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Nitrate Pollution of the Thiaroye Aquifer in the Suburban Parts of the Dakar Region, Senegal.

Using Chemical and Stable Isotope Analyses to Identify the Sources of Nitrate and the Processes at the Groundwater/Surface Water Interface.

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Geotechnology
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We herewith confirm to collaborate on the following master project and master thesis:

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Involved students: Mrs. Vibeke Brandvold, Master student at NTNU, Norway.

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Other collaborations: NGO urbamonde Geneva/Dakar (Cyril Royez, Djibril Diallo, Papa Ameth Keita), Univ. of Dakar (Dr. Seydpu Niang, Prof. Seringue Faye).

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Lausanne, 15/10/2012

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Abstract

The current report, with the title *Nitrate pollution of the Thiaroye aquifer in the suburban parts of the Dakar Region, Senegal – Using chemical and stable isotope analyses to identify the sources of nitrate and the processes at the groundwater/surface water interface*, constitutes the master thesis of Vibeke Brandvold. The thesis is made up by a total of 102 pages + appendices and was written in the 2013 spring semester.

Flooding is a major problem in the departments of Pikine and Guédiawaye, in the suburban parts of the Dakar Region, Senegal. The region is very densely habited, but no public wastewater system is developed. Sanitary facilities consist of pit latrines and permeable septic tanks. The groundwater of the Thiaroye aquifer is, in this region, polluted with concentrations of nitrate that largely exceeds the WHO regulatory limit of 50 mg-NO_3/L for drinking water. Today, drinking water is transported from Lake Guiers, in the northeast of Senegal, and from the Sebikotane aquifer, southeast of Dakar. Some families have a hand-operated pump, called Diambar pump, which extracts water from the uppermost part of the groundwater. This water is mainly used for domestic purposes like washing and given to animals, but it is not suited as drinking water. Almost all of the wastewater in the region infiltrates into the ground and recharges the aquifer. Precipitation is the only other source of recharge. Many areas are flooded throughout the year and especially during the rainy season from July to October, when surface runoff collects in low-lying areas. To reduce the extent of flooding, several retention pools, 3-4 m deep, have been constructed. In the region there are also areas of urban agriculture, called the “Niayes”.

During the work on this master thesis, the water qualities of the groundwater of the Thiaroye aquifer and of different surface waters in the suburban areas of the Dakar Region were studied. 34 samples from Diambar pumps, dug wells, flooded zones, Niayes and retention pools were analysed for the contents of anions, cations, organic and inorganic carbon, together with stable environmental isotopes of water ($^{2}H/^{1}H$ and $^{18}O/^{16}O$), nitrate ($^{15}N/^{14}N$ and $^{18}O/^{16}O$) and algae ($^{15}N/^{14}N$). The research was especially

focused on the pollution of nitrate, in hopes of being able to identify the sources of nitrate and the processes that happen at the ground-/surface water interface.

The surface waters have in general higher conductivities and concentrations of salts than the groundwater, due to more extensive evaporation. The isotopic composition of water was used to quantify the extent of evaporation from both the groundwater and the surface waters, and it has given new insight to the hydrological connectivity at the ground-/surface water interface. The hypothesis that there is a good connection between the waters, and that the groundwater recharges the surface waters during the rainy season, have been strengthened.

The groundwater is very rich in nitrate, with concentration ranging from 76 to 785 mg/L, which is a result of leaking pit latrines and septic tanks. The isotopic composition of nitrogen and oxygen in the nitrate (mean $\delta^{18}O$ = +7.8 ‰ and $\delta^{15}N$ = 12.2 ‰ in the Diambar pumps) show clearly that the nitrate originates from human wastes, and to a certain extent from organic fertilisers and the degradation of organic nitrogen. The surface waters contain almost no nitrate, but the processes responsible for this lowering are still not fully understood. The main process is most likely the uptake of nitrate by aquatic plants and algae. This is witnessed by the negative correlation between the amounts of organic matter vs. nitrate, the obvious eutrophic state of the surface waters, together with the enriched values of $\delta^{15}N$ of the algae ($\delta^{15}N_{Algae}$ up to +25 ‰). The isotopic composition of nitrate in the surface waters are enriched with around 18 ‰ for the N and 22 ‰ for the O, compared to the surrounding groundwater. This could suggest that denitrification is taking place. However, the results obtained are only indicative, and other indications are ambiguous. Thus, it cannot be concluded nor excluded that denitrification is an important process in the lowering of the nitrate concentrations in the surface waters. Other possible processes that contribute to the reduction and/or fractionation of the nitrate are remineralisation of organic nitrogen and volatilisation of ammonia. Dilution by mixing with precipitation does not contribute significantly to the sink of nitrate in the surface waters.

Sammendrag

Denne rapporten, med tittelen *Nitrate pollution of the Thiaroye aquifer in the suburban parts of the Dakar Region, Senegal – Using chemical and stable isotope analyses to identify the sources of nitrate and the processes at the groundwater/surface water interface*, utgjør den avsluttende hovedoppgaven for Vibeke Brandvold. Oppgaven er på totalt 102 sider + vedlegg og ble skrevet i løpet av vårsemesteret 2013.

Oversvømmelser et utbredt problem i departementene Pikine og Guédiawaye, som utgjør de tett befolkede, halvurbane forstedene til Dakar, i Senegal. Det eksisterer ikke et offentlig vann- og avløpssystem, og sanitære forhold er begrenset til latriner og lekkende septiktanker. Grunnvannet i Thiaroye-akviferen er, i denne regionen, svært forurenset, med konsentrasjoner av nitrat som overskrider WHOs grense for drikkevann på 50 mg-NO_3/L. I dag blir drikkevann fraktet fra Guiers-sjøen nordøst i Senegal, og fra Sebikotane-akviferen sørøst for Dakar. Noen familier har hånddrevne pumper, kalt Diambar-pumper, som tar ut vann fra de øverste meterne av grunnvannet. Dette vannet er ikke egnet som drikkevann, men det blir brukt til husholdningsaktiviteter som vasking og gis også til dyrene. Nesten alt avløpsvann i regionen infiltrerer ned i bakken og mater grunnvannet. Regnvann er den eneste naturlige kilden av vanntilførsel til akviferen. Mange områder er i dag oversvømt året rundt, mens i løpet av regntiden fra juli til oktober, forverrer situasjonen seg dramatisk fordi overflatevann samler seg i de lavtliggende områdene. Et tiltak som er blitt gjort for å redusere omfanget av oversvømmelsene er å grave ut oppsamlingsbasseng med en dybde på rundt 3 til 4 m. I regionene finnes det også urbane jordbruksområder, kalt ”Niayes”.

Gjennom arbeidet med denne oppgaven ble vannkvaliteten av Thiaroye-akviferen og av flere overflatevann i de halvurbane strøkene i Dakar-regionen kartlagt. 34 prøver fra Diambar-pumper, brønner, oversvømte områder, Niayes og oppsamlingsbasseng ble analysert for innhold av anioner, kationer, uorganisk og organisk karbon, samt stabile isotoper av vann ($^2H/^1H$ and $^{18}O/^{16}O$), nitrat ($^{15}N/^{14}N$ and $^{18}O/^{16}O$) and alger ($^{15}N/^{14}N$). Arbeidet har spesielt vært fokusert på nitrat, i håp om å kunne identifisere kildene til nitrat og de prosessene som skjer i overgangen mellom grunnvann og overflatevann.

