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Dynamics and Interactions between Surface Water, Irrigation Water, and Groundwater in the Senegal River Delta

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Abstract The Senegal River delta is located in a semi-arid sahelian zone of West Africa. Due to low pluviometry in the delta, this river is an exceptionally important water resource for the region. The importance of surface water from the Senegal River is elevated more by the fact that much of the groundwater accessible by shallow wells is saline. Salinization in the Senegal River delta originates from marine water invasion, both past and present, into the continent. Marine invasion and even full transgressions have been known to what is now the delta throughout geological history. Evidence of cyclical marine transgressions and regressions go back to the Jurassic, and multiple transgressions have occured in the Quaternary period alone. The main interest of this work is on the hydrogeological aspect of salinization of shallow aquifers in the the Senegal River delta. The objective is to be able to characterize salinization dynamics and the related surface water-groundwater interactions. Identifying mechanisms of groundwater freshening, and to understand the role of surface river water to this end, will be investigated in depth. Irrigated agriculture is not a primary object of study, although it’s presence and impact on groundwater is closely linked and evaluated. To approach the problematic, a combination of multiple monitoring methods was used in the interest of characterizing groundwater salinizationand/River water intrusion in the Senegal river delta. Collection of data for this study was founded onfield work. This included hydrochemical monitoring as well as geophysical profiling over multiple selected sites. Field work was performed during the months of February and March 2016, in the middle of the dry season. Analysis of geochemical and geophysical data collected during the course of this study has brought together strong evidence of river water recharge into the shallow aquifer from the Senegal River delta, and to have dimensioned the sub-surface hydraulic intrusion. The magnitude of intrusion seems to be a function at least of the relative difference in head and of the debit of the surface water that is in closest proximity. In other words, even the most simple hydrodynamic parameters play an important role in the phenomenon. Other factors - geologic, climactic, chemical - have their part. Comparing the data of this study with historical context and data that has been collected over at least the past century has aided in constructing such additional factors controlling water dynamics.

Keywords: *ERT, Fieldwork, alluvial groundwater, salinization, irrigation,hydrogeophysics, Senegal River Delta*

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1. Introduction

The Senegal River delta is a coastal delta located in the semi-arid sahelian zone of West Africa. The delta is host to large-scale irrigated agricultural activity; however, much of the groundwater accessible by shallow wells is saline.

Groundwater salinization in the Senegal River delta originates from marine water invasion into the continent that has occurred in both past and present. Marine invasion and even full transgressions have occurred along the Senegalese coast throughout geological history, with evidence of cyclical marine transgressions and regressions dating back to the Jurassic, and multiple transgressions having occurred in the Quaternary period alone [1-16] In modern times, natural invasions of varying intensity occur on a seasonal basis following from the tropical climate regime. Because of a drought that was established over most of the country from the 1970s to the 21st century, fresh water resources were diminished, and continental marine invasions were likely to intensify. It could be argued that resources have not fully recovered from these water shortages.

The focus of this article is on the shallow, unconfined aquifer system within the delta. This system contains a Quaternary aquifer and an alluvial aquifer, with irregular spatial contact and communication existing between them [1]. This system is found to have an exceptionally shallow water table (< 1 meter in many places). Recent marine transgressions have formed the Quaternary aquifer sediments, including salt precipitates in the soil [16]. The alluvial aquifer was shaped largely by river dynamics, with sediment transport and meander paths leaving a prominent mark. To be sure, recent transgressions have also left salt precipitates in the alluvial sediments. The shallow and saline groundwater is able to travel to the surface of the earth via capillary effect, where waters are then lost by evaporation and salt precipitates are deposited at the surface. This phenomenon often leads to the formation of brines in the aquifer.

Agriculture is practiced extensively in the delta, and has been for millennia. Seasonal rain-fed agriculture was the traditional practice for thousands of years. On the other hand, irrigated agriculture is now the established method, becoming the dominant approach in the 20^{th} century. Currently, the delta and valley of the Senegal River is a region with some of the most irrigated lands in all of West Africa [10]. Major crops include rice (by far the most cultivated), tomatoes, and onions.

Irrigation practices are burdensome to the soil and groundwater - on top of the already existing burden of salinization - and have secured infertile soils for the foreseeable future in some areas due to heavily concentrated dissolved solids in irrigation waters. But irrigation practices have also played a major hand in the move towards food self-sufficiency in Senegal, and are needed for continual and long-term food security in the country. As the population is only forecasted to increase, there is a need for increased crop yield. For the time being, Senegal is a net-importer for food.[10]

Efforts have been made to lower the impact of marine invasion in the delta, including the construction of two multi-purpose dams. These are the Manantali dam in western Mali, near the headwaters of the Senegal river, and the Diama dam in the low delta, on the border with Mauritania. Both were constructed in the 1980s. The Diama dam function is both to stabilize river levels throughout the year, effectively erasing the natural seasonal variations in river head, and to prevent saltwater intrusion upstream. While saline water is still present in the shallow delta, saltwater intrusion has been significantly diminished because of the dam.

The studies of [10] focused on the shallow aquifer and set to define some of the prominent influences on shallow groundwater and salinity dynamics.

Main conclusions by [10] were as follows:

Principal influences on the shallow aquifer are climate, the Senegal River regime, and irrigation. These influences are themselves a function of geography.

The shallow aquifer has a global signature of marine origins, with a strong sodium chloride facies.

Groundwater undergoing strong evaporation tends to evolve from seawater into brines. Groundwater located in proximity to river waters tends to have a softer signature than marine waters, with added influence of Ca and HCO_3^-.

No lasting ionic dilution is observed in and around irrigated parcels, despite large quantities of fresh water being used in these parcels.

For this paper, a primary goal, of studies in the Senegal River delta, has been to determine the extent of salinization and to characterize interactions between river water and groundwater. Specifically, attempts have been made to understand the role of surface river water as a mechanism for groundwater freshening. Irrigated agriculture is not a primary object of study, although it's presence and impact on groundwater has been loosely included in data analysis. Determining relevant causes and effects of surface water-groundwater interactions may lead to more effective management in the future [8,9].

2. Presentation of the Study Area

The Senegal River Delta (SRD) is located in the Saint Louis region of northwestern Senegal, at 260 km from the capital, Dakar. Covering an area of 3500 km^2, it takes the form of a wide low land, limited to the north by the Senegal River, to the west by the Atlantic Ocean, to the east by the Lake Guiers system and to the south by the dunes (Figure 1). With potential irrigated land estimated at 150,000 ha [1], the SRD is an agro-economic area that hosts many agricultural development projects.The climate is of Sahelian type marked by low rainfall (on average 250 mm/year) and a strong evaporation recovery.

The hydrographic network includes the main branch of the Senegal River, which constitutes its northern and northwestern limit and has many drifts [2], the main ones being the Gorom upstream, that takes its source in the village of Ronkh, and the Gorom downstream, which passes through the Djoudji Park. Its two drifts join at the village of Boundoum to give the Lampsar. We also note the presence of Lake Guiers, which is a 300 km^2 depression fed by the river through the Taoué canal. These different branches of the river as well as the lake allow the irrigation of many agricultural areas through a complex system of open canals. The drainage water from these areas is discharged through canals and rejected into the natural depressions of Ndiael, Noar and Krankaye [13].

The geological context of the delta is part of that of the Senegalo-Mauritanian basin, whose formations are described in numerous studies [12,13,14]. The geological formations that outcrop in the SRD zone are mainly composed of quaternary deposits (Figure 2). Indeed, except the Eocene formations that are outcropping around Lake Guiers, the quaternary formations are the most important to understand the relatively recent history, on the geological scale of the SRD [23]. The quaternary is characterized by alternation periods of marine transgressions and regressions that have allowed the installation of 60 meters thick deposits [26].

From a hydro-geological point of view, various studies indicate the presence of three aquifer systems [15-19]: the superficial aquifer represented by the Quaternary alluvial formations and the sandy or clay-sand deposits of the Continental Terminal, the intermediate aquifer of the Tertiary calcareous formations and the deep aquifer of the Maastrichtian sandstone formations. The superficial aquifer of the Quaternary formations that contains the alluvial groundwater is complex and occupies the entire major bed of the river. Schematically, it is described as a single aquifer consisting of two superimposed reservoirs that can be separated, in places, by a discontinuous lenticular clay layer.The upper reservoir is contained in the fine Nouakchottian sands. It can be captive or free depending on the presence or absence on the surface of semi-permeable, clayey layers belonging to the Post-Nouackchottian. The water table contained in this reservoir is generally between 1 and 3 meters under the ground, according to the period of year. This reservoir has an average thickness of 10 meters and is more important in the west (30 meters in St-Louis) than in the east (5 meters in Richard-Toll).

