 1998). All these conditions are observed in the study region and the rise of the groundwater has been exacerbate by mobilization of millions of cubic meters of water in the Diama dam reservoir for irrigation purpose. Percolation of this water through the aquifer, coupled with the irrigation process, combine to favor the rise of groundwater to the surface. It have been reported also that sodic soil are mostly found in the clayey depression and that a soils with a high content of dispersible clay is naturally more prone to sodification than those soils having a lower clay content (Moreau, 1996). The geomorphology of the study region has a landscape with alternating dunes and depressions. Depressions are occupied mostly by three type of soil unit: “hollalde”, “false hollalde” and “fonde” soils with respectively 75 to 90%, 30 to 50% and 10 to 30 % of clay content.

In SAED irrigated areas, salinity has already been present for a long time. Rice, with some salt tolerance, is mostly cultivated in these areas. Moreover, the management combines leaching methods and drainage to remove salt from the rice root zone. A considerable amount of water is needed to satisfy the leaching requirement. Generally sodic soils are characterized by impermeable sodic B horizon, which facilitates the ability of flowing water to wash away the overlaying surface horizon. These soils are vulnerable to water erosion and according to Moreau (1996) irrigation is not recommended in the saline-sodic soils where soluble salt can be replaced by exchangeable sodium.

CHAPTER 6 - Summary and recommendations

6.1- Summary of important findings

Based on the results described in the previous chapter, it is possible to detect and track the soil surface salinity distribution over time in the Senegal River valley with remote sensing techniques.

- Supervised classification in conjunction with soil surface chemical characteristics such as exchange sodium percentage (ESP), cation exchange capacity (CEC) and the electrical conductivity (EC), allowed mapping the spatial-temporal distribution of different types of salt affected soils in the delta area using Landsat TM data. The results confirmed (between May 2001 and March 2003) a decrease in Non-saline soil and an increase in Saline-sodic and Sodic soil. The Saline soil class appears with a small areal extent for both May 2001 and March 2003 maps. Natural saline soils, with visible salt efflorescence on the soil surface, are easier to detect because of the high reflectance of the soil crust. According to Mane (1998) if salt efflorescence is absent from the top soil, it will be difficult to distinguish the presence of the high salt quantity and reflectance will be due to other soil factors such as color, moisture, and roughness.
- Sodic and Saline-sodic soils are replacing the natural saline soil built up over geologic time; with Saline-sodic soils as a transitional class type between Saline and Sodic. Results indicate that Saline-sodic soils have the largest areal extent, however this soil type is also being replaced over time by Sodic soils.
- The spatial distribution of Sodic soil is strongly related to land use, because of its expansion into and all around irrigated areas located upstream of Diama dam. Change detection results suggest that there is a considerable increase in Saline-sodic soil into the irrigated rice crop area managed by SAED. Water management in the delta is contributing to secondary salinization (or man made salinization) which is replacing natural salinization.
- In contrast to the supervised classification method, unsupervised classification methods only allowed the separation of salinity into degree classes (not salinity

types). Results indicate that there is change in the degree of soil salinity with a trend toward less salt affectd soils from June 1973 to March 2003.

- Construction of Diama dam in 1986 has had an important impact on the salinity cover of the delta region. Saline soil has been progressively replaced by the Moderately saline soil. The Dam, by blocking sea water intrusion near the river mouth, has positively impacted the local environment in terms of decrease in the surface area of salinity. However, others have noticed eutrophication upstream from the dam and a proliferation of invasive species.
- Beside human activities, fluctuation in the extent of saline soils is also influenced by the climate and its strong seasonal variability. During the years impacted by drought, the extent of salt-affected soil cover is greater.
- Wetlands are affected both by the management implemented in the region and climate change (including the strong seasonal variability). This land cover class is highly and negatively correlated with salinity. A large areal extent of Saline soil coincides with a loss in overall wetland coverage.
- Finally, perhaps due to the lack of relevant ground truth (water truth) data, the classification methods did not do well in differentiating water into brackish, fresh, and sediment laden classes.

As is the case with a number of studies in GIS and remote sensing, this research has shown that geographic analysis using satellite images can make significant contribution to detect and differentiate land cover features like SAS cover over time. Remote sensing and GIS are good practical methods for detecting, mapping and monitoring change in land cover/use for several decades; given the existing record of satellite images. Remote sensing and GIS offer several advantages over conventional ground-based methods for mapping and monitor SAS features. Abundant MSS and TM/ETM+ data images, available in an archive that spans over 30 years, are very appropriate for time series analysis. Compare to traditional quantitative assessment of land management, soil analysis using image differencing techniques is an affordable alternative to rapidly detect and estimate SAS variability. However, for more accuracy in characterizing the types of salts present, the supervised classification method needs a large amount of relevant training sample data. According to Lu *et al.* (2004), a variety of change detection techniques have been developed but it is important to select a most suitable method for each specific research purpose or study.

The classification and post-classification change characterization methods used in this research allowed as assessment of the hypotheses. Notwithstanding, this research effort confronted several difficulties related to the quality and the difference in resolution of some of our selected images. While Landsat MSS images helped extend the time period available to detect change and covered the major drought years, the larger spatial resolution of the MSS data presented a data management challenge. In addition, salt affected soils are best identified with images from late in the dry season (after the evaporation process has had time to generate the salt crust). Uncertainties exist in the classification of cover types due to similar spectral reflectance associated with some cover types (which directly affects classification accuracy). It is very important to minimize any time–lag between field survey and the dates of imagery used for classification.

