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Assessing of the Suitability for Irrigation Water and Their Repercussions on Land Degradation Process in Delta and Lower Senegal River Valley

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Abstract In arid and semi arid zone, irrigation constitutes one of determinants of agricultural production expansion. However, the irrigated agriculture development can be a threat to the environment in these areas due to multiple soils degradation that can result (salinization, sodisation and alkalinization). Most of problems come from of the irrigation water typology, land use characteristics, water resources management and farming systems or irrigation schemes. In Delta and Lower Senegal River valley, irrigated agriculture produces currently many problems related to the degradation of soils and waters quality. Indeed, the use consequences for agricultural of different water qualities, impose the need to classify them according to their suitability for irrigation. The assessment and monitoring of water quality and soil are essential to ensure a profitable and sustainable irrigated agriculture in the delta alluvial plain. Thus, in this study water sampling was carried out during two campaigns (in July 2005 and December 2013). RICHARDS and WILCOX diagrams and statistical analysis through Ascending Hierarchical Classification (AHC) were used to classify and evaluate the impact of water on soils physical and chemical characteristics. Establishing suitability maps of water for irrigation from these different approaches, made it possible to highlight the different quality of water classes (Excellent, Good, Acceptable and Bad) and their repercussions on intrinsic characteristics of the natural environment especially potential risks to degradation by salinization and alkalinization in irrigated soils.

Keywords: *irrigation, water suitability, repercussion, salinization, soil, delta and lower senegal river valley*

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1. Introduction

The Senegal River valley was a traditional farming area based on rainfed crops and flood recession crops. With the drought persistent of 70-80s consecutive of declining annual rainfall totals [1] and decadence of the hydrological regime [2], ecosystems as well as traditional exploitation modes of natural resources and the livelihoods and people lives were greatly upset [3]. The populations that lived mainly through agriculture practiced in the flood plains have severely felt the impacts of climate change that affected their socio-economic conditions and many different aspects of their environment [4,5]. In this context of major climatic uncertainty and disillusionment of living actors near the river, the authorities of the three riparian countries of the Senegal River (Mauritania, Senegal and Mali) under the auspices of the OMVS (Organisation pour la Mise en Valeur du fleuve Senegal), initiated and carried out important projects of hydraulic infrastructure (dams, irrigation channels) and land development to: (1) ensure better control of water resources for sustainable development, (2) increase opportunities to practice agriculture less dependent on weather hazards and (3) reduce food dependency for the populations of the valley. In Senegal, developed areas increased from 9,000 ha in 1975 to 35,000 ha in 1988 of which (95%) is found in the river valley [6]. The continuing of water-control policy for irrigated agricultural production had planned an increase developed areas of 130,000 ha of which about 90,000 ha are exploitable. The annual exploited surfaces are in order of 50,000 to 60,000 ha in the Senegal River valley. Actually, the Millenium Challenge Account project (MCA, 2010-2015) aims a valorization of water resources with the implementation of many irrigation infrastructure and agro-industrial production competitive that passes through an expansion of irrigated areas in the departments of Dagana and Podor. This project will have as a main effect of increasing the attractiveness of the area with the massive arrival new farmers and intensification of large-scale irrigation practices in the lower valley and Senegal River delta. This context will not fail to pose new challenges with especially inefficiency of structural and regulatory framework to insure a sustainable and rational management of water resources and irrigated land. Thus, most is of the environmental problems have-been accentuated The damage of the long-term irrigation due to the soil salinization and to the gradual degradation of water resources quality, could constitute a threat to a massive environmental and economic disaster: changing the chemical composition of natural water resources, degrading the quality of water supply to the domestic and agriculture sectors, contribution to loss of biodiversity, loss of fertile soil, collapse of the agriculture activities and agro-business etc. In addition, this threat situation coupled by an inadequate or inefficience drainage system of irrigation discharges, make that the sustainability of irrigation systems is greatly affected. It is in this context that this paper falls within the overall framework of the assessing of irrigation impact on the dry land deltaic and fluvial environments, has been initiated to evaluate the suitability of water for irrigation in the estuarine area and the lower valley and their impact on soils degradation processes. Also the current study does it answer to preoccupation for prevent and limit the risk of soil degradation under irrigated land in order to establish a monitoring system of the status of soils and waters resources.

2. General Context

Located about 250 km north of Dakar, the estuarine area and the Lower Senegal River Valley is between 15°40’ and 16°35’ West longitude and 15°35’ et 16° 35’ North latitude. This region is bounded to the north by the Senegal River, to the west by Atlantic Ocean, to the east and to south by the vast arid region of Ferlo (Figure 1). The climate is characterized by a Sahelian regime that can be locally influenced in coastal part by the maritime trade winds that blow continuously for most of the year bringing moisture and freshness. It’s characterized by a coastal climate type often continentalized with a longue dry season from November to May and a short rainy season from June to October. At the annual scale, temperatures vary between a minimum of 22 °C (January) and a maximum of 35°C (in June) with an annual average of 27°C. The ETP (Evapo-transpiration Potential) varies between 2,000 to 2,500 mm. Rainfall amounts which vary between 200 and 450 mm, are characterized by a high spatial and temporal variability.