Overflatevannene har generelt høyere konduktivitet og større konsentrasjon av ioner enn grunnvannet, på grunn av mer evaporasjon. Den isotopiske sammensetningen av vann ble brukt til å kvantifisere evaporasjonen fra både grunnvannet og overflatevannene, samt at det har gitt ny innsikt i den hydrologiske kontakten i overgangen fra grunn- til overflatevann. Hypotesen om at kontakten er god og at strømningene går fra grunnvannet ut mot overflatevannene i de tørre månedene av året, er blitt underbygget.

Grunnvannet er svært nitratholding, med konsentrasjoner på 76 til 785 mg/L, noe som skyldes infiltrasjon av forurenset vann fra latrinene og septiktankene. Den isotopiske sammensetningen av både nitrogen og oksygen i nitratet (i gjennomsnitt er $\delta^{18}O = +7.8$ ‰ og $\delta^{15}N = 12.2$ ‰ i Diambar-pumpene) viser tydelig at det stammer fra menneskelig avføring og urin, samt i enkelte tilfeller fra gjødsel og nedbryting av organisk nitrogen. Overflatevannene inneholder derimot veldig lite nitrat, men årsakene til denne nedgangen er fortsatt ikke helt forstått. Den dominerende prosessen er mest sannsynlig opptak av nitrat i alger og vannplanter. Observasjoner som den negative korrelasjonen mellom konsentrasjon av organisk materiale og nitrat i vannet, den isotopiske sammensetningen av nitrogen i algene ($\delta^{15}N_{Algae}$ opptil +25 ‰) og at overflatevannene er tydelige eutrofe, vitner om at opptak av alger og planter er en viktig faktor for nedgangen av nitrat i overflatevannene. Anrikningen i den isotopiske sammensetningen av nitratet i overflatevannene er på rundt 18 ‰ for nitrogen og rundt 22 ‰ for oksygen, sammenliknet med grunnvannet. Dette kan tyde på at en denitrifikasjon har skjedd. Målingene er imidlertid kun omtrentlige og andre observasjoner gir sprikende resultater. Det er derfor ikke mulig å hverken bekrefte eller avkrefte om denitrifikasjon er en prosess som bidrar til de lave nitratverdiene i overflatevannene. Andre mulige prosesser som kan bidra til nedgangen og/eller fraksjoneringen av nitratet er remineralisering av organisk nitrogen og fordamping av ammoniakk. Fortynning ved innblanding av regnvann er ikke en avgjørende faktor.

Résumé

Ce rapport, du titre *Nitrate pollution of the Thiaroye aquifer in the suburban parts of the Dakar Region, Senegal – Using chemical and stable isotope analyses to identify the sources of nitrate and the processes at the groundwater/surface water interface,* constitue le travail de mémoire de Vibeke Brandvold. La thèse, qui compte un totale de 102 pages + annexes, fût écrit pendent le semestre du printemps 2013.

Des inondations cause des sévères problèmes dans les départements de Pikine et Guédiawaye, des départements qui constitue la zone périurbaine de la région de Dakar, au Sénégal. La région est très peuplée, mais aucun système de drainage et/ou de traitement des eaux usées n'est développé. Les systèmes sanitaires actuellement en place sont fait des latrines et des fosses septiques perméables. Aujourd'hui, la nappe phréatique de Thiaroye est, dans cette région, polluée avec des teneurs en nitrate qui dépasse largement la limite de 50 mg-NO_3/L, suggérée par WHO pour l'eau potable. L'eau potable est alors transportée du Lac Guiers, dans le nord-est du Sénégal, ainsi que de l'aquifère de Sebikotane, au sud-est du Dakar. Quelques familles ont une pompe manuelle, nommée pompe Diambar, qui extrait de l'eau à partir de la plus haute partie de la nappe. Cette eau est, en générale, utilisée pour des activites domestiques, comme le lessivage, et pour abreuver les animaux, mais elle n'est pas apte à être utilisée comme eau potable. Presque toutes les eaux usées de la région s'infiltrent dans le sol et contribue à la recharge de la nappe. La seule autre source de recharge sont les précipitations. Plusieurs endroits sont aujourd'hui inondés toute l'année, et pendant la saison humide, entre Juillet et Octobre, les inondations s'aggravent à cause du ruissellement vers les bas-fonds des dunes. Une des mesures mise en oeuvre pour diminuer les inondations est la construction des bassins de retention, d'une profondeur de 3-4 mètres. Dans la région de Dakar, on trouve aussi de l'agriculture urbain, dans des sites nommé les « Niayes ».

Dans ce mémoire, la qualité d'eau de la nappe de Thiaroye ainsi que différentes eaux de surface dans la zone périurbaine de Dakar ont été étudiée. 34 échantillons, pris des pompes Diambar, puits, zones inondées, Niayes et bassins de rétention, ont été analysés pour leur teneurs en anions, cations, ainsi que carbone organique et inorganique. Ensuite,

les isotopes environnementaux stables de l’eau ($^{2}H/^{1}H$ et $^{18}O/^{16}O$), du nitrate ($^{15}N/^{14}N$ et $^{18}O/^{16}O$) et des algues ($^{15}N/^{14}N$) ont été analysés. L’étude est focalisée sur la pollution de nitrate, dans l’espoir de pouvoir identifier les sources différentes de pollution et les processus qui se passent sur l’interface entre eau de la nappe et eau de surface.

Les eaux de surface ont, en générale, une conductivité et des teneurs en sels plus élevées que la nappe. Cela est grâce à l’évaporation plus prononcée des eaux de surface. La composition isotopique de l’eau a été utilisée pour estimer le taux d’évaporation et la connectivité hydrologique à l’interface. Les hypothèses qu’il y a une bonne connectivité et que les écoulements souterrains vont de la nappe vers les basins de rétention pendant la saison sèche sont affirmées.

L’eau de la nappe est très riche en nitrate, avec des teneurs entre 76 et 785 mg/L, qui proviennent des latrines et des fosses septiques. La composition isotopique de l’azote et de l’oxygène dans le nitrate (en moyenne, $\delta^{18}O$ = +7.8 ‰ et $\delta^{15}N$ = 12.2 ‰ des pompes Diambar) prouve qu’il provient principalement d’excréments humain Dans quelques cas il provient de fertiliseurs organiques et de la dégradation d’azote organique. Les eaux de surface, par contre, sont appauvries en nitrate, mais les processus qui sont responsable pour cette diminution ne sont toujours pas compris. Le processus principal est probablement l’assimilation de nitrate par les algues et les plantes aquatiques. Cela est justifié par la corrélation négative entre le teneur en carbone organique et la concentration de nitrate, l’état de eutrophication des eaux de surface, et la composition isotopique de l’azote dans les algues très élevée ($\delta^{15}N_{Algae}$ jusqu’à +25 ‰). La composition isotopique de nitrate dans les eaux de surface est enrichie avec environ 18 ‰ pour le N et 22 ‰ pour le O, comparé avec l’eau des pompes Diambar, ce qui pourrait indiquer que la concentration de nitrate diminue à cause de denitrification. Cependant, les résultats obtenus sont indicatifs et d’autres résultats sont ambigus. Pour cette raison, il ne peut pas être ni conclu ni exclue que la denitrification est un processus important dans la diminution de nitrate dans les eaux de surface. D’autres processus possible affectant soit la diminution et/ou le fractionnement de nitrate sont la reminéralisation de matière organique et la volatilisation de gaz d’ammoniac. Une diminution de teneur en nitrate liée à la dilution, par mélange avec eau de pluie, n’est pas importante.

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Preface

This master thesis is written for the Department of Geology and Mineral Resources Engineering at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in collaboration with the University of Lausanne (UNIL), Switzerland. The work is associated to the activities of the NGO urbaMonde in Geneva, Switzerland, on the project named UrbaDTK in Dakar, Senegal. The University of Cheikh Anta Diop (UCAD) in Dakar has been a contributing partner. The project was defined by the author together with Bjørge Brattlie at NTNU, and Hans-Rudolf Pfeifer and Torsten Vennemann at UNIL.