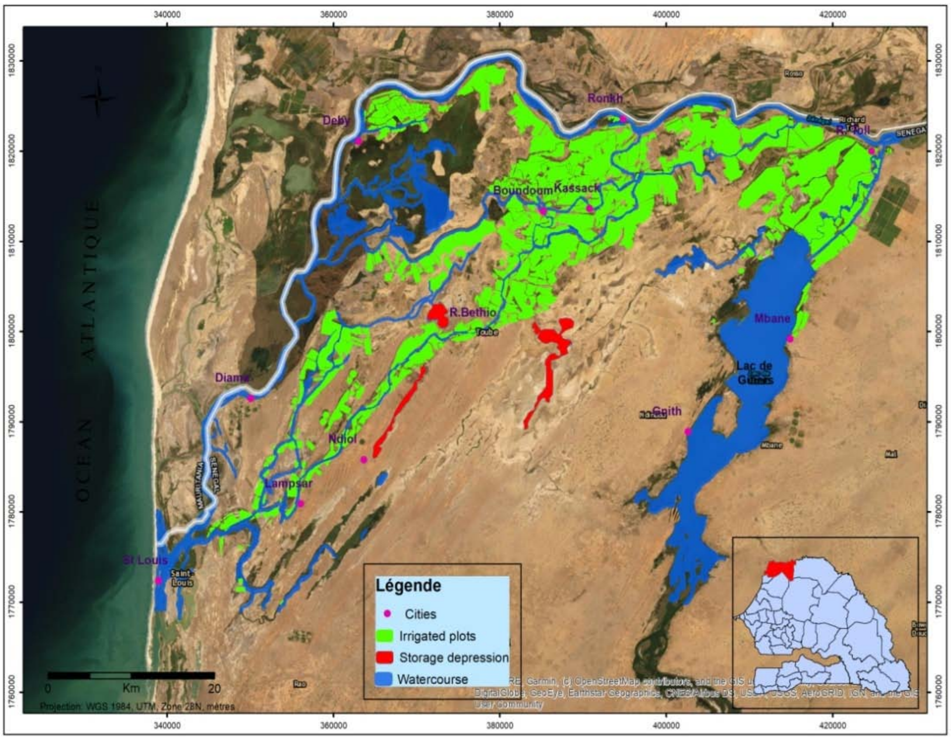

Figure 1. Situation map of the Senegal River Delta

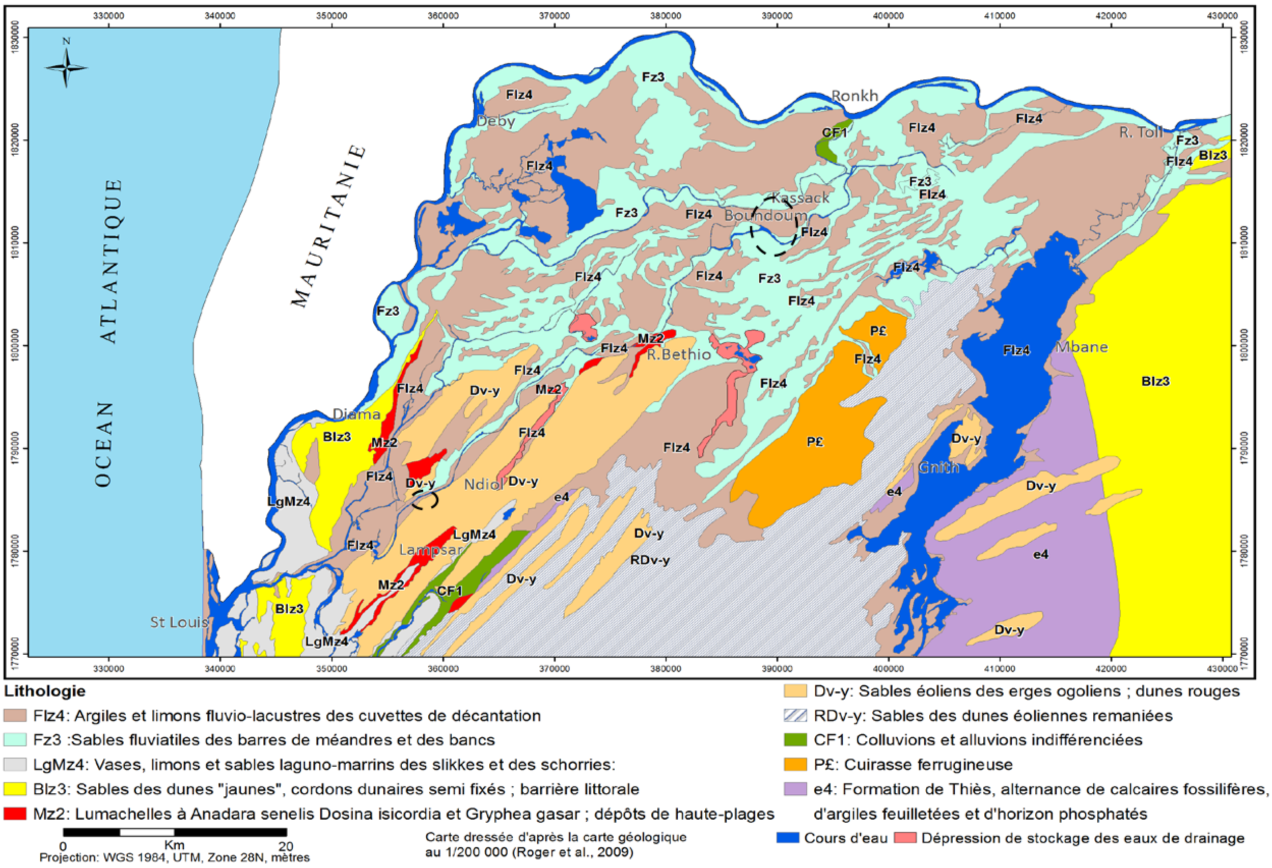

Figure 2. Geological map of the Senegal River Delta, with study sites marked by dashed

The lower reservoir is contained in the medium to coarse sands of the Inchirian. This reservoir can be separated from the previous one by a semi-permeable layer of clay or silt, belonging to the sediments of the Inchirian roof or the Nouakchottian base. The discontinuity of this semi-permeable barrier allows hydraulic communication between the two groundwater in some areas. For hydrodynamic parameters, the synthesis of [20] summarizes the hydrodynamic characteristics of the superficial groundwater as follows: transmissivity (T) varies from 5.5 to 2.5x10 -3 m²/s; hydraulic conductivity (K) from 2x10 -4 to 3x10 -4 m/s and the storage (S) from 5x10 -4 to 2.5x10 -4.

The two monitoring sites constructed for this study are outlined in black-dashed ovals in Figure 2. At both sites, note the presence of sediments labeled "FlZ4", which are fluvial-lacustrine (lakeside) clays and silts making up the aforementioned settling basins. At the northeastern site, near the village of Kassack, there is also significant presence of sediments "Fz3", fluvial sands making up point bars. On site, point bars are recognizable due to their higher elevation (a difference of 0.5 to 1 meter). Clay and silt layers are sometimes encountered below the surficial sands of these point bars. Finally, at the southwest site, near the Lampsar, a boundary with "Dv-y" red sand dunes is approached. It can be expected that these different morphological units will have differing salinity profiles.

3. Materials and Methods

Fieldwork for the most current study was performed during the months of February and March 2016, in the middle of the dry season. Multiple techniques were used in order to characterize the shallow hydrogeological conditions, including field observations, geophysics, and geochemistry [18].

Interactions between fresh surface water and saline groundwater are assumed to occur around the numerous tributaries and distributaries in the delta as well as around the Senegal River itself. Three sites were chosen for this study, located in two areas – Kassack and Ndiaye. The locations of these areas are positioned in Figure 2 found, along the Gorom Upstream and Kassack distributaries, and along the Lampsar distributary. The choice of experimental monitoring sites for this study aimed to meet the needs for better understanding the groundwater-surface water interactions around the river.

Each monitoring site was set up with piezometers installed along a linear axis perpendicular to a surface water source. This configuration aimed to create a cross-section of the groundwater profile from riverside to inland. Each site differs in expanse, in proximity to surface water, and importantly in the surrounding physical environment.