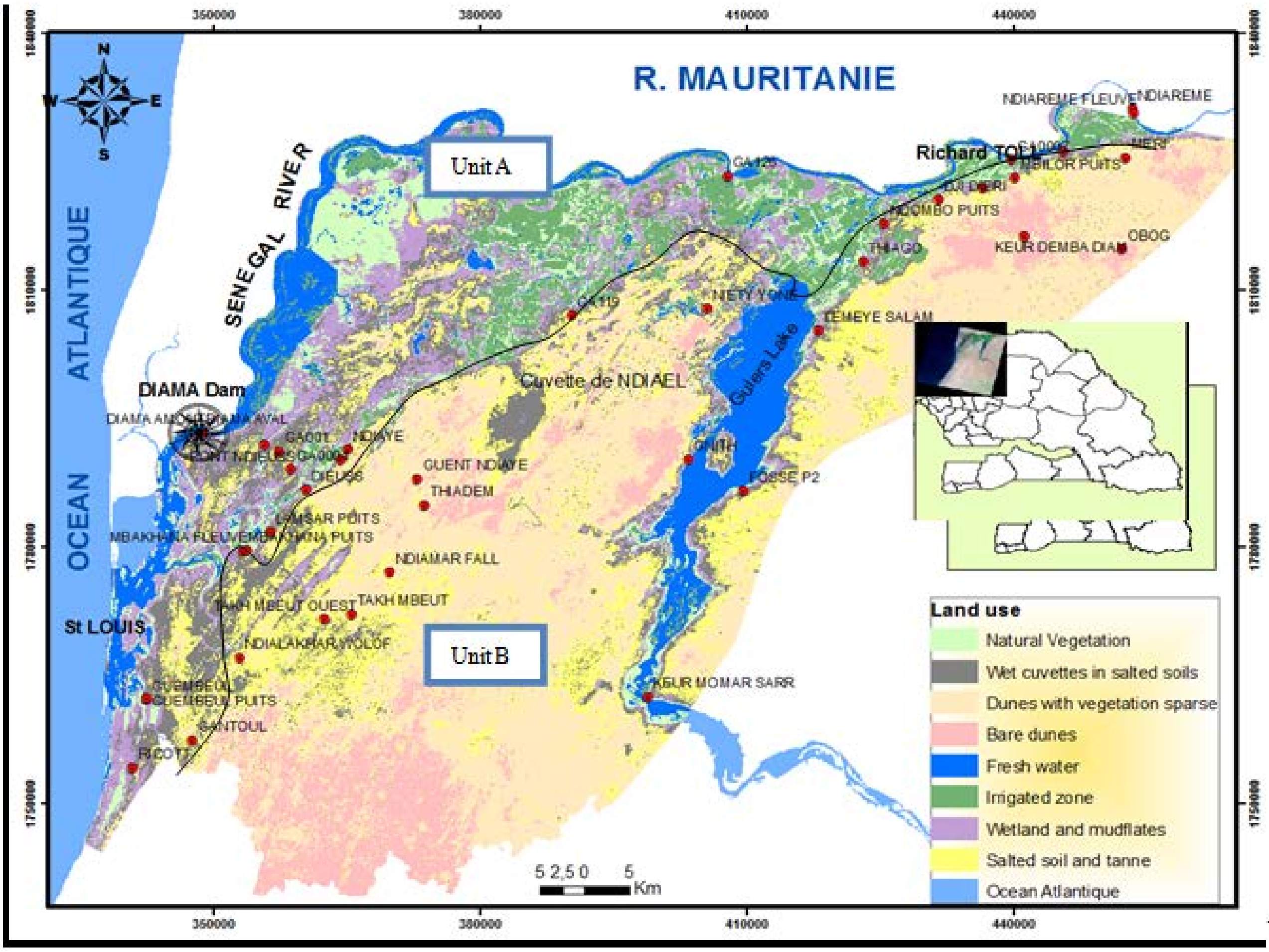

Figure 1. Location and land use Map of the area (extract of Image processing of LANDSAT 8- May, 2013).

In geomorphological context, the area is complex and varied; it is characterized by the existence of two distinct units which are contrasting to point of view altimetrical, phytogeographical and physical: The alluvial plain (consisting by Lowland wetlands or **unit A**) and the dune formations (consisting of low plateau with an arid ecosystem or **unit B**). In the geological setting, the unit B is characterized by the presence of continental dunes in NNE-SSW orientation. The dunes have been set up during the Ogolian (21,000-13,000 BP) as a result of the great marine regression (-100 m), of climate aridity and action continental trade winds [7,8]. The dunes are formed by deposits of ocher sandy sediments that are based on age and different nature substrates. They are relayed to the west and northwest by more recent formations of Holocene age made up of river alluvium, vases and coquillers sands. These deposits have been set up during the marine transgressive episode that occurs on the Senegal-Mauritania coast towards 5500 BP (unit A). This Nouakchottian transgressive episode that edifies and shapes marine terraces to the bordering of the Lower Valley from the dune sands revamped of Ogolian [7], belongs to a marine compartment. This compartment has been cashed in a subsidence basin [9] was gradually supplemented of sediments over the past thousand years [8]. This sediment from fluvial-deltaic and lagoonal, characterized by the presence of sand, silt and clay, have trapped substantial amounts of salts in deposits and its salts evolved within these soils closed circuit. The entrapment of residual evaporated seawater in the geological ***unit A*** of low conductivity, generates highly saline groundwaters which were formed by mixtures of saline groundwater originated from leaching of local paleo-saline sediments and dissolution of evaporites minerals [10]. In this section the chemical composition of different types of saline groundwater are directly related to the nature of the aquifer system layers, the deep and the proximity to a river. The upper aquifer is constituted by formations semi permeable to impermeable which are made up of sand clayey and clay. The groundwater level located on average -1 m below the sea level passes in lateral continuity to the east and northeast at the sandstone and clay deposits of Continental Terminal [11]. While ***unit B*** can contain a shallow fresh groundwater which is in hydrological contact with underlying hyper saline groundwater. Once, the natural hydrological balance is disturbed due to exploitation of the fresh groundwater, the salinization process starts. The rapid rates of fresh groundwater salinization due to rising underlying brines are found in some wells located in the dune formations of the delta. In the south and north east part, where the extension limit of marine facies is observed, the availability and quality of fresh groundwater can become more interesting and the aquifer becomes more productive with a water column thickness exceeding widely 15 m. This region which covers an area of 6000 km^2, is characterized by a surface water system dominated by the Senegal River that also feeds on either side of it course two large natural depressions that are Lake Rhiz in Mauritania and Lake Guiers in Senegal. In addition, the Senegal River serves a multitude distributary channels like: Gorom, Lampsar, Djeuss, Ndiaoudoune and Kassack (Figure 2). These distributary channels feed a series of decantation cuvettes and marigots network and ponds located mostly on salty soils (3 marigots area, Ndiael depression ect).

After the long drought period of 70-90s, extensive seasonal and traditional agricultural practices have been gradually replaced by intensive and sustainable irrigated agriculture especially in the alluvial plain of the valley. Water management in the dams: anti-salt dam of Diama in downstream and storage dam of Manantali in upstream, greatly affects the hydrological functioning of these rivers. It has primarily enabled better regulation of flows and levels in order to reduce seasonal and inter-annual contrasts of flow and improve the agricultural development of irrigated land and irrigable estimated to 100,000 ha in the lower valley and the river delta.