During an exchange year at UNIL in 2011/2012, I was introduced to the problem of groundwater pollution and flooding in the suburban areas of Dakar. In the autumn of 2012, I wrote a project thesis on the problems of flooding, which included a literature study of the natural, social-economic and political parameters that contribute to the flooding occurrences, and modelling of the groundwater level. The work on this master thesis is related to the same suburban area, but focuses on the geochemical aspect, studying the pollution of nitrate in the ground- and surface waters. The first part of the work on the master consisted of a 5 weeks sampling period in Dakar in January and February 2013. Water samples from the ground- and surface waters in the suburban region of Dakar were taken. Chemical and stable isotope analyses were done in February and April in the laboratories of the Institute of Earth Science of the University of Lausanne (ISTE-UNIL) in Switzerland. The synthesis of the results and writing of the thesis were done throughout the spring semester, mainly in Trondheim, Norway.

First I wish to give a big thanks to all the people in Senegal that helped me during the fieldwork. Thank you to Papa Keita and Djibril Diallo of the NGO UrbaDTK in Dakar for their help, hospitality, and interesting discussions. Thank you to Seydou Niang at the University of C.A. Diop Dakar (UCAD) for all his generosity and support in structuring of the sampling regime, for loan of equipment and time in the laboratory. I owe big thanks to Tiende Sarr and Imbrahima Sané, of the Community of Djiddah-Thiaroye-Kao (DTK), who spent long days with me in the field. Their effort made it possible to take all the samples I needed. At UNIL, I wish to thank students Jessica Roberts and Benoît Zen-Rufinen who took the time and helped me during the laboratory work. Thank you to also to Dr. Laurent Decrouy, PD Dr. Jorge Spangenberg and Prof. Torsten Vennemann, whose guidance and assistance in the work with isotopes is greatly appreciated, and to Prof. Hans-Rudolf Pfeifer, who introduced me to the project, gave me great counsel, and made my dream of working on a project in Africa come true. I also wish to say thank you to Prof. Bjørge Brattlie at NTNU, who has carefully read through my work and given valuable advice and comments along the way.

Finally, I thank Tekna and COWI AS for their financial support. Their contributions made it possible for me to travel to Senegal and Switzerland to do the field and laboratory work.

Trondheim, June 5th 2013
Vibeke Brandvold

Introduction

The departments of Pikine and Guédiawaye, in the suburban area of the Dakar Region, are among the most densely populated and poorest areas of Senegal. The region suffers from a shallow and continuously rising groundwater table, extensive flooding during the rainy season, and pollution of the ground- and surface waters due to a lack of sanitary systems. Sanitary facilities in the area consist of personal pit latrines and leaking septic tanks. The Thiaroye aquifer is an open, self-feeding aquifer covering Pikine, Guédiawaye and the northern part of Rufisque. It was exploited for drinking water from 1950 until recent years. The rate of exploitation was decreased gradually from 2003 and is today pumped at a negligible rate. The region gets its drinking water from Lake Guiers in northern Senegal and from the Sebikotane aquifer in the Ndiass horst system, southeast of Dakar. Because there is no existing wastewater system, all domestic water infiltrates into the ground and recharges the aquifer. Low-lying areas are today flooded throughout the year. To reduce the amount of flooding, 3-4 m deep retention pools are constructed. They localise the flooding and collect surface runoff during the rainy season. Many families have today a hand-operated, shallow, drilled well that extracts groundwater from 2-12 m depth. The water from these Diambar pumps, as they are called, is very polluted and has a high concentration of nitrate. This water is mostly used for domestic purposes like washing and given to animals. Surface waters found in flooded zones and retention pools have in general a higher conductivity, but contain less nitrate than the groundwater. This difference is thought to be a result of evaporation and nitrate uptake in plants and algae.

Several studies (Diédhiou et al., 2011; Gueye-Girardet, 2010; Re et al., 2011; Sall & Vanclooster, 2009; Tandia et al., 1999) have studied problem of nitrate pollution of the groundwater in the Dakar Region. Finger (2012) studied the potential of phytoremediation of the surface waters in the Dakar Region, and looked at chemistry of some Diambar pumps and the retention pools Bagdad and Nietty Mbar, with samples taken in July and August, 2011, in the beginning of the rainy season. The sampling in the current study was done during the dry season, in January and February, and the study of Finger (2012) can therefore be regarded as complementary to the results obtained here.

The objective of this master thesis was to study the physical, chemical and biological processes that happen at the ground-/surface water interface, in hopes of increasing the understanding of the effects that the retention pools have on the water quality and their hydrological connectivity to the aquifer. The study area lies in the area of Pikine and Guédiawaye of the Thiaroye aquifer. By interpreting data from *in situ* field measurements, and chemical and isotopic analyses, many processes can be determined. Concentrations of anions and cations were obtained by ion chromatography. These values are used to determine the type of groundwater and the extent of pollution. Isotopes of water, $^{2}H/^{1}H$ and $^{18}O/^{16}O$, tell us something about the origin of the water, mixing events, and amount of evaporation. Nitrogen and oxygen isotopes of nitrate are used to trace the NO_3^- in the environment. The sources of nitrate can be determined by looking at the $^{15}N/^{14}N$ ratios, while with the dual-isotope approach, combining $^{15}N/^{14}N$ and $^{18}O/^{16}O$, nitrification, denitrification and other processes can be detected. The isotopic composition of N in algae from the surface water sites were analysed. This can hopefully dentify the uptake of nitrate by plants and algae and possibly explain the relative low concentration of nitrate in surface waters compared to the groundwater.

An additional goal of the work with this master thesis was to obtain a general overview of the water quality in the suburban parts of the Dakar Region. The site covers an area between the “Niaye de Pikine”, which was studied in detail by Ndiaye (2009) and Gueye-Girardet (2010), and Lake Retba, currently being studied by Benoît Zen-Rufinen at UNIL. Together, the three studies cover large parts of the Thiaroye aquifer.

The first part of the thesis constitutes the site description. This part is based on the work done in the author’s project thesis during the 2012 autumn semester. It includes an introduction to the geology and hydrology of Senegal, history and demography of the area, and background for the problems of flooding and pollution. The theory part gives an introduction to the nitrogen cycle and processes affecting the nitrate in the aqueous environment. Further, basic isotopic geochemistry is covered, while isotopic processes of H, O and N are explained more in detail. The third part, “Materials & Investigations”, reports on the work that was done in the field and in the laboratory. Results are presented and discussed in the fourth part, before the chapters “Conclusion” and “Future Research” complete the thesis.

Site description

1 Geography and geomorphology

The Dakar Region is located in the mid-western part of Senegal, between 14°24´ and 15°5´ N and 16°55´ and 17°32´ W (Re et al., 2010). It is often termed the Cap-Vert Peninsula (la Presqu'île du Cap-Vert in French), which stretches 50 km in the W-E direction and a maximum of 15 km in the N-S direction (Figure 1.1). At the narrowest part, by the Cambérène isthmus, it is only 4.5 km wide (Faye et al., 2003). The study area of the current master thesis is situated in the suburban parts of the Dakar Region, in the departments of Pikine and Guédiawaye, between the "Niaye de Pikine" in west and Lake Malika in the northeast (Figures 1.1 and 5.1).