3.1. Piezometer Installation

3.1.1. Kassack 1 and Kassack 2

Figure 3 gives a satellite image of the area considered at both Kassack 1 to the west and the more extensive Kassack 2 to the east. Kassack 1 and Kassack 2 are separated by approximately 3 kilometers. Both lie along the Gorom Upstream, but as shown in the satellite image, the Kassack 2 site also crosses over the Kassack distributary.

Kassack 1 is the smallest of all study sites with a total length of 150 meters from first piezometer to last piezometer, and a length of 200 meters for an ERT profile. There are dry irrigation canals and an out-of-use water pump on site.

Kassack 2 extends over 5 kilometers and traverses land of mixed use, as can be seen in the satellite image (Figure 3) of Kassack. An irrigation pump is located on the Gorom Upstream close to the riverside piezometer and was active during the entire timeframe of the study. A large primary canal at the site was filled by the pump, and was punctually included in field conductivity measurements. Three piezometers from the Kassack 2 configuration are also near secondary irrigation canals and active irrigated parcels, both of rice fields and onion fields (implementing different methods of irrigation).

Figure 3. Localization of piezometers installed at Kassack. Variable land use and distance from river distributary is visible. Satellite image via Google Earth

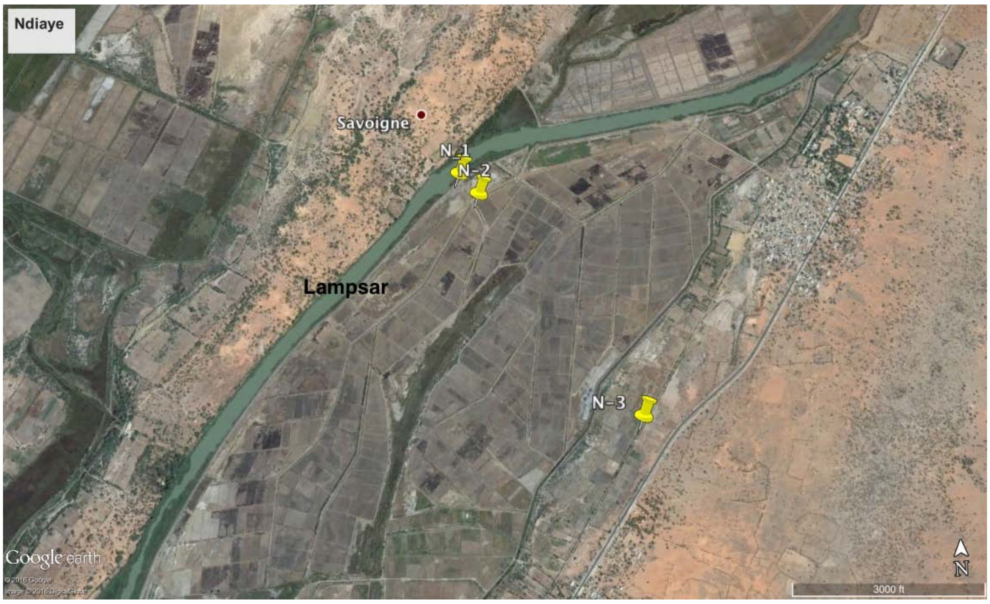

Figure 4. Localization of piezometers installed at Ndiaye. Variable land use and distance from river distributary is visible. Satellite image via Google Earth

3.1.2. Ndiaye

A third site is located at Ndiaye in the lower delta, near the Lampsar distributary (Figure 4). The Lampsar has a riverbed that is considerably wider than that of the Gorom Upstream.

Ndiaye is located within an alluvial settling basin, and is a site that has long been dominated by irrigated perimeters. Many sites that were observed were parcels of onion fields, receiving non-submersive watering once a week. The study site in particular extends over approximately 1.5 kilometers, and includes primary, secondary, and drainage canals in proximity to the piezometers. Fields all along the Ndiaye study zone were active for the entire duration of monitoring.

A total of 11 new piezometers were installed over the span of 5 days at the end of February 2016. 3 piezometers were installed at Kassack 1, 5 piezometers were installed at Kasack 2, and 3 piezometers were installed at Ndiaye. Nomenclature as follows: **KN1 - KN3** and **KN4 - KN8**, and **N1 - N3**, respectively.

Piezometers were drilled using a manual auger with an advancement tube. All were drilled to approximately 6 meters (between 5 - 6 m) depth, with screening between 1.5 - 5.5 meters depth, inclusive. PVC piping was used to secure the boreholes. At Kassack 1, piezometers were installed at 50 meter intervals. K1 lies approximately 35 meters from the Gorom Upstream and is considered a riverside piezometer. KN3 is located approximately 180 meters inland.

The five piezometers installed at Kassack 2 were placed at increasing spatial intervals, from 100 meter to 3 kilometer spacing. KN4 is located within 20 meters of the Gorom Upstream and is thus considered a riverside piezometer.

Finally, N1 lies within 15 meters of the Lampsar and is a third riverside piezometer. N2 is at a crossroads of secondary irrigation canals (and thus irrigated parcels), and N3 is located inside a parcel that was in a preparation phase for cultivation. N3 was located within 30 meters of an active onion field.

Previous studies have identified up to three or four classes of piezometers from different areas in the delta in order to better organize the analysis [10]. These have included classes of piezometers that are far inland and outside of irrigated zones, piezometers that are located along the river, and piezometers located in an irrigated parcel. In a very loose manner, the classifications in this study largely include what will be defined as riverside piezometers and inland piezometers. Irrigation-impacted piezometers are an additional class to consider.

Table 1. Distance from Kassack 1 and 2 piezometers to proximal distributaries. Measured with Google Earth

Piezometer	d_{gorom} [m]	$D_{kassack}$ [m]
KN1	35	2066
KN2	90	2010
KN3	150	1960
KN4	10	3300
KN5	200	3000
KN6	700	2600
KN7	2050	1600
KN8	5450	1600

Table 2. Distance from Ndiaye piezometers to the Lampsar distributary Measured with Google Earth

Piezometer	$D_{lampsar}$ [m]
N1	25
N2	160
N3	1550

The distances from each piezometer to a respective body of surface water are noted in Table 1 for the Kassack sites and Table 2 for the Ndiaye site. Distances were measured using Google Earth, with error of ±5 meters. As a rule of thumb, piezometers within 50 meters of riverside may be considered as riverside piezometers. Piezometers more than 50 meters of riverside may be considered as inland.

In all boreholes, both at the Kassack sites and at Ndiaye, the quaternary aquifer matrix in the saturated zone appears to converge with depth to near-homogeneity, over the entire study region. The aquifer evolves into grey siltysandy layers, with some areas showing evidence of oxides. Otherwise, each borehole differs only in the ratio of sands to silts at depth.

Four previously existing piezometers were included in the monitoring network: piezometers 119 and 120, which are several kilometers to the south of the Kassack distributary, and piezometers P3 and P4, located within irrigated parcels at Ndiaye, close to the N2 piezometer drilled during the current study. 120, P3, and P4 are screened into the same aquifer as the piezometers installed during this project, while 119 is screened into the limestone aquifer of the Eocene.

3.2. Geophysics

The electrical resistivity tomography (ERT) are utilized to characterize a salinity profile within shallow aquifer. Contrasting resistivity (or equally conductivity) of fresh and saline waters can be exploited to locate the horizon of each body [24,25]. ERT measurements can provide a 2-dimensional vertical resistivity tomography into the subsurface [3,4].

Two of the three sites - one at Kassack 1, one at Ndiaye - were chosen for geophysical surveys, with both methods being utilized at each site. ERT surveys were carried out in parallel and in proximity to the piezometer setups so that results could readily be compared to hydrochemical data. With this configuration, a simplifying assumption is made that the resistivity profile is constant in the direction parallel to the riverside (perpendicular to the profile). The shoreline is in fact not even close to being linear, so this assumption may only be held to a very local scale.

One ERT profile of 200 m was carried out at each site

Schlumberger arrays were used for the ERT profiles at Kassack and at Ndiaye. This array offers relatively strong vertical and horizontal resolution, with a good signal strength, and a depth of investigation (DOI) generally exceeding 20 meters.[17] For our surveys, the potential electrode separation a was set to 15 meters while current electrodes were placed 95 meters from the corresponding potential electrode, with n = 6 meters. The entire survey spanned 200 meters with 5 meter spacing between electrodes. While neutral silicate materials make up the bulk of the solid phase, the presence of clays, evaporites, and small quantities of iron oxides may have a non-negligible impact on the common assumption that the rock matrix is an insulator. Quality of data was assessed using a Res2DInv software built-in resolution parameter [6].