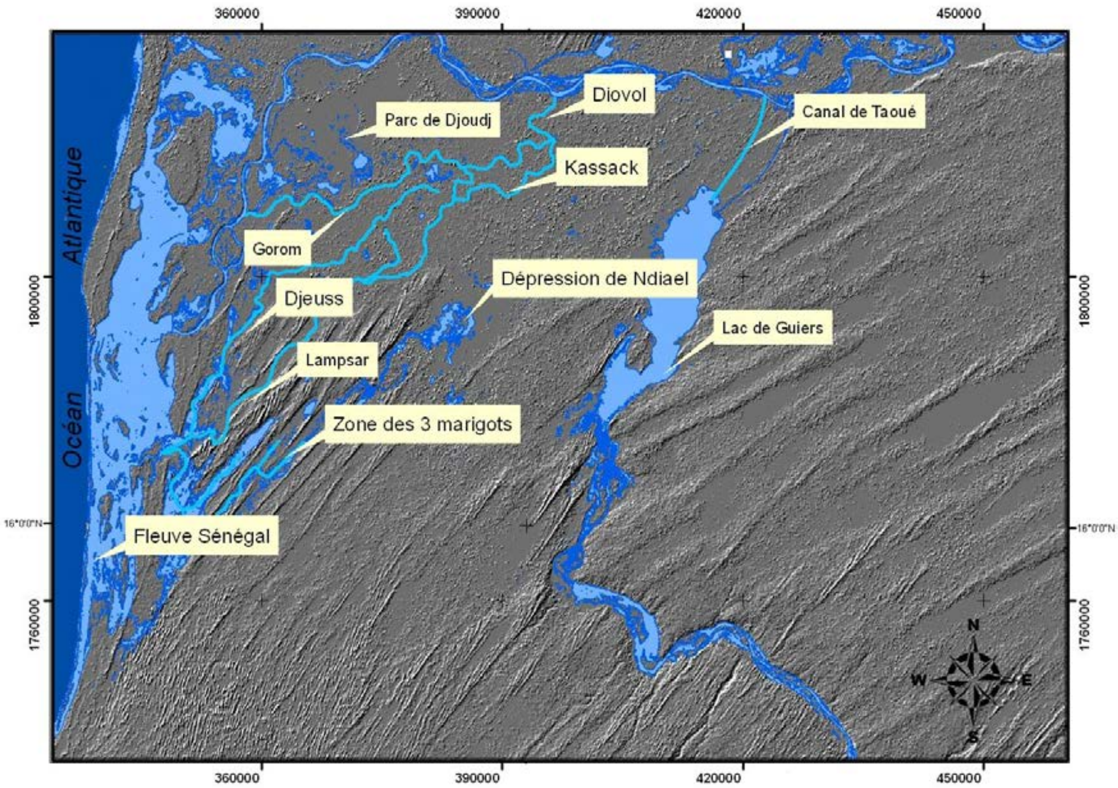

Figure 2. Hydrographical map of Delta and Senegal River lower Valley on background image SRTM-2000

Indeed, with the changes brought about in the late 80s following the putting into service of dams (Diama and Manantali), irrigated agriculture known a tremendous expansion and constitutes the engine of development in the area through better management of water resources and technology. Thus, the development of irrigated agriculture has shifted the entire production system by irrigated areas extension and dramatic rise in yields that it makes possible [12]. In addition, between 1982 and 1992 irrigated areas have doubled and more than half of this doubling is made by "privates sector" [13]. However, the promotion of private initiatives on direct production activities associated with transformation of the socio-economic environment (salary or business income, experience on rice cultivation, access to rural credit, etc) have promoted the production diversification other than rice crops such as tomatoes, green beans, onion, wheat, maize, sweet potato in the cold season as well as peanuts in hot season and also sugar cane crops and horticultural for exportation. Thus, about 100,000 ha of land are now irrigated in the valley of which 60,000 ha are grown in the rainy season (June to September) and 20,000 to 40,000 ha in the dry season (March to June). In the area, rice cultivation occupies an average area of 8,025 ha (with yields of 3.5 to 6t/ha), sugar cane 7,300 ha and tomato 1,200 ha. This prodigious growth of irrigated areas and speculations that polarize more and more land and populations (40-60%), as well as types and practices of irrigation crops in the long term, irregular management of hydraulic structures [14], associated of the climate changes effects have a negative and multiform environmental impact especially on soils degradation by salinization. The extent of soils degradation by salinization will be justified and discussed widely in outcomes section.

3. Methodology

Surface water samplings concerns the Senegal River following a west-east transect, the distributary channels (Djeuss, Mbakhana and Lampsar) and the Lake Guiers following a North-south profil. Groundwater samplings have been collected through a vast point network distributed in the alluvial plain (unit A) and the dune formations (unit B) during dry season and after the rain season respectively in july 2005 and December 2013. In each site, geographical coordinates through GPS as well as pH, Temperature (°C), Electric Conductivity (µS/cm) and water alkalinity (mg/L) have been measured in situ. Chemical analyses of waters have been effectued to hydrochemical and hydrology laboratory of Geology department of University Cheikh Anta Diop of Dakar. The concentrations of the major ions have been examined by Ionic chromatography Dionex DX 120, fitted of AS4 column for anions and of CS12 column for cations. Water classification has been effectued by using chemical and physico-chemical parameters such as SAR ($SAR = \frac{Na}{\sqrt{1/2(Ca+Mg)}}$), Electric conductivity (EC) and Sodium percentage ($\%Na = \frac{Na+K}{Ca+Mg+Na+K}$ *100). Piper diagram has been used to determinate chemical facies, while Residual sodium Carbon (RSC = $[HCO_3^- + CO_3^{2-}]$ - $[Ca^{2+} + Mg^{2+}]$) and WILCOX (1948) and RICHARDS (1954) diagrams have been used to characterize the risks of salinization and sodisation of soils. Multi-varied analyses with package ADE-4 of R software [15] have been leading on the various chemical and physic-chemical parameters. Ascending Hierarchical Classification (AHC), Ward jump and biplot function have been used to identify water classes. The waters of the suitability classes for irrigation defined by RICHARDS and WILCOX diagrams have been mapped for the campaign of dry season in July 2005. These maps have been established by using GIS software Arc 9.3.

4. Results and Discussions

4.1. Characteristics and Evolution of Irrigated Soils

The performance and sustainability of irrigated agriculture depends in part on the quality of irrigation water and the behavior of irrigated land. In delta and Senegal River Valley, the data on the soil structure, its evolution and behavior under cultivation in irrigated areas were obtained and evaluated through many work of several authors [16-23]. Most irrigated areas are located on clayey soils (more than 40% of clay: "*Holladé*") and silty-sand soils (with 25% of clay: "*Fonde*"). These hydromorphic soils are present at a depth about 1 m under a clay horizon and a marine terrace [24]. This terrace consists of fine sands, trapped a certain amount of salt during its setting up [8]. The origin of soil salinity is attributed to marine transgression of Nouakchottian (toward 5500 BP) during which the Valley and Delta have been filled by lagoonal or salted marine deposits [25]. However, we can note that these soil salinization phenomena could be influenced and exacerbated by climate change effects and human activities especially with irrigation which the main threats could come from:

The Soil types especially for irrigated rice called ''*Holladé* or false *Holladé*'' are characterized by very low internal drainage capacity. The high evaporation in the area (2000-2500 mm), would lead to a rapid increase in salt concentrations in the water blade of the plots under cultivation. Indeed, if the removal of these salts by percolation is insufficient, the root zone of the soil becomes more salty leading to a drop in crop yield and a lateral extension of salt diffusion [23,26,27]. Salinization of water resources is also attributed to accumulation and leaching of salts from the soil which affects agricultural management.