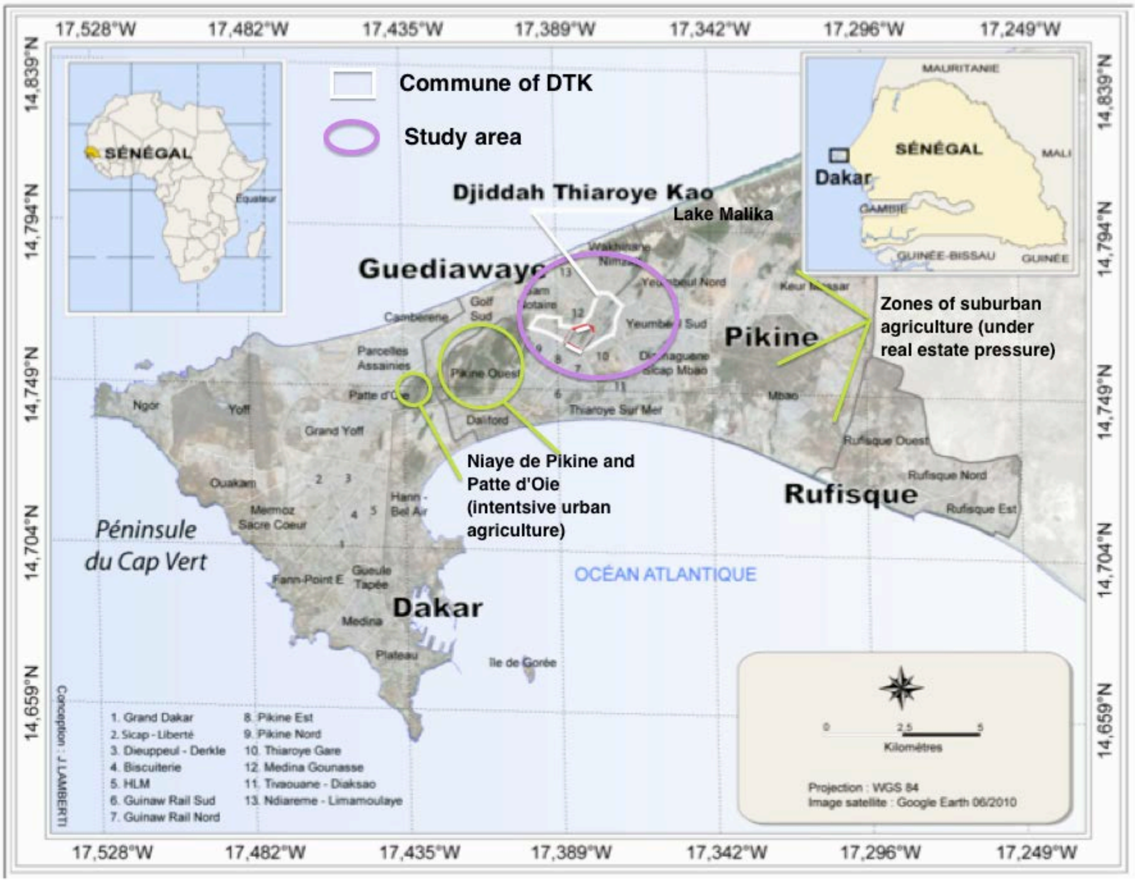

Figure 1.1: Map of the Dakar Region. White delimit the commune of DTK, purple circle locates the study area of this project.

There are three major lithological units on the peninsula. The western unit is characterised by an uplift of the sedimentary and volcanic deposits, while the eastern unit is a plateau of limestone in the Rufisque department (Re et al., 2010). The middle unit constitutes a massive dune formation that is separated from the Atlantic Ocean in the north by a continuous coastal strip. The dunes are oriented SW-NE. The “Niayes” are located in this area. These are the depressions between the dunes that collect runoff from a local catchment without having a natural outflow towards the ocean. The region of the “Niayes” stretches from Pikine to Saint Louis, 250 km further northeast (Figure 1.2). The “Niayes” in the Dakar Region are regularly flooded during the rainy season, a few are flooded throughout the year, and urban agriculture is developed around some of them. Small lakes like Mbeubeuss and Malika and the hyper saline Lake Retba (Lac Rose) are still present in the region. Along the southern coast, the marly pre-Quaternary basement outcrops in Rufisque and Barigny as a plateau 30 m high (Re et al., 2010). In Figure 1.3 the depressions zones between the “Grande Niaye de Pikine”, Lake Malika and Lake Mbeubeuss are visible in blue.

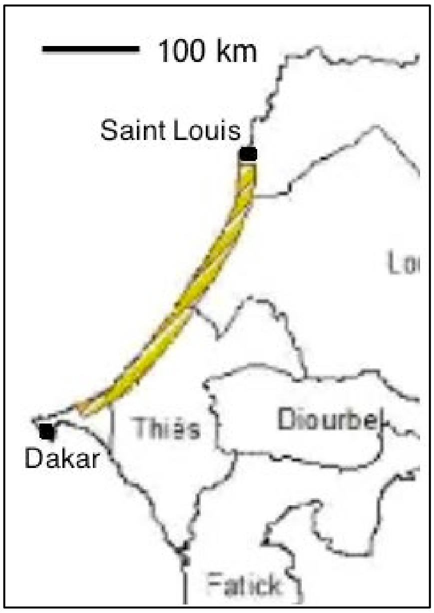

Figure 1.2: The region of the Niayes (in yellow) stretches along the north coast.

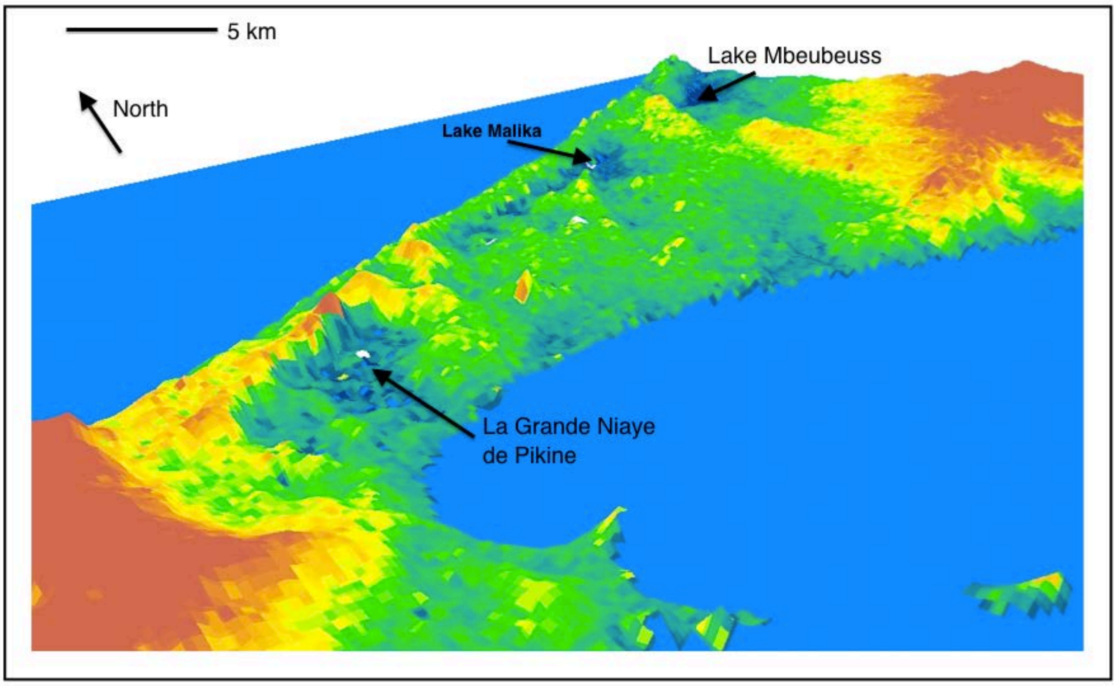

Figure 1.3: Topography of Dakar Region (adapted from State of Senegal, 2010)

2 Hydrology and climatology

2.1 Precipitation

The Dakar Region experiences in general the typical climate of Sahel, with a dry season from October to June, and a wet season, called “hivernage”, from July through September. However, due to its position at the coast, the climate is also affected by local variations. This results in very variable rainfall. There can be large differences from one year to the next. The principle trends during the last 120 years are as following (Plan Directeur de Drainage (PDD) no. 1, 2011):

- 1896-1969: annual mean of 550 mm/y
- 1970-2004: annual mean falls to 340 mm/y

2005-2009: annual mean increases to 483 mm/y

98% of the annual precipitation falls in the 4 months between July and October, and 70-80% during August and September (PDD no. 1, 2011).