3.3. Hydrochemistry

With a proper chemical analysis, saline waters (sea water) are discerned from fresh waters, and a salinity flux can be traced to depict a spatial evolution. An attempt to discern the precise origins of the present salinity (modern intrusions, fossil waters, dissolution of ancient marine salt precipitates) is made. Quantifying the magnitude of salinity is rather straightforward, but flow properties and the determination of origins requires a more in-depth analysis.

Geochemical data collection included multiple tasks:

Regular measurements of temperature, pH, and conductivity from every piezometer in our monitoring network, using a CyberScan series 600 multiprobe, along with groundwater levelling. Surface water (distributaries, primary irrigation canals, secondary irrigation canals) properties were also sporadically measured.

CTD divers installed in piezometer KN1, 20 meters from the Gorom Upstream riverside, and piezometer KN8, 2.3 kilometers inland, to allow for continuous chemical monitoring in two different environments.

Water samples collected from piezometers for testing in the ULg geochemistry laboratory.

In total, multiprobe data was collected over a period of three weeks. In theory, it is assumed that the water measured is coming from the top of the groundwater column, though it should be kept in mind that piezometer installation and groundwater mixing in a more open space (inside the piezometer) might have an important impact on the vertical salinity flux at a given point. Water in the piezometer column may have self-redistributed according to density, so that the most concentrated saline waters fall to the bottom of the column, and the freshest waters remain at the top. After some weeks, an important amount of mixing between any different water bodies could occur in the column.

CTD divers were installed on March 9. A baro diver was installed in KN1 along with one of the CTDs, and the pressure data collected from this baro was considered relevant for the CTD diver in KN8. The diver installed in KN1 was set at a depth of 4.21 meters, and the diver installed in KN8 was at a depth of 2.25 meters. Both of these are considerably greater depths than the measurement level with the multiprobe.

For the last field outing on March 27, water samples were collected from all of our installed piezometers, as well as from P3, P4, 119, and 120. Piezometers were not pumped before collection. Samples were filled to ensure a minimum of contact with atmosphere, but underwent extreme change in temperature and pressure when transported from the subsahara to northern Europe. These samples were measured at the University of Liège, nearly three weeks after collection. Only one sample was collected from each piezometer due to a limited number of available sample jars.

4. Results and Discussion

4.1. Hydrogeophysics

Results from both ERT profiles were of good quality and are useful. Topography was ignored for these models, as the terrain relief is predominantly flat (less than 1 meter over the length of both ERT profiles).

4.1.1. ERT at Kassack

To evaluate the quality of the resistivity results, specifically to what depth the resulting model is relevant, the resolution parameter is used. This parameter is calculated with Res2Dinv.

Figure 5 and Figure 6 show the Kassack model as blocks, with removal of all cells below a resolution threshold of 0.02 A commonly used cutoff value is 0.05 [17-22], though with a refined mesh, the cutoff value should also be refined.

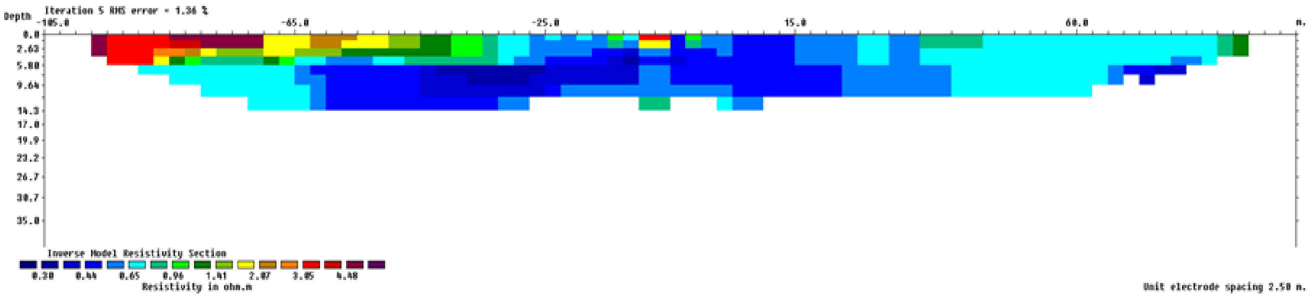

Figure 5. Inverted Kassack model with removal of cells with a resolution value lower than 0.02

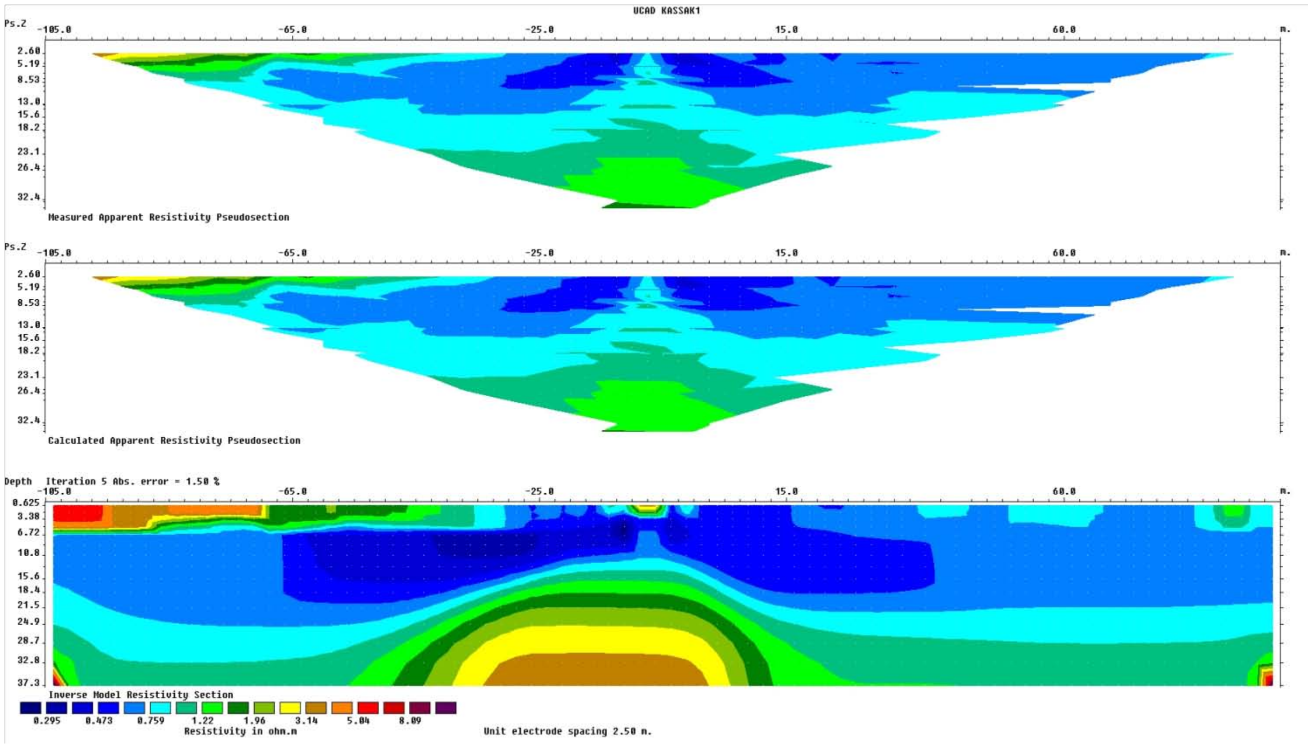

Figure 6. Least squares finite difference inversion of ERT profile at Kassack 1 using an extended model. A distinctive increase in resistivity is observed to the left (corresponding to the riverside end of the profile) of the inverted model

In Figure 5, the intruding resistive lens on the riverside is visible so that its existence is certified. The existence of the resistive body in the center of the tomography at depth is less certain. A resolution cutoff of 0.02 removes this depth from the model. As this depth of the subsurface is not necessarily of direct interest for this project, this is not an issue.

The cut model suggests that there exists a factor which has somewhat compromised the depth of resolution. Where some terrains might offer 30 meters or more of resolution, with the resolution parameter apparently only 15 to 17 meters are offered. This may be due to the low resistivity values overall, and the contrasting values located at the surface. It should also be noted that the resolution cutoff might be overestimating the depth to which data may no longer be trusted in comparison to the DOI index.

The ERT data from Kassack was inverted with a refined mesh, using a model cell width of 2.5 meters. A 'fine' mesh was chosen in order to optimize the treatment of relatively large resistivity variations near the surface. The tradeoff is a superficial numerical 'rippling' effect that might be observed in some areas.