The context where irrigation is practiced without adequate drainage system [14,28] which has become the most common practice in the Senegal River basin. In addition, this situation is associated with the flatness of the terrain which makes it difficult gravitational dynamics of sewage that are directly discharged through the drainage stations in natural depressions endorheic (Ndiael, Krankaye, Noar, and Mbeurbeuf Pardiagne) or in hydraulic axes (Senegal River, Lake Guiers). But despite these drainage systems, irrigation schemes are regularly confronted with wastewater discharge problems that are often directly released on the edge of irrigated areas or on the against-bottom of reliefs. Thus, irrigated lands as well as amenagable lands may suffer of increased salinity diffusion of these soluble salts from the highly loaded draining water. These phenomena appear to be more regular in the private amenagements because of the uncontrolled use of agricultural inputs (pesticides, chlorinated organic fertilizers and organophosphates). There are no standards that govern the various forms of wastewater which can lead to water resources pollution and the absence of volumetric water management injected into plots helping thus to increase the drainage water volume released estimated 9,000 m^3/ha or nearly 3 times the volume expelled in the public and conventional amenagements (3,500 m^3/ha). Pollution of irrigation drainage water could constitute long-term a serious environmental problem in the Senegal River basin, although the extent of water contamination by pesticides and fertilizers is still poorly documented. This situation, which is the main cause of the accumulation of soluble salts (see Picture1C), is responsible for the decrease in permeability of the soils by swelling of clay particles, dispersion of colloids and clogging of surface layers making the hard ground, compact and asphyxiant for plants [29]. It is also responsible for the rice productivity declines and even irreversible loss of a lot of lands in the delta in benefit of new lands causing a model which akin to an itinerant rice cultivation [30], which is the main cause of the rice sector instability in the Senegal River Valley. Thus, in 1999 an evaluation on the status of the delta irrigated areas shows that only 46 percent of these areas are in normal conditions to be highlighted due to soil salinization.

The gradual rising of alluvial groundwater level induced by management of water level rising in the Diama dam in the downstream (2.0 m IGN), irrigation frequency and uncontrolled water management through poorly control of the amenagement polities especially with the failure of large agricultural amenagements initiated by SAED (*Sociètè Nationale d'Aménagement et d'Exploitation des Terres du Delta du Fleuve Sénégal et de la Vallée*). This failure promoted the immergence and proliferation of private agricultural amenagements (60% for all) on most slight textured soils (less clayey) "*Fonde*" which is characterized by percolation potential from 4 to 5 mm/day. Indeed, these soils are more likely to remove salt from irrigation water by internal drainage. Thus, irrigation on these soil types require large consumption of water, the amount of water leaking through the unsaturated zone has increased and water irrigation excess has also increased saline groundwater levels [31]. The rise of saline groundwater and mobilization of salts stored in the unsaturated zone accentuated salts rising by capillarity in soil profiles under permanent evaporation effect [22]. This high evaporation (5.5 mm/day in cold season and 8.5 mm/day in hot season) is responsible of the salinization of the surface horizon and the apparition of saline efflorescence and crusts in surface (see Photo 1A and 1B). These phenomena are usually accompanied of the problems of aeration and nutrition for plants [32]. For most soils affected by salinity, the aforementioned chemical and hydrological processes can act or inter-act according of the domain accumulation characteristics to them intensifies [21].

In order to illustrate the effectiveness and degradation dynamic of soils salinization process, an environmental monitoring of land cover have been conducted on Landsat ETM$^+$ images of 2003 and 2013, which have been processed through ARC GIS 9.3. This monitoring has enabled to define land cover classes in order to detect changes in each class particularly in salted soils class. Statistical analysis of surface covered by salted soils between 2003 and 2013 (Figure 3), indicate occupation percentages passing respectively from 23% to 27% (1,530 km^2) highlighting on the dryland salinization, the most wide-spread phenomenon to land clearing and replacing the natural vegetation with annual crops and pasture.

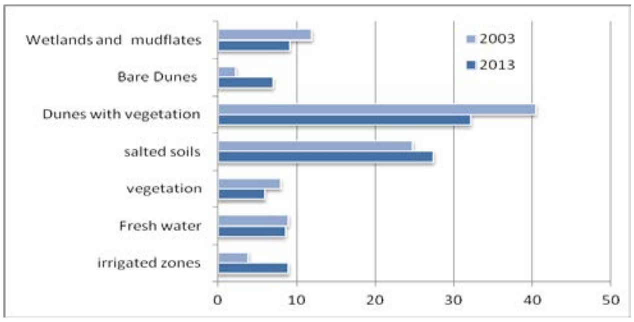

Figure 3. Percentages of land cover classes of the area through processed images ETM$^+$ of Landsat 7 (mars, 2003) and Landsat 8 (mai, 2013)

However, these salinization mechanisms which were observed everywhere in delta zone, have been also showed more in upstream in the middle valley of Senegal River basin [19,23,27,33]. Which currently results a preoccupation to find answers to these questions is both diverse and complex, since these soil salinization degradation mechanisms are beginning to take serious proportions by being generalized in the downstream valley of the Senegal River Basin. The real impact of the evolution of these arable soils is poorly known. The use of evaluation of the quality of water resources for irrigation and their impact on the environment is necessary because to the many problems facing currently the region in respect to soil degradation processes. A good spatio-temporal knowledge of water chemistry and soils future is indispensable to better ensure sustainable use of water and soil resources.

Photo 1. (A and B): Saline efflorescence of soils in the delta; (C): Salted soils on the edge of irrigated rice areas

4.2 Evaluation of water for irrigation

The characteristics of water for irrigation are discussed with reference to the physico-chemical water classifications established by [34] according to Table 1. Indeed, according to the interpretation criteria defined in Table 1, the results showed that the pH are < 8.5 and the HCO_3 contents in water do not exceed the maximum permissible limits (8.5 meq/l), so that the alkalinizing processes is significantly reduced. Thus, to better characterize sodisation process, we took into account of Sodium Percentage in water (% Na) which the maximum threshold is fixed at 60% for agricultural use.