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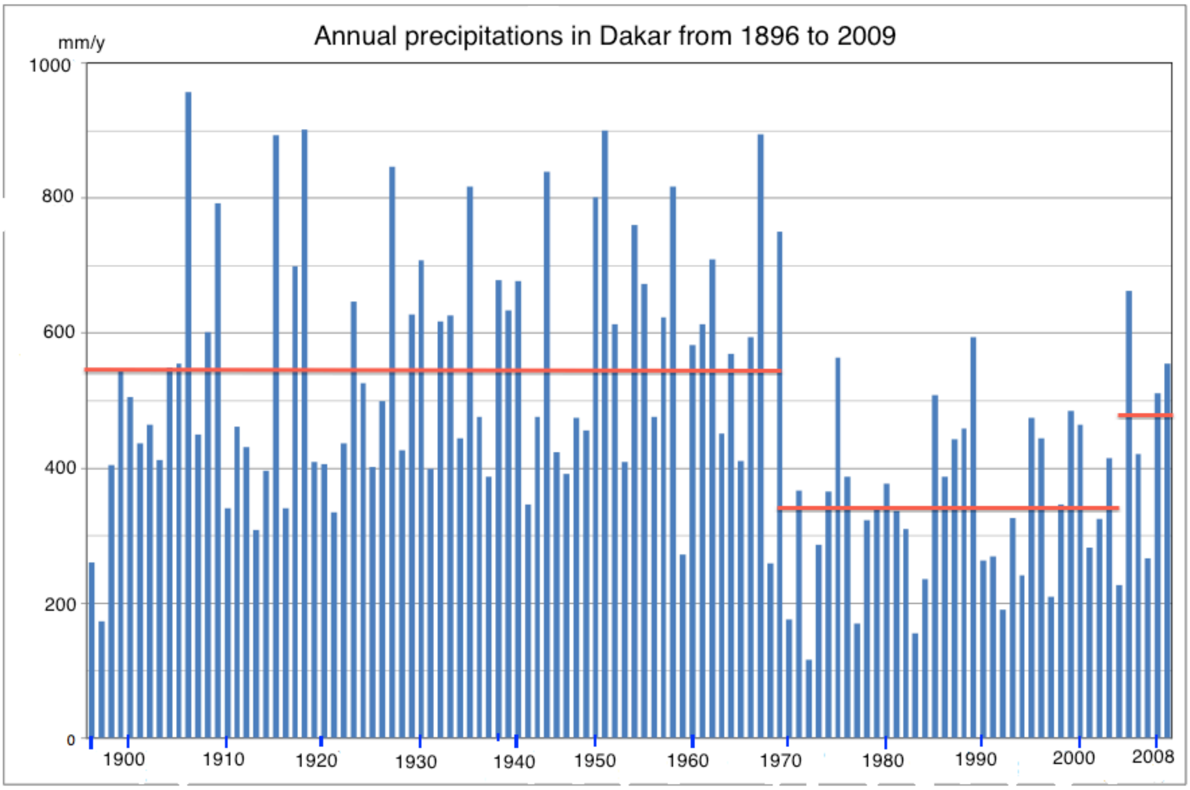

Figure 2.1: Annual rainfall at Dakar-Yoff . Red lines show the average rainfall (PDD no. 1, 2011)

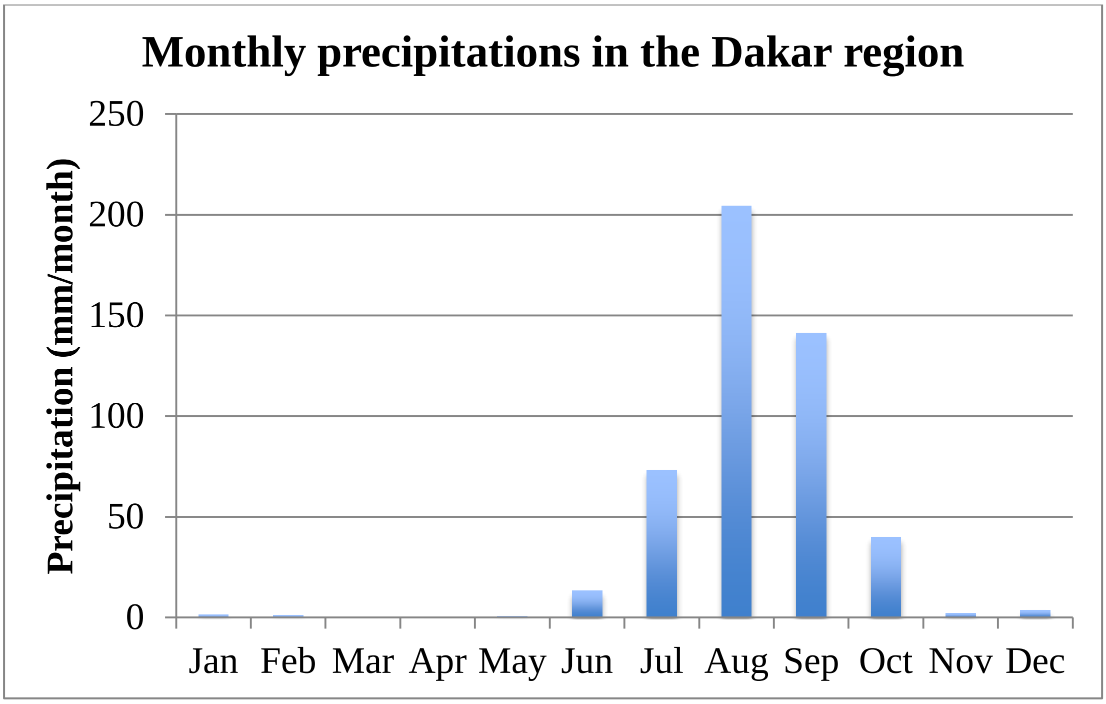

Figure 2.2: Average monthly precipitation (mm) from 1947 to 2009 at Dakar-Yoff (PDD no. 1, 2011)

2.2 Temperature and humidity

Both the temperature and the humidity are fairly constant throughout the year. The average air temperature at the station Dakar-Yoff is 21.3°C at its minimum in January, 28.1°C at its maximum in October and 24.7°C as an annual mean. The Cap-Vert Peninsula has its own microclimate due to its exposure in the Atlantic Ocean. The humidity stays relatively high during the whole year, ranging from 65% in December to 81% in September (PDD no.1, 2011).

2.3 Evapotranspiration

Many studies have tried to estimate the evapotranspiration in the Dakar Region, but the results are very variable. There are several methods that can be used, including Albrecht, Blaney-Criddle (Tabari et al., 2005) and Turc (von Gunten, 2012). The evapotranspiration during a year depends on many different factors, such as daylight hours, solar radiation, temperature, humidity, soil properties, vegetation, etc. Table 2.1 summarises previous estimates of evapotranspiration in Dakar.