Kassack profile inversion results are given as an extended model in Figure 6, with resistivity values corresponding to this model given in Figure 7 (due to the low readability in the beginning image). The resulting model is of good quality and nicely represents what was hoping to be found. The number of iterations chosen was 5, from which a satisfactory and relatively stable RMS error was obtained. Between 4 and 6 iterations, the RMS error deviated by 0.35%. An extended model was chosen to limit numerical boundary effects.

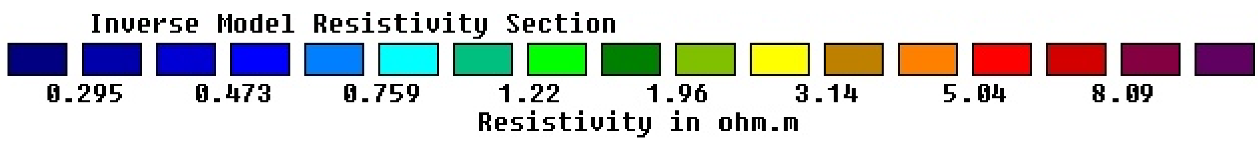

Figure 7. Resistivity values corresponding to the calculated model in Figure 6

In this tomography, the position labeled at -105.0 meters is located along the riverside, whereas the position labeled at 95.0 meters is inland. Each tick mark counts 2.5 meters. Piezometer KN1 is located between the electrodes at -85 and -80 meters, and KN2 is located next to the electrode at -25 meters. Finally, KN3 is located at +30 meters.

With knowledge on the local geology and other subsurface conditions, and with information gathered from the synthetic model that was previously constructed, it is nearly certain that the high-resistivity lens at the top left of this tomography results from an intrusion of river water from the Gorom Upstream. Nevertheless, this freshwater recharge is limited in depth and in impact. These readings alone suggest that intrusion in the region does not surpass 7 meters depth before a sharp boundary is encountered and the model becomes highly saline. In addition, the word ‘fresh’ in this context is extremely relative. Water at 5 Ω.m is still not suitable for human consumption or agricultural use.

The small resistive body detected in the upper middle portion of the tomography could be the result of one of several sources. It could be water that invaded from the river several months before, which has not been able to evacuate due to physical geological barriers. It could also be simply a numerical artifact, as it is located directly between our two potential electrodes in the middle of the profile. In any case, it is difficult to define with certainty the source of this resistive point.

Resistivity in this section does not attain even 10 Ω.m. Knowing that the water table is located at approximately 1 meter depth, it is assumed that the aqueous phase dominates the resistivity readings. In addition to this argument, noting that the resistivity of seawater is in the environs of 0.35 Ω.m, this model suggests that this area is less saline than seawater, which is in agreement with hydrochemical data presented below. Increased resistivity may also be due to the rock matrix. The highest resistivity measured in the shallow zone is approximately 5 Ω.m, or 0.2 S/m conductivity, and the lowest resistivity is at approximately 0.3 Ω.m, or 3 S/m conductivity.

4.1.2. Ndiaye

The resolution parameter has been used once again to evaluate the quality of results at depth for the Ndiaye profile.

Figure 8 shows the inverted Ndiaye model as blocks, with removal of all cells below a resolution threshold of 0.02. The intruding resistive lens that represents river water intrusion is preserved, for the most part. In the case of both cutoff values, depth is substantially compromised, probably due to the extensive resistivity variations occurring at the surface. In the end, it is presumed that data quality is acceptable at least up to 10 meters, and possibly up to 20 meters.

Again, use of the actual DOI index may give evidence of qualitative data further down than 20 meters into the subsurface.

As with the Kassack data, the Ndiaye dataset was inverted with a refined mesh in order to optimize treatment with large resistivity variations. Figure 9 is the inverted, extended model from data gathered at Ndiaye, with the Lampsar riverside close to meter -105. The RMS deviated by 0.42% between iterations 4 and 6 [11].

Similar to the Kassack profile, there is a large resistive body on the riverside of this profile. It is assumed that this body represents river water intrusion from the Lampsar. Assuming this case, it appears that the intrusion at this site has both larger dimensions and a larger magnitude than was observed at Kassack. If the hydrodynamics of the Lampsar distributary versus the Gorom Upstream is accounted for, this is not surprising. The Lampsar has a larger riverbed and a faster flow rate, and the Gorom Upstream is additionally weighed down by invasive plants, especially at the riverside in the water. It is feasible that water penetrates at much greater rates from the Lampsar to inland.

A second high resistivity body is observed at the 15-meter mark. This coincides with an area where the profile intersected the terminus of an irrigation canal, and not far from an irrigated onion field. The high resistivity is assumed to be a result of penetrating irrigation waters.

The very low resistivity body below the presumed irrigation field is of concern. It is unlikely that this would be a numerical artifact due to its extension and contrast in value. Irrigation waters may be pushing salts and saline waters further into the subsurface, or it is possible that some of the ions are coming directly from the irrigation waters. It has been seen that complex ionic exchanges are evolving around irrigated rice fields in the delta. [5]

The background resistivity of this profile is generally slightly higher than the background resistivity at Kassack, suggesting that the water is slightly fresher in this zone. This is likely due to a stronger output from the Lamspar.

It should be noted that, due to the density of irrigated fields in the vicinity of the profile carried out at Ndiaye, the theory that the subsurface resistivity profile is constant in a direction perpendicular to the profile is weaker, and some of the bodies to the right side of the 0 meter mark may have influence from variable resistivity profiles around these zones.

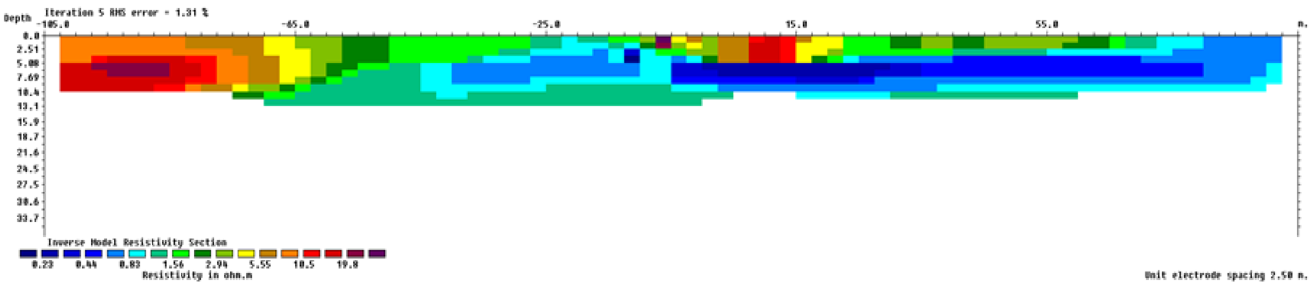

Figure 8. Inverted Ndiaye model with removal of cells with a resolution value lower than 0.02