Table 1. Classification criteria for irrigation water [34]

Interpretation criteria/Unities	Limit values (FAO)	Intensity of problems
CE (mS/cm à 25°C)	< 0.7 0.7 à 3 >3.0	no problem growing Problem serious Problem
Cl (meq/L)	< 4 4 à 10 >10	no problem growing Problem serious Problem
SAR	< 3 3 à 9 >9	no problem growing Problem serious Problem
HCO_3 (meq/l)	< 1.5 1.5 à 8.5 > 8.5	no problem growing Problem serious Problem
pH	6.5 à 8.3 < 6.5 > 8.4	no problem growing Problem serious Problem
%Na	<40% 40-60% > 60%	no problem growing Problem serious Problem

4.2.1. Surface Water

Surface water, whose potential is estimated at nearly 11 billion m^3/year for the Senegal River and nearly 601 million m^3/year when the water plan reaches to 1.80 m IGN for the Guiers Lake, is subject to an artificialized hydrological regime. They constitute the main source of water for irrigation and present chemical characteristics that can modify in long-term the soils characteristics. According to criteria classification, these waters are classified as excellent quality except in the downstream portion of the Guiers Lake and Djeuss often used as spillway of irrigation drainage water. These waters are generally characterized by a more or less low mineralization (80-400 µS/cm), natural pH ranging from 6.7 to 8.5, SAR values are below 6 (Table 2) and typical facies bicarbonates (Figure 4). The determination of the water alkalinity is a key indicator to identify the soil salinization processes.

Table 2. Parameters of surface water quality for irrigation

Designation	Name	pH	CE (µS/cm)	HCO_3 (meq. L)	Cl (meq. L)	%Na	SAR	ESP
Senegal River	Ndiareme fleuve (P5)	6,7	50	0,5	0,12	32,5	1,91	0,03
	Mbakhana fleuve (P5)	6,9	80	0,8	0,27	45,35	2,3	0,04
	Diama amont (P3)	6,8	80	0,7	0,03	56,76	1,83	0,03
	Djeuss (P2)	6,6	650	1,75	3,77	74,3	3,98	0,09
Guiers Lake	Nietty Yone (P21)	7,1	240	1,2	0,8	61,04	2,9	0,06
	Gnith (P22)	8,5	220	2,65	0,64	44,14	4,02	0,09
	KM Sarr (P14)	7,4	390	2,75	1,31	58,44	4,16	0,15

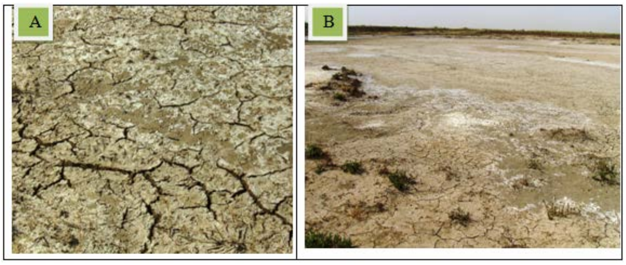

Photo 2. (A) Cracked and indurated clays; (B) Surface crusting produced by waterlogging soil from salt waste water in the Krankaye cuvette

Therefore, if we find that the surface waters are alkaline solutions, its alkalinity can be reduced to the carbonate alkalinity [35]. During the solution concentration phenomenon, if the sum of calcium and magnesium equivalents is less than to the alkalinity in the initial solution, the alkalinity increases and the calcium and magnesium molarities decrease. Future evolution of the ground then can follow the alkali-salinization or alkalinization mechanisms. To predict the evolution of the chemical solution composition, the concept of residual alkalinity is used. This concept which is equivalent to the Residual Sodium Carbonate (RSC) is defined as: Alkalinity – $[Ca^{2+}]$ - $[Mg^{2+}]$. The continuing use of alkaline water for irrigation can confer positive residual alkalinity calcite [36], which may facilitate the ability of such waters to quickly mobilize calcium from the soil. So that, the sodium, which is not involved in the precipitation of minerals, is concentrated in the solution. It can be adsorbed on the soil exchange complexes which become more and more enriched and leads to soil sodicity phenomena. Once, the sodic soils are contacted with the low concentration solution (below 100 µs/cm), this can lead to degrade their physical and hydrodynamic properties [37] which manifest itself, most often, by phenomena explosion aggregates and clays dispersion [20,29,38,39,40]. The structural disaggregation and dispersion of these soils may be manifested by induration [41] or by surface crusts formation [42,43]. These observations are consistent with the macroscopic illustrations from photographs (see Photo 2). These phenomena are often controlled by the natural environment and the disturbances that affect it, by the management of hydro-agricultural infrastructure and the irrigated soils. The knowledge on current soil geochemistry of the valley [19,22] and the best understandings on mechanisms of sodisation and alkalinization of soils [20,40,44,45,46] lead one to consider the water residual alkalinity as one of the causes of soil sodisation. Indeed, this latter is one consequences most damaging and most widespread irrigated land under arid climate [46]. Based on these observations, an evaluation and monitoring of water for irrigation have been proposed to avoid this progressive degradation since the type of irrigation water and its quality determine the salinity and fertility of the soil and eventually the quality of the underlying water resources [47].

4.2.2. Groundwaters

The groundwater samplings have been effected into each geomorphological unit: the alluvial plain and the dune formations. Groundwaters are essentially used for water supply and for irrigation of peoples. Indeed, the irrigation with water of various chemical facies (Figure 4) and differently loaded in dissolved salts could be practiced with most precaution. All use of this water for irrigation which not predict a frequent leaching of irrigated soils predispose them to be affected by gradual salinization.

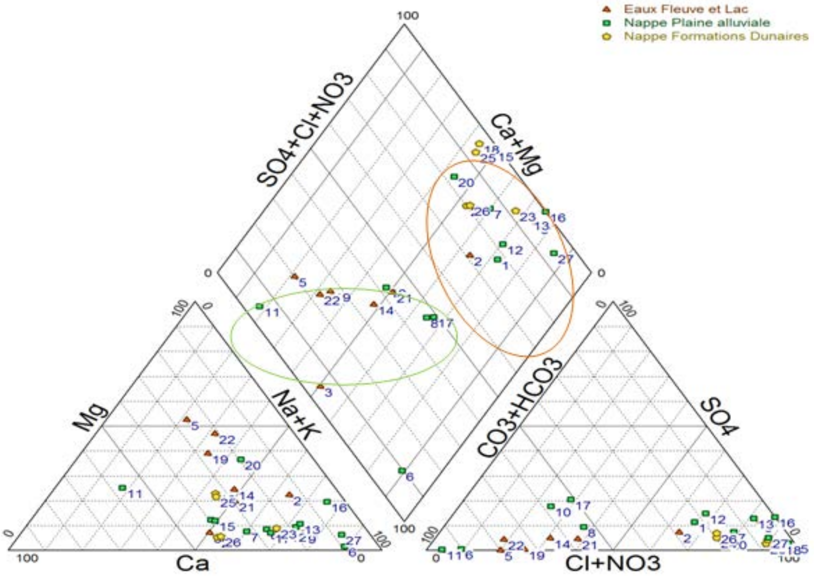

Figure 4. Representation in Piper diagram of surface water and groundwater of Senegal River delta (july, 2005)