6.2- Recommendations and perspectives

Natural resource management, planning and monitoring programs depend on accurate information about the land cover in a region. Establishing whether a salt-affected soil is saline, saline-sodic or sodic is a first step toward soil reclamation. Management strategies for soil improvement are different for each of these types of SAS and different techniques have been developed to reclaim SAS. Saline soils are the easiest to reclaim if good quality water is available (Ray *et al.,* 1992). In addition to the selection of plants and crops with a salt tolerance salinity, subsurface drainage to lower the water table, and mulch to reduce evapotranspiration are also necessary. Sodic soil has higher sodium content and a relatively lower salt content. Management of sodic soils requires an increase in the concentration of other salts, perhaps by adding calcium or gypsum depending of the location, in combination with adequate drainage and selection of drought tolerant plant species. Saline-sodic soils have both high salt and sodium content. For this soil type, excess sodium should be replaced by calcium and then leached to avoid sodium accumulation. All SAS soil management techniques need subsurface drainage. According to Masoud and Koike (2006), biological drainage, through plant uptake and transpiration, has proven to be very effective in lowering shallow ground water tables and facilitating the leaching of salt from surface layers of salinized soils in some areas. Successful natural resource management requires methods to map the spatial distribution of SAS.

The Organisation pour la Mise en Valeur du fleuve Senegal (OMVS) constructed Diama and Mannatali dams for development of the SRB. Their main objectives were to develop irrigation, to make the river navigable in all seasons from Saint Louis to Kayes, and to produce electrical energy. To maximize these development goals, research investigation and application of new technology is required. Since the irrigated rice crop is the main target of water managers, investigation should be directed to develop rice varities that are resistant to high salt concentrations. Rozema and Flowers (2008) reported that between 1996 and 2006 there were more than 30 reports of the transformation of rice with different genes aimed at increasing salt tolerance.

It has been reported that thousands of hectares of land in the study area have been abandoned because of salinization. Development of saline agriculture could be a solution to assist with reclaiming these lands. Rozema and Flowers (2008) reported that there are several halophytic plants that can grow under saline conditions, so saline water mixed with fresh water could be used to for irrigation. An example is *Salicornia bigelovii,* a oil-seed crop which can produce 18 tons/ha of biomass and 2 tons/ha of seeds over a 200 day growing cycle (Rozema and Flowers, 2008). An alternative hydrophyte is *Suaeda foliosa,* which is usually found in saline or alkaline wetlands; this species is cultivated and eaten as a vegetable. *Suaeda foliosa* seeds have been ground and eaten by Native Americans and some species are used as a source for red or black dyes. Bio-drainage by cultivating salt tolerant trees is also a solution in reclaiming SAS (Masoud and Koike, 2006).

In the field of GIScience, this study has shown that GIS and remote sensing are useful and affordable technologies to identify, map, and monitor SAS change trends. Further investigation should be done to improve the application of GIScience for assessment of ongoing changes to soil resources.

6.3- Conclusion

Environmental change caused by human activities and climate change are important and complex problems faced by any developing country. Changes in demographics, land cover, water resources, and biodiversity have created a situation with great impact on the economy and food security in countries with limited financial resources to address these changes. The Senegal River Basin, in the Sahel zone of West Africa, is one of the most vulnerable areas to coupled human and climate-induced change. Rainfall deficits, high temperatures, sea level rise, population growth, and declining soil resources combine to impact sustainability of local ecosystem.

Countries sharing the Senegal River Basin have targeted the area to enhance conditions for local residents and hopefully strengthen their national economy. Several billion dollars have been invested in the area without strong and convincingly positive result because of the combination of several negative factors:

- naturally saline soils caused by past sea level rises during geologic history;
- rainfall deficits during major drought periods producing significant inter-annual variations which stresses the resilience of local communities;
- and, natural resource management policies that need flexibility to adapt to the changing situation.

Irrigation developed rapidly in the Senegal River valley, especially during the 1980s (9000 ha) following completion of Diama dam. Irrigated rice cropping has been suggested by some as the most important cause of local soil degradation through salinization. New techniques that can quantify physical and chemical change in the environment are needed to assist with efforts in sustaining the environment. Remote sensing and GIS were used in this research to contribute in assessing and documenting land cover change in the Senegal River valley with an emphasis on salt affected soils. GIScience methods were used to classify saline, saline-sodic, sodic, and non saline soils. Results showed a decrease in salinity or primary salinity and an increasing trend in secondary salinity (or human-induced salinity) with a rapid expansion of saline-sodic soils.

These GIScience techniques are more affordable in terms of time invested and expense than traditional field-based methods. Plus, GIScience techniques enable use of a three decade archive of natural resource oriented remotely sensed satellite images. Improving quantitative assessment of soil analysis will help decision makers and farmers to better manage natural resources and prevent further soil degradation problems. Moreover, use of Landsat remotely sensed data to measure, map, and monitor change provides the potential to limit future environmental disturbance. Results of this study provide a strong foundation for the development of a national program of research and exploration of the value of GIScience in natural resource assessment and management. Such a program could increase awareness, educate citizens, and track change in order to avoid or mitigate hazards and assist with sustainable development.

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