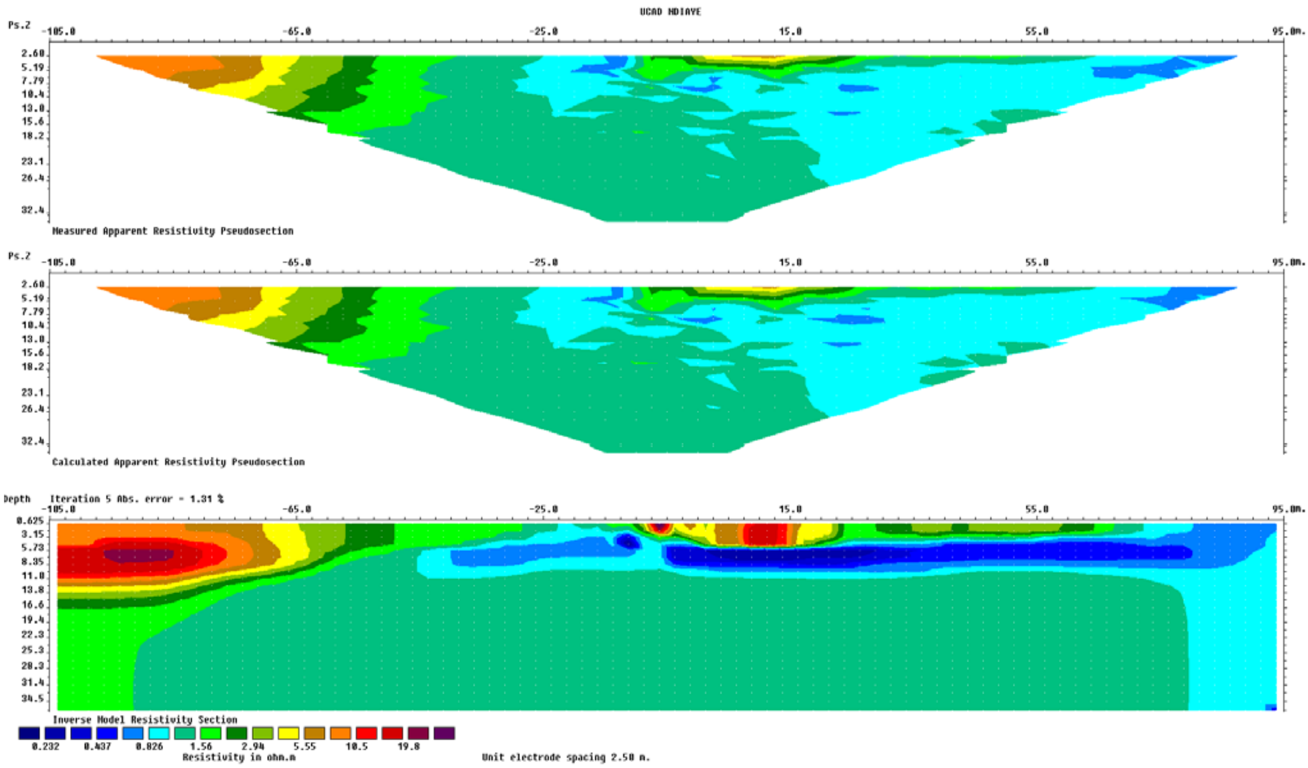

Figure 9. Least squares finite difference inversion of ERT profile at Ndiaye. Similar to Kassack, a zone of increased resistivity is observed to the left on the riverside

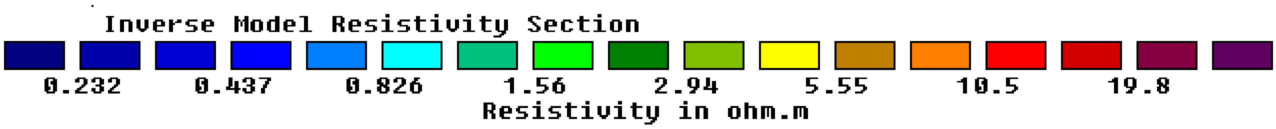

Figure 10. ***Resistivity*** values corresponding with Figure 9

4.2. Hydrogeochemistry

Hydrochemical analysis begins with the data gathered from our field multiprobe. Laboratory chemical analysis, discussed afterwards, verifies the ionic characteristics of the groundwater.

Conductivity, along with pH and temperature of tested waters, measured in the field with the multiprobe, renders a preliminary grasp into the chemical state of the groundwater in the delta. The data obtained from field measurements allowed us to quantify the level of salinity over each site in real-time.

A first scan of the multiprobe results - averaged over 5 weeks of rather stagnant data - in Table 3, and a trend in groundwater conductivity magnitudes is immediately evident.

Every groundwater point measured is salinized. Nonetheless, the electrical conductivity measured at each riverside piezometer is at least an order of magnitude less than even its closest inland neighboring piezometer. The weakest conductivity is measured at N1 along the Lampsar, with a value of 3258 µS/cm. To note as well are the remarkably high conductivity values at KN3, KN7, and P3, all of which are higher than 50000 µS/cm.

Another point from this table is the magnitude of groundwater temperature. Temperatures are much higher than what is commonly found in northern climates with less sun. Groundwater temperature should bring into question the thermodynamics of ionic reactions in the subsurface. However, it is difficult to identify invasive river water in the aquifer with the assumption that surface water would be cooler than groundwater. While KN1 and KN4 have relatively low temperatures, N1 groundwater is quite warm.

Figure 11 and Figure 12 offer spatial representation of the average field conductivity measured over the span of our six-week study. These simple graphics clarify a trend of increasing salinity from riverside to the inland points.

Table 3. Results of multiprobe field measurements in groundwater. Values collected during the monitoring period have been averaged, as they remained stable during the time of study.

Piezometers	Temperature	pH	Conductivity (µS/cm)	CTD (µS/cm)
KN1	27.1	6.6	8128	45439
KN2	27.3	6.3	37332	
KN3	28.0	6.4	66273	
KN4	26.6	6.8	6223	
KN5	27.6	6.4	36019	
KN6	26.8	6.4	32592	
KN7	28.7	6.4	51045	
KN8	29.4	6.5	30080	36120
N	30.7	6.6	3258	
N2	29.3	6.5	34155	
N3	30.5	6.4	34773	
P3	29.1	6.1	70560	
P4	28.7	6.4	4540	
120	28.6	6.4	2365	

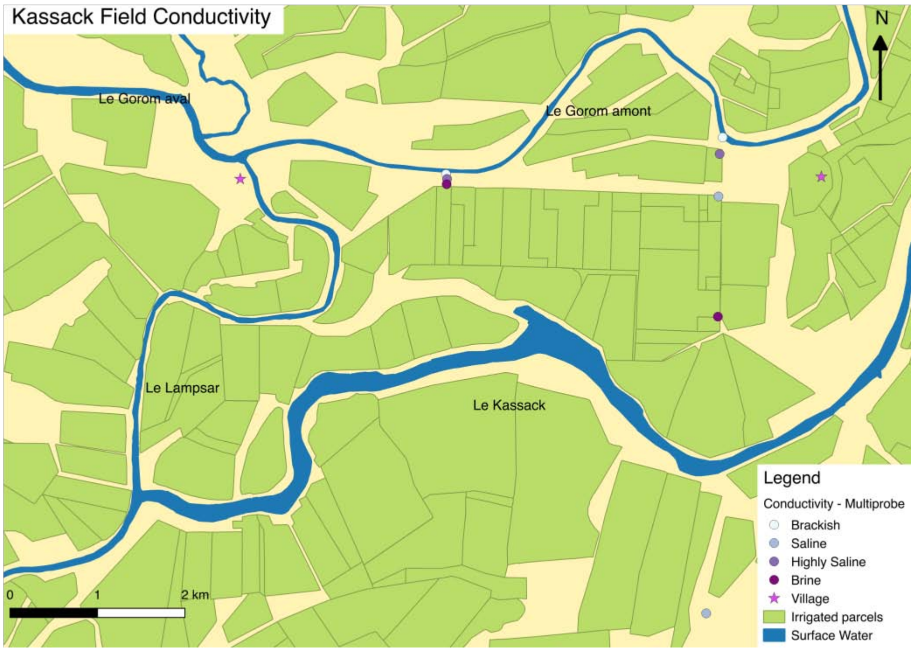

Figure 11. Averaged measurement of groundwater conductivity multiprobe data. Conductivity remained rather stable at each point for the duration of monitoring

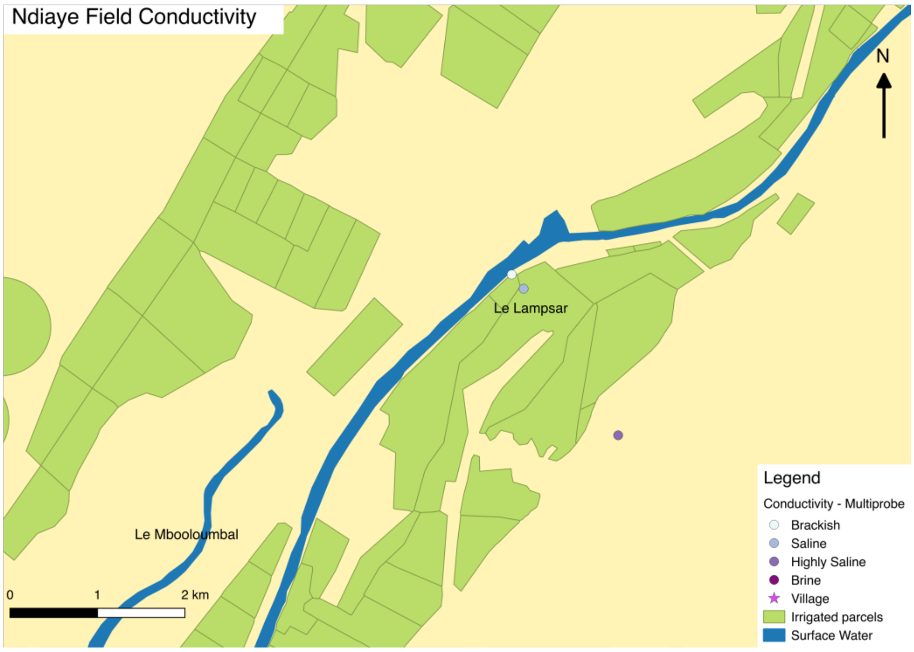

Figure 12. Averaged measurement of groundwater conductivity multiprobe data. Conductivity remained rather stable at each point for the duration of monitoring

The riverside piezometers at Kassack 1, Kassack 2, and Lampsar measure brackish waters, which is the lowest salinity class encountered in the delta. Brackish was detected exclusively at riverside piezometers and piezometers located in irrigated parcels. All inland piezometers were categorized as 'saline' at minimum. Brines were detected at multiple points.