Alluvial Plain aquifer

The groundwater in the alluvial plain close to the hydraulic axes (P6, P8, P10, P11, P17), have physico-chemical characteristics similar to those surface water (Figure 4). They are characterized by pH values between 5.3 to 7.0, SAR values < 9, carbonated chemical facies (Ca-HCO_3 and Na-HCO_3), and can be used for irrigation according to FAO classification (Table 1). However, other groundwaters categories in the alluvial plain are characterized by chemical facies type Na-Cl and Na/Ca-Cl, pH values more acid between 3.4 to 7.3 and SAR <9. However, these distant groundwaters of hydraulic axes are directly related to the saline sediments of shallow aquifer system layers. Thus, they may have high values of Conductivity Electric, Chloride, SAR and Na% (Table 3) that can certainly affect the quality of these waters and intensify the problems that they can bring in irrigated soils (P1, P7, P13, P15, P16 and P27).

Table 3. Parameters of groundwater quality for irrigation in alluvial pain

Name	Designation	pH	CE (µS/cm)	HCO_3 (meq. L)	Cl (meq. L)	%Na	SAR	ESP
Savoigne puits	P1	7,3	3430	7,3	21,5	78,03	8,78	0,23
Ndiareme Puits	P6	6,9	190	1,75	0,17	91,13	1,4	0,02
Dagana	P7	6,2	1110	1,35	6,45	65,48	5,89	0,15
Mbilor puits	P8	6,6	530	2,65	1,82	70,87	3,89	0,09
Keur Mbaye	P10	6,7	200	1,1	0,45	54,94	2,98	0,06
NDombo	P11	7,1	470	5,15	0,19	23,74	6,12	0,16
NTiago	P12	5,3	110	0,45	0,21	77,71	1,65	0,02
Temeye Salam	P13	7,1	7010	4,35	45,5	80,42	13,2	0,36
El Qouss	P15	7,3	10580	1,75	97,4	56,47	21,54	0,61
Nguenth	P16	3,4	3080	00	22,1	84,19	6,96	0,18
Tiadem	P17	6,7	460	2,1	1,08	73,4	3,59	0,08
Mbakhana Puits	P18	6,1	890	1,45	5,2	57,18	5,83	0,15
Gueumbeug	P27	8,5	5900	3,6	51,6	89,74	8,17	0,22

Dune formations aquifers

The groundwater in dune formations has chemical facies Ca/Na-Cl or Na/Ca-Cl types, pH values are between 6.2 and 9.5 and SAR values < 9 (Table 4). They can be moderately loaded and become good and allowable for irrigation provided that it not compromises the becoming irrigated soils.

However, with geological time, a fragile hydraulic equilibrium has been established between fresh groundwater and deep saline groundwater. Wells construction and massive groundwater abstraction in the surrounding villages as such P9 and P23, affect this delicate hydrological balance. Exploitation of this paleowaters, with a low possibility of modern replenishment, can lead to rapid salinization of the groundwater resources which can have high values of Electrical Conductivity, Chloride, SAR and %Na that can exceed thresholds and seem not in accordance for agricultural use.

Table 4. Parameters of groundwater quality for irrigation in dunes formation

Name	Designation	pH	CE (µS/cm)	HCO3 (meq. L)	Cl (meq. L)	%Na	SAR	ESP
Takhmbeut	P23	7,8	7000	5,25	60,93	73,04	14,04	0,39
Nialakhar	P24	9,5	400	0,35	1,81	59,71	4,1	0,10
Gantour	P25	6,2	700	0,4	4,76	53,97	5,28	0,13
Ricott	P26	7,4	1800	3,2	11,21	59.84	8,76	0,23
Keur D.Diam	P9	7,0	10350	4,85	84,94	80,34	14,85	0,41
Lampsar	P20	6,2	790	0,3	4,64	53,6	5,93	0,15

4.3. Assessing of the Salinity Risk

The salinity problem is a global phenomenon but it is more severe in water –scarce areas, such as arid and semi arid zone [47]. Salinization is probably the major risk to irrigated soils, mainly arid climate; it can be appreciated by the Electrical Conductivity (EC) of irrigation water. However, another major risk is the sodisation and alkalinization soils as a result of ion exchange, especially for sodium, calcium and magnesium between the water and clays of soil [48]. This risk can be appreciated by the Sodium Absorption Ratio (SAR). Indeed, the interest of SAR calculation in irrigation water to represent the degree of water alkalinization and the risk that they can bring about the decline in soil permeability that they irrigate, has been demonstrated by the results of several studies [34,49,50,51,52]. EC-SAR couple has shown that WILCOX diagram allowed to do a water classification according to their suitability for irrigation therefore according to salinization risk measured in x-axis by conductivity (in letter C) and alkalinization measured in y-axis by sodium absorption ratio (in letter S). According this diagram (Figure 5), five classes have been observed:

- C1S1: This class which includes (9/27) surface water (river and lake) and groundwater close hydraulic axes up stream (P6, P10, P12) is considered as excellent quality for irrigation because it corresponds to the minimum values of the SAR and EC.
- C2S1: This class which includes (9/27), the surface waters of the distributaries channel of the river and downstream Lake (P2, P14), the groundwater of the alluvial plain fed by hydraulic axes (P8, P11, P17, P20) and of dune formations (P18, P24 and P25), is enough good quality for irrigation. It is favorable for all crops (horticulture, current and shrubs), except the very salt sensitive crops.
- C3S1: This class which includes (2/27) generally P7 and P26, is suitable for salt-tolerant crops (cucumber, onion, pepper, tomato, cabbage, potatoes, corn, carrots etc). This class is mostly admissible when soils are well drained to prevent salt deposits and soil salinity.
- C4S2: This class of poor quality (2/27) is not suitable for irrigation (P1 and P16), but can be used under certain conditions: very permeable soils, leaching good, very salt tolerant plants (cabbage, beets, melon, yams, rape, and spinach). In addition, the wells located in the flood plain and in estuary and punctually in dune formation (P9, P13, P15, P23, P27) observed out graph (4/27), can be considered as the waters of poor quality and unsuitable for irrigation (EC> 5000 µS/cm). The interpretation of WILCOX diagram is summarized in Table 5.