Table 2.1: List of estimates of evapotranspiration in the Dakar Region (adapted from von Gunten, 2012)

Reference	**Evapotranspiration mm/y**	**Method used**
PDA, rap.6, 2010, p.18	450	Not described
Koukoui & Ndiaye, 2003, p. 48	290	ET function of potential evaporation, soil capacity and pluviometry. Albrecht.
Faye et al, 2003, p.92 (1948-1996 in Dakar-Yoff)	221-511 190-561	Albrecht Turc
Comte, 2008, p.150	300	Based on literature (Martin, 1970)
Tandia, 2000, p.32 (1978-1998 in Dakar-Yoff)	270-440	Evapometer PICHE and Turc method
PDD no. 1, 2011, Annexe 1 p. 47	95	20% of precipitation evaporated
Cabinet Merlin, 2007, p. 51	375 (before infiltration) 75 (from soil)	75% of 500 mm/y evaporated Evaporation down to 3 m
Brandvold, 2012, p. 41	294 mm/y for 480 mm/y rain (before infiltration) + 250 mm/y (from soil)	25 % Turc + 75 % Blaney-Criddle calculated pr. month. (Depend on temperature and amount of rain)

An evapotranspiration of 450 mm/y as proposed by the PDA seems too simplified. It does not include evapotranspiration during the dry season, nor is it relative to the amount of annual precipitation. On the other hand, an estimate based on that only 20% of the precipitation evapotranspires (PDD no. 1, 2011) does not seem plausible. Other sources propose that as much as 75% of the precipitation evapotranspires (Cabinet Merlin, 2007). Three of the other sources have estimated an evapotranspiration ranging between 190 – 561 mm/y in their studies, which gives an average of 340 mm/y (von Gunten, 2012).

In the study of Brandvold (2012) a combination of the Turc and the Blaney-Criddle method were found to give the best fitting results. These two methods probably represent an over- and underestimate of the amount of evapotranspiration. The Turc and the Blaney-Criddle methods were weighted 25% and 75%, respectively, in the Brandvold (2012) model. The amount of evapotranspiration should be calculated for each month before summing up for a year to obtain a more accurate estimate.

In the region of Dakar, the water table is very shallow and evapotranspiration happens during the dry season as well. This parameter is in the Brandvold (2012) study called E_{GW}. ANTEA (2003) proposed that the actual evapotranspiration from the soil is a function of depth. During the calibration of the water budget model in Brandvold (2012) an E_{GW} of 250 mm/y (20.83 mm/month) was found to give the best fit.

To sum up, the ETR calculated by one or a combination of methods (Albrecht, Turc, Blaney-Criddle, or others) can be thought of as the part that evaporates after a rainfall, before the infiltrated water reaches the groundwater. E_{GW} is the amount that evapotranspires directly from a shallow groundwater.

3 Geology

The geology of the Cap-Vert Peninsula distinguishes itself from the general geology of Western Africa, where different granites, gneisses, schist and quartzite dominate (Legoux, 1945). Relevant to this study are the Tertiary and the Quaternary formations. The region is characterised by long periods of volcanic activity from Tertiary (southern Dakar horst) to Quaternary (northern Dakar horst) and by cycles of transgression and regression of the Atlantic Ocean (Re et al., 2010). Outcrops, hydraulic wells and petroleum explorations made it possible to map the geology.

The general evolution of the area has created two main fault systems: 1) those trending NW-SE to N-S, parallel to the Mid-Atlantic Ridge, and 2) those trending W-E, perpendicular to the Mid-Atlantic Ridge. As shown in Figure 3.1, the fault systems delimit two main horsts, the Dakar horst in the west and the Ndiass horst in the east, with the Rufisque graben in between (Lo & Diop, 1999). The southern Dakar horst forms a plateau 50 m above sea level, which mainly consist of Tertiary volcanic products. The northern Dakar horst reaches an elevation of 105 m and is formed by Quaternary volcanic rocks. The Ndiass horst consist of Tertiary sedimentary rocks: marl and limestone from the Eocene, karstic limestone from the Paleocene, and sandstone and limestone of Maastrichtian age (Re et al., 2011).

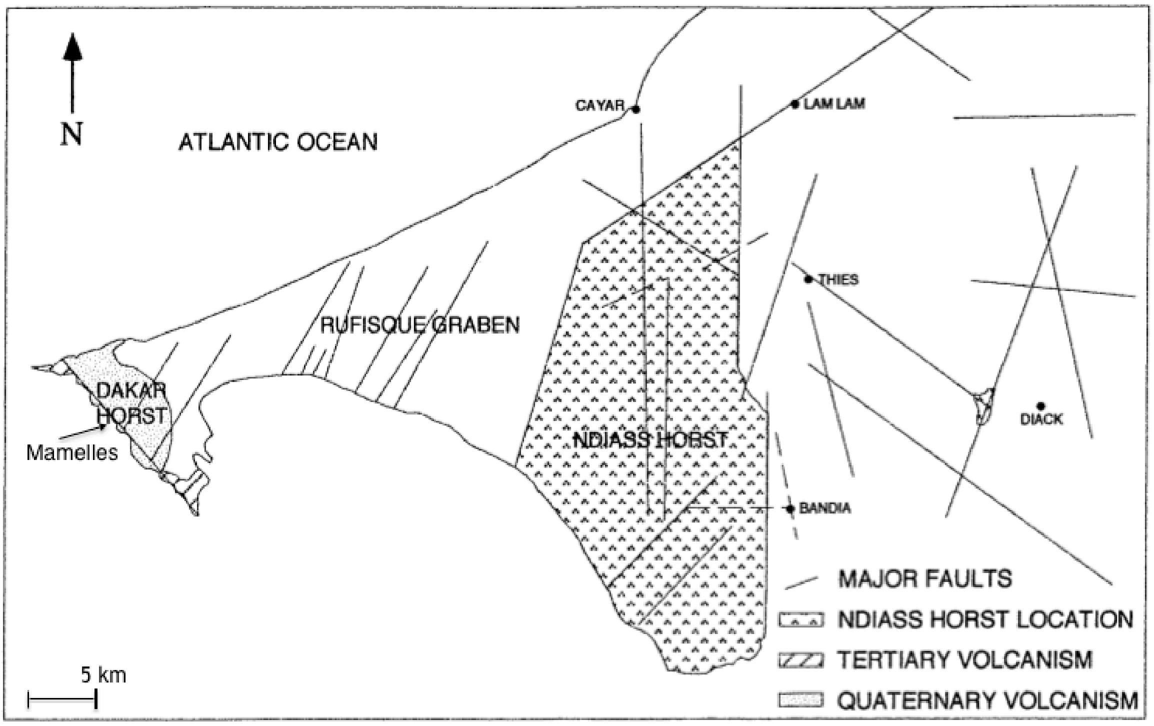

Figure 3.1: Fault systems in the Dakar Region (Lo & Diop, 1999)

Quaternary eolian sediments cover almost the entire region of Dakar. The volcanic activity at the head of the peninsula, in the area of Dakar City, has resulted in layers of basalt intervened in the sand deposits. The older Quaternary deposits are composed of marine sand, from Inchirian[1]. These deposits are only preserved under the basaltic rocks from the volcanic activity of the Mamelles (Figure 3.1) and in deep circular depressions and paleo-valleys of the Thiaroye aquifer (Ouedraogo, 2009). The major part of the Quaternary sediments consists of Ogolian[2] fine-grained orange quartz sand, deposited during the Weichsel[3] glaciation, the last glacial maximum in Europe. A thin film of iron oxide covers the grains, which makes it orange (Koukoui & Ndiaye, 2003). Younger sediments of fine-grained white quartz dune sand compose the upper geological unit

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[1] Inchirian: 40,000 – 25,000 years B.P. Term used in western Africa.