Recalling Figure 2, note that the majority of the piezometers are located in settling basins with a fine granulometry that limits the surface porosity. Piezometers located on the riverside may be in a sandier environment, but this zone is almost certainly affected by the annual river 'crue' and thus rinsed semi-regularly. Only one piezometer is located in or near the red sand dunes, which are generally brines.

What should take one's attention is that the rate of salinity evolution is not equivalent from site to site. It is found at Kassack 1 that the groundwater seems to evolve from brackish to brine in a space of 200 meters. At Kassack 2, over 200 meters it is found that water evolves from brackish to highly saline, and a slight decrease from highly saline to saline waters further inland. Only KN7 is measured to be brine, while KN8 is saline. KN8 is across the Kassack distributary and also located on a point bar. The complex salinity pattern at Kassack 2 is also very likely to be influenced by irrigation practices, most notably by the large primary canal and running pump on site. There are no irrigation practices in proximity to the Kassack 1 site.

The salinity increase at Lampsar is lighter than either profile at Kassack. This is likely due both to the important flow rate of the Lampsar distributary, and to high density of irrigated parcels. N3 is located at a border with red sand dunes, which are generally more saline than settling basins because they are isolated from the annual river ‘crue’ or recharge. Salinity is likely diluted at N3 in the shallow subsurface because of irrigation water recharge.

4.2.1. Water Column

The data collected from the multiprobe, as well as water samples collected for laboratory measurements, represent the conditions at the top of the groundwater table. These data are of extreme necessity for the purposes of this study, but do not give any significant information on groundwater chemistry at depth within the shallow aquifer. What is the salinity profile of the alluvial aquifer at 5 meters depth, 10 meters depth, or even 20 meters depth. While a 2D profile is offered with the ERT profiles, the only hydrochemical data from this study that is available at depth is from the CTD divers, principally at KN1.

The two divers placed at Kassack were installed at differing depths below the water table, somewhat haphazardly. This meant that on the average, the KN1 diver is immersed more than 1 meter below the water table, whereas the KN8 diver is immersed less than 1 meter below the water table. Figure 1é reports the average conductivity measured at KN1 and KN8 with the CTD diver. Notably in KN1, the conductivity measured via the CTD diver is much higher than that measured with the multiprobe.

It has been noted previously by [20] that across the delta, the water salinity found in the alluvial and other shallow aquifers tends to increase quickly with depth, giving a more sharply defined interface zone, although the phenomenon is not homogeneous. Comparison of CTD diver data with hydrochemical multiprobe data gave evidence for this type of salinity increase:

KN1, a riverside piezometer, has measured a relatively low conductivity with multiprobe data. The CTD diver at depth in this piezometer gives measurements in the neighborhood of 44000 µS cm, nearly five times higher than measured by the multiprobe (approx. 8000 µS/cm).

KN8, an inland piezometer, is measured to have a high conductivity and is saline. The CTD diver in this piezometer still gave measurements of a mildly higher conductivity at a slight depth, measuring 30000 µS/cm.

This data leads us to believe that vertical groundwater salinity evolution is more dynamic along the riverside than it is farther inland. It also suggests that the salinity interface is encountered much closer to the surface than suggested from ERT data. However, the water column in a piezometer is not necessarily at the same equilibrium as would be found in a sandy aquifer. Within the piezometer, water will be more systematically vertically organized as a function of density. Forcibly, the least dense waters will float to the top of the piezometer water column, and the densest will sink. This should be a major consideration when analyzing all hydrochemical data presented here.

4.2.2. Ionic Characterization

Ionic measurements of water samples were carried out at the University of Liège Geology Department. It was found that the majority of groundwater samples from the current campaign were oversaturated in cations. Riverside piezometers and piezometers located in proximity to irrigated fields had ion concentrations significantly weaker than those of inland piezometers.

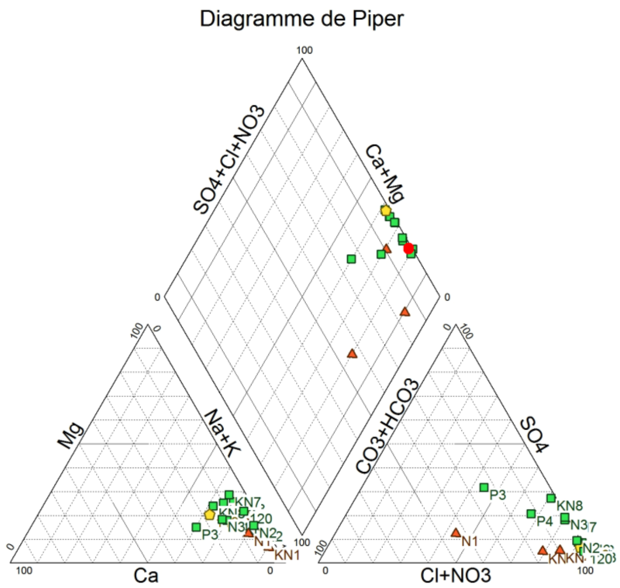

Figure 13. Piper diagram of groundwater samples collected for this study, including seawater facies for comparison. The **red circle** denotes seawater, **Green squares** are inland piezometers, **orange triangles** are riverside piezometers (<20m from surface water), and the **yellow pentagon** is from piezometer 119 that captures an aquifer below the quaternary.

Figure 13 is a Piper diagram constructed from the results of the water sampling campaign. For all points included at the Kassack and Ndiaye sites, a general classification of riverside piezometers (>40m from surface water) and inland piezometers (<40m from river water) was used. A third class includes piezometer 119, which is implanted into the Maastrichtian aquifer.

All of these sites are found to have water of a dominant sodium-and-potassium-chloric nature, and a strong Na-Cl facies. Some points show a tendency towards facies of Ca/Na-HCO3 and Ca/Na-Cl.

Points that ‘deviate’ from a strong signature of NaCl are KN1, KN4, N1, P3, and P4, in other words, all riverside and irrigation piezometers. P3 and P4 are slightly more ‘acidic’ due to their location inside irrigated parcels. In general, a glance at the measured concentrations of ions brings attention to Mg^{+}, K^{+}, HCO_3^{-}, and $SO2_4^{-}$ in addition to Na^{+} and Cl^{-}. Higher HCO_3^{-} concentrations signify that rain water - or other fresh water sources - recharge is probably affecting that given zone in a notable way. [7] Piezometer N1, for example, has a relatively fresh signature. N1 is in close proximity to irrigated fields of mixed cultures, and is also implanted within 10 meters of the Lampsar distributary, which is one of the largest distributaries in the delta, with an important surface flow rate in comparison to such other distributaries as the Gorom Upstream or the Kassack. These important features of the Lampsar are the probable reason for the relative freshness found in N1.

A more subtle detail from the Piper diagram is that all riverside piezometers are poor in Ca^++Mg^+ concentrations compared to results from inland piezometers. It has been proposed that since Ca^++Mg^+ is only present in the groundwater of the delta and not the river water, the diminution of their concentration in a piezometer is another testimony to river water (or irrigation water) intrusion at the riverside. [10] Relative Ca^+ and Mg^+ concentrations suggest a cation exchange with the rock matrix, which requires a certain residence time of saline waters in the aquifer in order for these exchanges to occur. Calcium and magnesium presence in the sediment is relatively weak, but is significant in that it means that sodium that adsorbs into the rock matrix can lead to a release of calcium or magnesium into solution in exchange.

P4 and P3 are relatively rich in Ca^+ and Mg^+ probably as a result of ions carried from irrigation waters. These two piezometers are very ionized, although their ionization is more diverse than in piezometers outside of irrigated areas.