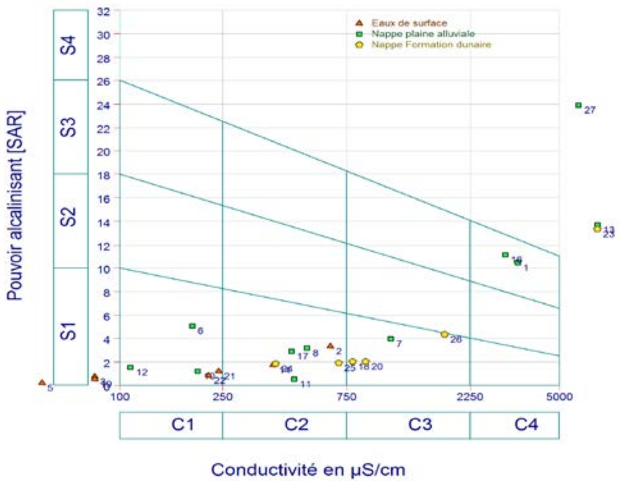

Figure 5. Irrigation water represented in the WILCOX diagram (july, 2005)

Table 5. Recapitulative of results in the Wilcox Diagram

Water Class	Surface water	Groundwater in alluvial plain	Groundwater in dune formation	observations
Excellent	C1S1	C1S1		suitable to all crops (horticultures, current, shrubby) except the very sensitive crops to salts
Good	C2S1	C2S1	C2S1	
Admissible			C3S1	suitable for salt tolerant crops when the soil is well drained
Bad		C4S3 and out graph	Out graph	unsuitable for irrigation, Use: very permeable soils, good leaching, very tolerant plants to salt

The WILCOX diagram showed that the waters are marked by salinization risk than by alkalinization risk. Given that sodium plays a role in maintaining the permeability of the soil for irrigation, the relative proportions of (Na + K) (Ca + Mg), is decisive for the agricultural use. Thus, RICHARD classification that represents the EC-%Na couple highlights the same quality water classes Excellent, Good, Acceptable, and Bad. However, some of these water classes that are suitable for agricultural use are characterized by a potential risk of soil sodisation which results in the RICHARD classification by an enrichment of coefficient corresponding to the exchangeable sodium percentage of groundwater. (Figure 6). Since the possibility of increasing this sodisation risk begins to be felt from 45 to 50% of Na [53] and become effective from 60% [54]. The different classifications in the WILCOX and RICHARD diagrams have found that for given values of SAR and Na%, the risk is even higher than the irrigation water is mineralized.

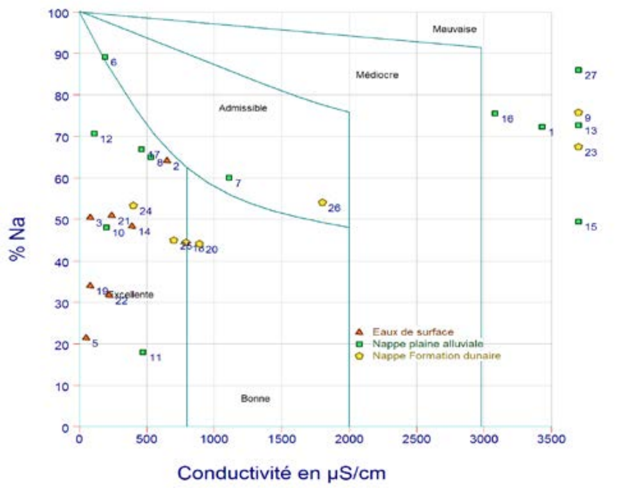

Figure 6. Irrigation water represented in the RICHARD diagram (july, 2005)

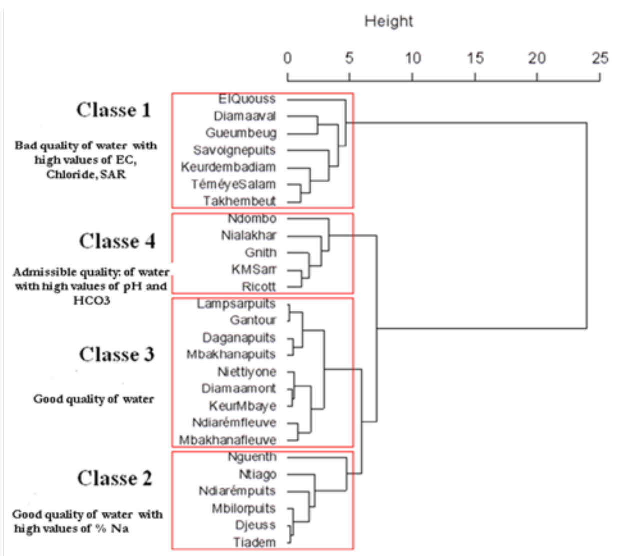

Figure 7. Dendrogram, water classification by AHC and jump Ward

Water classification by RICHARD and WILCOX diagrams is complemented by the Ascending Hierarchical Classification (AHC) which has identified 4 classes (Figure 7 and Figure 8):

- The Class 1 is characterized by waters whose values of EC, SAR, Chlorides and Na% exceeding the standards established by the FAO therefore unsuitable for agriculture;
- The Class 2 is used for irrigation, but it is characterized by an enrichment of the coefficient corresponding to the exchangeable sodium percentage that may increase the risk of sodisation soil.
- The Class 3 represents the water of excellent at good quality that present no risk;
- The Class 4 represents the water of enough good quality with slightly basic pH, whose their permanent usages may favor soil alkalinization phenomena.

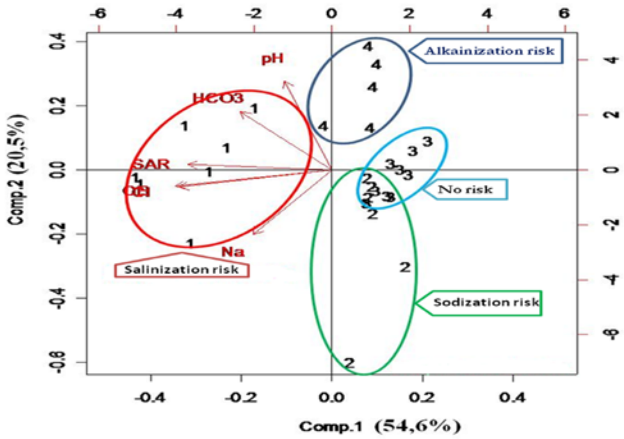

Figure 8. Representation of water classes obtained by AHC

4.4. Establishment of the Suitability Maps for Irrigation Water

The determination of the suitability map of waters for irrigation of the area has been conducted by combining different information layers from the interpretation criteria established by the FAO (SAR%, Na, HCO_3, Chloride and EC) and the classifications established by the diagrams of WILCOX and RICHARDS and by the Ascending Hierarchical. The approach used is the interpolation of each of these data by IWD method (Inverse Distance Weighted), the codification of each information layer and the crossing of these layers codified from the ARC GIS 9.3 software. Indeed, this process seems to be one of the most suitable means for a good spatial representation of the suitability of water for irrigation which highlights four categories (Figure 9).