[2] Ogolian: 25,000 – 13,000 years B.P. Term used for deposits during an arid period in western Africa.

[3] Weichsel: 25,000 – 13,000 years B.P. Term used for the last glacial maximum in northern Europe.

(Figures 4.2 and 4.3). These deposits form a littoral strip along the north coast, stretching from Dakar all the way to St. Louis further northeast (Chaoui, 1996). They play an important hydrological role because they isolate the small lakes from the ocean (ANTEA, 2003).

4 Hydrogeology

There are three main aquifers present in the region of Dakar. The “Infra Basaltic” aquifer is located under Dakar City (with a “Supra Basaltique” part which is still present in Rufisque). The Thiaroye aquifer is part of a Quaternary sand formation and spreads out over an area of about 300 km^2, while southest of the peninsula, the “Paleocene of Sébikotane” aquifer is found in karstic and marly limestone (Figure 4.1, Ouedraogo, 2009). This study focuses on the Thiaroye aquifer, which is the aquifer related to the problems of flooding and the one that is the most exposed to anthropogenic pollution. The name is derived from Thiaroye, a sub-community of Pikine.

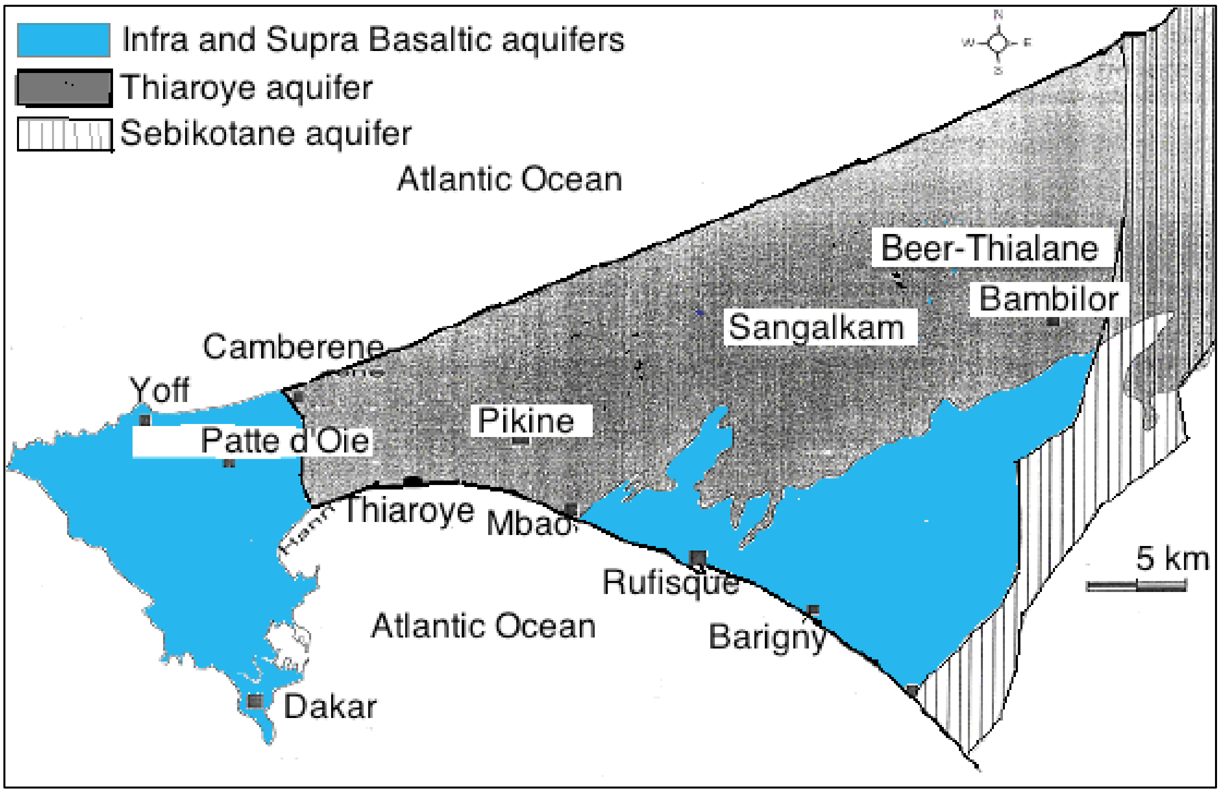

Figure 4.1: The three aquifers of the Cap-Vert Peninsula (adapted from Ouedraogo, 2009)

4.1 Geometry of the Thiaroye aquifer

The Thiaroye aquifer is located in the departments of Pikine, Guédiawaye and the northern part of Rufisque (Figures 1.1, 4.1 and 5.1). It stretches from Cambérène in the west to Kayar in the east (Figures 3.1 and 4.1). The surface relief is between 2 m and 35 m above mean sea level (Faye et al., 2003). The aquifer thickness varies from 5 m in the southeast to 70 m in the north. The Thiaroye area of the aquifer is of important thickness with a circular depression where the sand formation is 50 m thick (Cabinet Merlin, 2007).

Marls and clays from younger Eocene form the substratum of the aquifer (Figures 4.2 and 4.3). In general, the substratum dips towards the north. The composition of the aquifer itself varies vertically. At the base, the sediment is clayey sand, followed by coarser sands in some areas, while fine-grained dune sands constitute the dominant unit (Chaoui, 1996). Several additional geological profiles are shown in Appendix I.