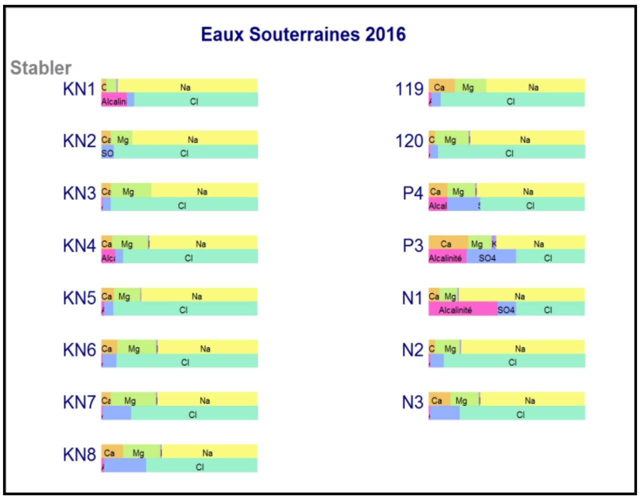

Figure 14. Stabler diagram of groundwater samples highlights the deviation of facies measured in KN1, KN4, N3, and N4

The Stabler diagram in Figure 14 offers more evidence on the dominant facies measured in groundwater, representing water types which are classed by location. There is an increase in alkalinity (HCO_3^-) in all piezometers classified as riverside as well as those located in an irrigated parcel. On the contrary, alkalinity is highly suppressed in all other piezometers. In addition, presence of a SO_4^{2-} facies seems to show itself in the P4 and P3 piezometers, as well as in N1 and KN8. This acidity is likely to correspond to location in agricultural parcels as well as low-topography zones, where gypsum dissolution may be occurring.

Other reactions involve magnesium, which is present in all piezometers, as well as sulfate. Magnesium may also be of marine origin as it is commonly found in ocean waters, and the same is possible for sulfate [10]. The fact that these minor ions are significantly present regardless of the piezometer location suggests this fact.

5.2.3. Ion Correlations

Binary relations help to determine ionic correlations as well as apparent origins of the ionic activity. The most relevant relations for the present interest would be Na/Cl binary diagrams. Na/Cl ratios of marine waters and of waters containing pure halite dissolution have been established. From these relations, follow-up reactions such as brine formations can be defined.

With an R^2 = 0.99, it is certain that these two ions are strongly correlated in the tested environment. There is very little deviation from a net linear relation between points.

Nevertheless, the deviations that do exist from a perfect linear relation are significant [21].

Note from [10] that pure marine waters exhibit a Na/Cl ratio of 0.86, and a ratio of 1 signifies that salinity is a result of halite dissolution as the reaction is ideally in perfect ionic balance. Otherwise, a Na/Cl ratio between these two values represents a mixing of the two phenomena. A ratio greater than 1 may indicate cation exchanges between saline groundwater and the aquifer matrix, as seen by an enrichment of Na+ in solution, or more rarely, a dissolution of silicate minerals. A ratio less than 0.86 indicates evaporation of marine waters and evolution into brines. It has been previously found that many groundwater measurements in the delta display an Na/Cl ratio less than 0.86.

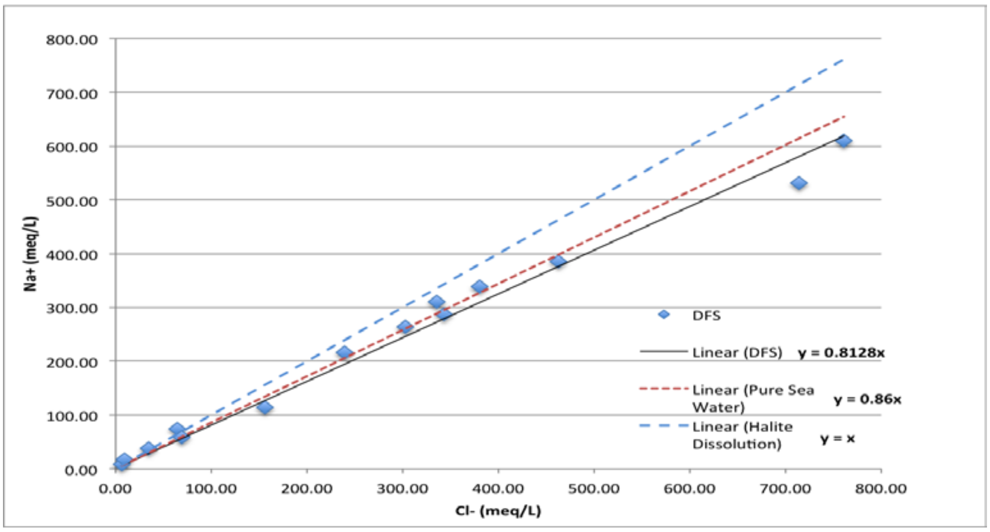

Figure 15: Na/Cl binary diagram with definition of ratio boundaries that define origins of NaCl

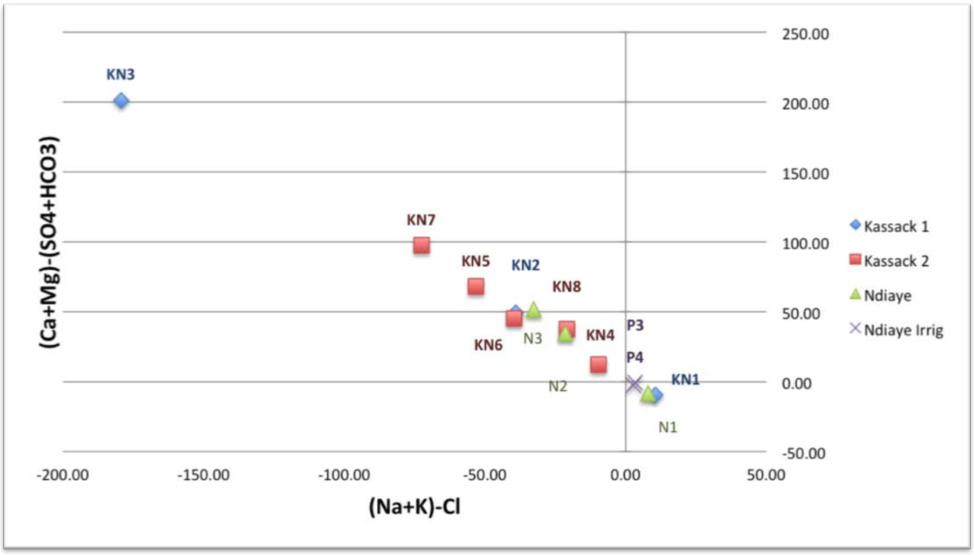

Figure 16. Summary graph of ionic correlations measured in the Senegal River delta

Figure 15 represents a binary Na/Cl graph with a linear regression defined at the origin and fit to our data, as well as the linear trends of Na/Cl = 0.86 and Na/Cl = 1 for comparison.

The trend for the group of data points sampled in these images falls below the 0.86 mark, which would confirm, once again, that brine formation is regularly occurring in the groundwater. However, only half of individual sample points fall below the mark of 0.86. There are also an interesting number of samples that appear to be more-or-less in line with marine waters. Notably, all riverside piezometers are found with a Na/Cl ratio greater than 1 except for KN4, which has a ratio of 0.86 exactly. P4 and P3 also fall into this camp.

Going further, other piezometers which have Na/Cl ratios greater than 0.86 are very far inland - KN7, KN8, and N2 in particular. Two possibilities: one being that halite dissolution is complementing marine salinity, which is a perfectly possible occurrence at inland points, and another being that all of these points are located in settling basins with higher clay content and therefore with higher ion exchange rates.

This simple analysis brings in to evidence the near certitude that a large portion of saline groundwater in the delta is of direct marine origin. The trends on display in this analysis also suggest a spatial element in salinity origins. Riverside locations are likely to contain less marine water and more salinity due to evaporite dissolution.

Figure 16 offers a summary of ionic correlations and substitutions that were measured from samples in the delta.

5. Conclusion

Analysis of geochemical and geophysical data collected during the course of this study has brought forth strong evidence of river water recharge into the shallow aquifer in the Senegal River delta. The magnitude of intrusion seems to be a function at least of the relative difference in water levels, and of the flow of the surface water that is in closest proximity. Comparing the data of this study with historical context and data that has been collected over at least the past century has aided in identifying such additional factors controlling water dynamics.

General forms of freshwater lenses existing in the subsurface around the river have been decrypted, most notably with ERT surveying.

The extreme salinity that is present in these terrains is troublesome, especially when facing the hard fact that the present agricultural activity needs to continue to grow in order to support a growing population. Solutions to such a quagmire do exist; it just takes finding the right balance of technologies. Irrigation in itself has opened thousands of hectares up for activity, parcels that would otherwise be dead lands. Finding the most sustainable solution for these issues is the end game.

In essence, as long as the Senegal River delta remains an important area for agriculture, the dynamics of salinity in the shallow aquifer system should continue to be monitored.

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