However, the class distribution of water suitability in the Senegal River delta (Figure 10), show that:

- The category of excellent water quality is represented by surface water and groundwater close to the hydraulic axes that occupy 2% of the territory.
- The category of good quality water is localized in the floodplain in connexion with the surface network, in the lake basin and in dune formations in southwest; it represents 29% of the territory.
- The category of mediocre and admissible quality water is localized in the transition zone between the alluvial plain and dune formations in the southwest and punctually in dune formations to the east. It represents the largest proportion of area and occupies 48% of the territory;
- The category of poor quality water that occupies 21% of the territory is located downstream in the north west of the alluvial plain in the area of extension of the saline groundwater in the delta.

The spatial distribution of the suitability water classes for irrigation is directly related to the nature of the layers of aquifer system exploited, geomorphological distribution (alluvial plain-dune formations), distribution (upstream and downstream), proximity a hydraulic axes and the groundwater depth.

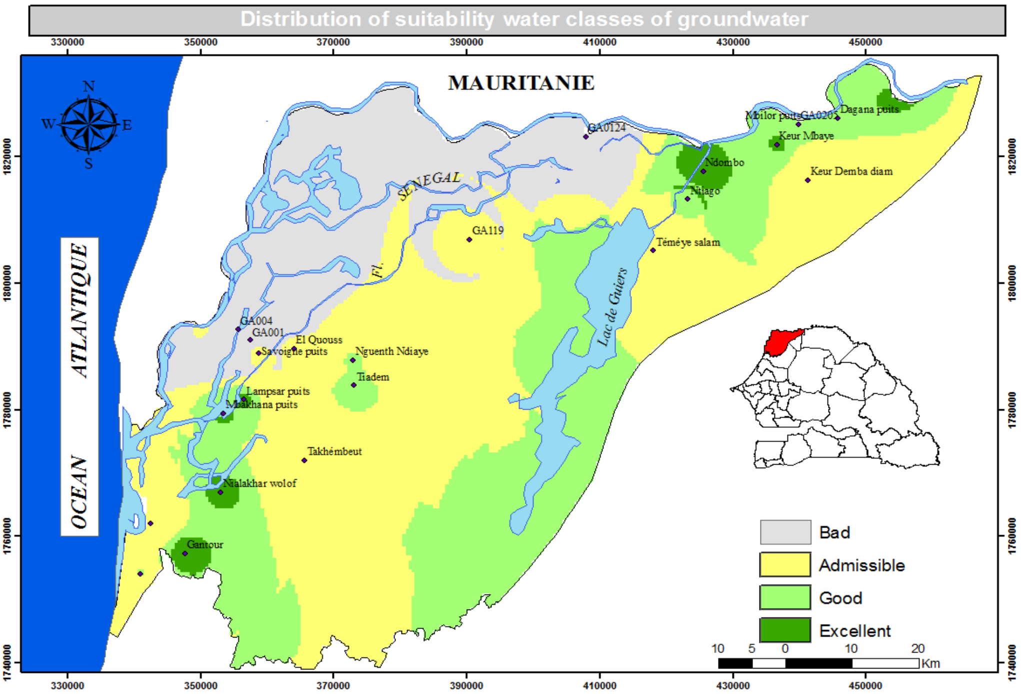

Figure 9. Suitability map of groundwater for irrigation in Delta and the lower valley of Senegal River basin (july, 2005).

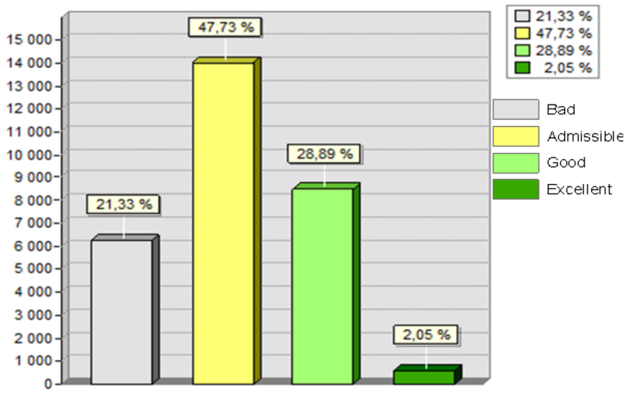

Figure 10. Distribution Classes of groundwater suitability for irrigation in the Delta and the lower valley of Senegal River basin (july, 2005).

5. Conclusion and Recommendations

The study has allowed to determinate chemical and physico-chemical characteristics of water for irrigation (as classified by FAO) and to evaluate their suitability by RICHARDS and WILCOX diagrams. Indeed, taking into account of this evaluation, results showed that majority of groundwater encountered in alluvial plain (close hydraulic axes) and dune formations are suitable for irrigation (78% of groundwater); excepted in north-western part where groundwater is affected by high salinity (EC above 5,000 µS/cm). Statistical analysis using Ascending Hierarchical Classification, has allowed identify different processes that affect soils degradation.

The results highlight also that soil degradation mechanisms in irrigated areas are mainly due to uprising shallow saline groundwater due to inappropriate management of irrigation water and irrigated land uses. In addition to the situation, irrigation water typology (alkalin) can promote to sodisation/alkalinization phenomena which progress from down to up in soil profiles. This latter kind of degradation can be serious and their restoration can be more difficult. However, if salinization effects are known, knowledge of these mechanisms such as physical and chemical processes, soils mineral constituents' evolution and their transformations remain insufficient for an accurate diagnosis and a risk assessment. In order to better understand the current dynamics of soils degradation, it would necessarily to: assess and rehabilitate water resources management plans and irrigation schemes; address the drainage problems and drainage water management by implementing more efficient irrigation systems and agricultural wastewater collectors (eg Delta Emissary) to minimize water use and reduce deep percolation responsible for salinization; develop lands salinity restoration strategies and monitoring mechanisms in order to prevent the risk of soil degradation under irrigation and to ensure a profitable and sustainable irrigated agriculture in the delta and the lower valley of the Senegal River.

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