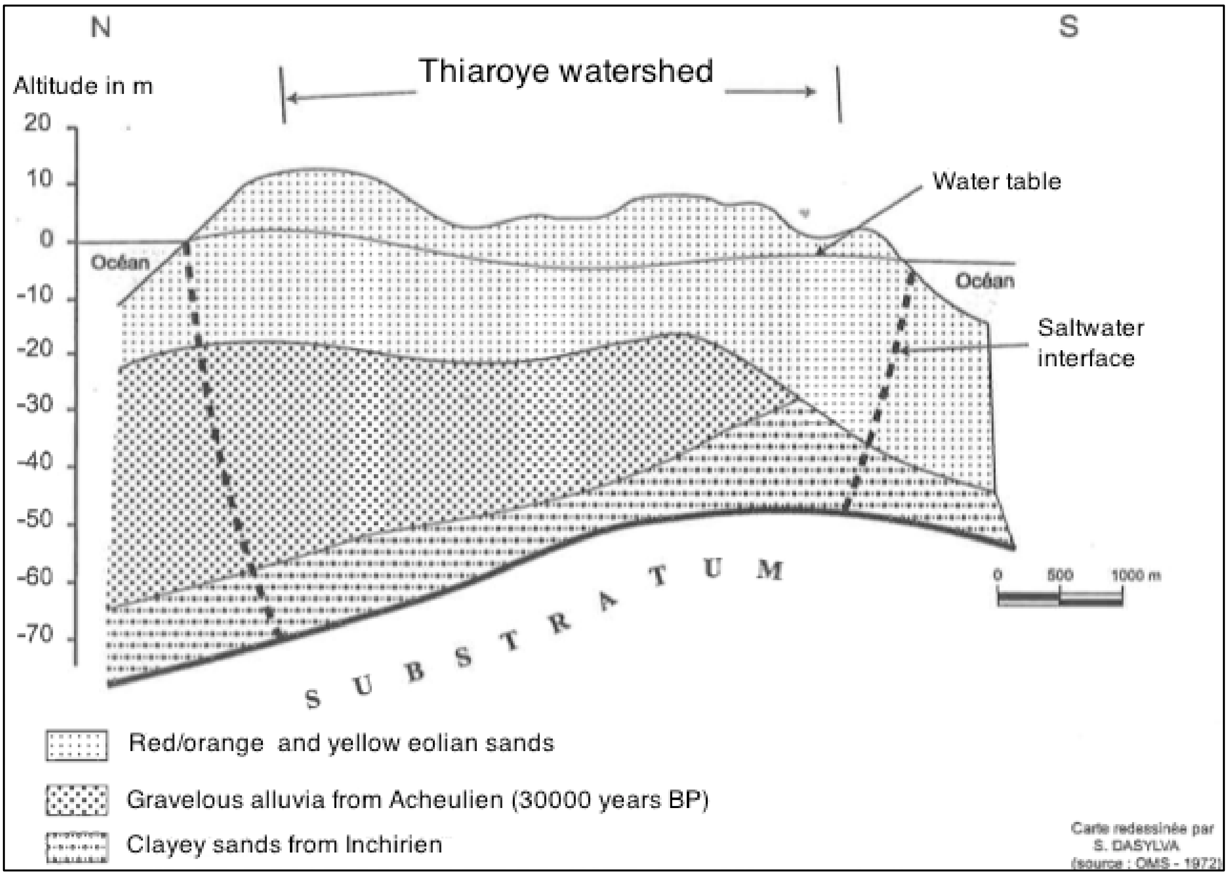

Figure 4.2: N-S section of the Thiaroye aquifer (Chaoui, 1996)

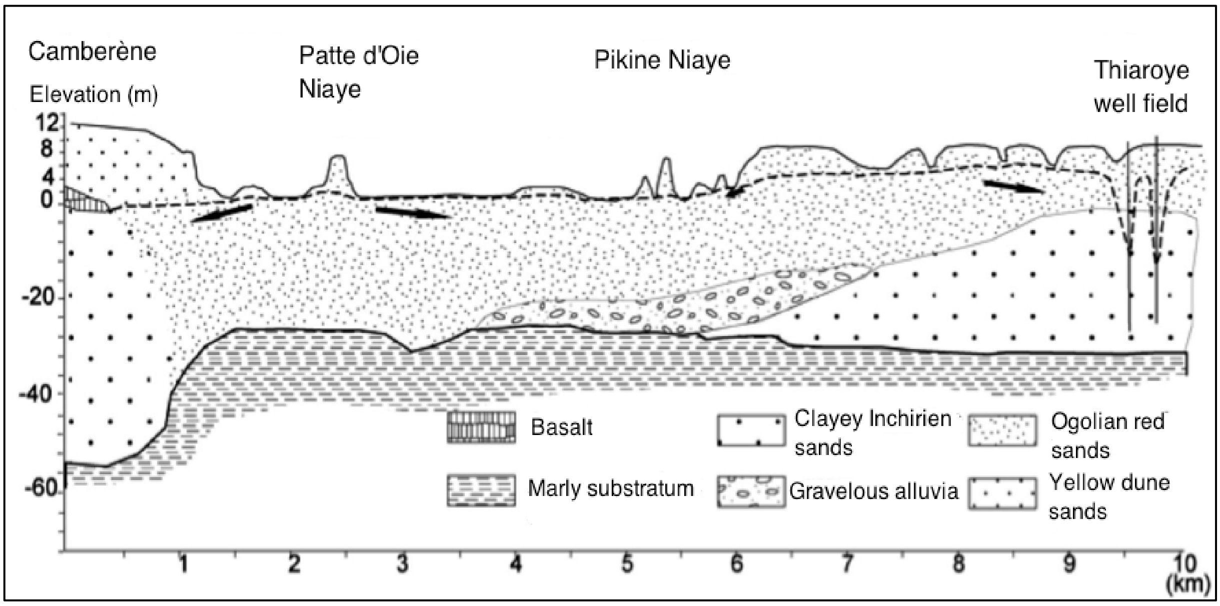

Figure 4.3: W-E section of the Thiaroye aquifer (Dasylva, 2001)

The Thiaroye aquifer is an open aquifer with a water table situated at 0-12 m below the ground surface. In the Thiaroye suburban area, the water table is found at less than 3 m depth. Although there is some clay content in certain areas, which might create local semi-confined properties, the aquifer as a whole behaves as one open unit. Hydraulic heads range from 20 m in the southeast to 0.5 m in the north along the coastal zone (Faye et al., 2003). The general flow direction at depth follows the substratum towards N-NW (Figure 4.2, Cabinet Merlin, 2007).

The Thiaroye aquifer is self-feeding and all its natural recharge comes from the infiltration of rainwater. Because the precipitation is limited to 4 months of the year, the water table level experiences big fluctuations. The rise starts approximately one month after the start of the wet season in July and the water table usually reaches a maximum during November. The decline during the dry season is a result of evapotranspiration and to a certain extent the direct outflow to the ocean and to the surrounding aquifers. The majority of the evaporation happens from natural and artificial the lakes between the Niayes of Pikine and Patte d’Oie (Figure 1.1) and Lake Retba (Lac Rose) and in areas where the water table is less than 3 m deep (Cabinet Merlin, 2007). The evolution of the hydraulic head in the last century has been governed by the annual rainfall and by exploitation of the aquifer during the last 60 years.

4.2 Properties of the aquifer

The formation consists of fine- to medium-grained sand, with some clay content in certain areas. The hydraulic conductivity is estimated based on long duration tests which concluded with a horizontal conductivity of 0.5-9x10^{-4} m/s and a transmissivity in the order of 10^{-3} m^2/s (Faye et al., 2003; Cabinet Merlin, 2007; Ouedraogo, 2009). In the horizontal plane, it is isotropic, while the vertical conductivity is set to one tenth of the horizontal conductivity.

Results from different studies show very variable values for the porosity. ANTEA (2003) found the porosity to lie between 10-15% based on pumping tests, but during calibration of their 2D model, best results were obtained with a porosity of 25%. According to Faye et al., (2003), Koukoui & Ndiaye (2003) and Ouedraogo (2009), an effective porosity of 20% seems the most probable. However, values between 17-32% may be possible (von Gunten, 2012).

Because the Thiaroye aquifer is unconfined, the storage coefficient, S, is approximately equal to the specific yield, Sy. The specific storage, Ss, being several magnitudes smaller then Sy, can be neglected. The specific yield is assumed equal to the effective porosity.

4.3 Saltwater intrusion

The Thiaroye aquifer is in direct contact with the ocean both along the northern coast and in the south between Thiaroye and Grand M’Bao (Cabinet Merlin, 2007). The density difference between freshwater and seawater forms an equilibrium called the saltwater interface. This interface declines towards the continent. The position of the interface depends on the hydraulic head of the water table. A small head creates a shallow interface while an increased head will have a deeper interface (Antonellini et al., 2008). Exploitation of the aquifer alters the position of the interface and causes the saltwater to migrate into the freshwater aquifer. Increased salt content in the water extracted from the Thiaroye aquifer will limit the use of the water even further. If the water is to be used for irrigation in the future, it is very important to minimize the risk of saltwater intrusion. The water table should for this reason be situated above a minimal head, which depends on the recharge and rate of pumping. Cabinet Merlin (2007) proposed a maximal rate of exploitation that will not result in saltwater intrusion.

5 Demography

Senegal has a population of 12,970,000 (July 2012) of which 42% live in urban areas. Dakar, the capital city, is located at the head of the Cap-Vert Peninsula and is the westernmost tip of the African continent (Figures 1.1 and 5.1). The Dakar Region includes the departments of Dakar, Pikine, Guédiawaye and Rufisque. Dakar City covers most of the metropolitan areas, Pikine and Guédiawaye the suburban areas, while Rufisque still remain mostly rural. The Dakar Region covers only 0.3% of Senegal's national territory of 196,722 km^2 (Okuda, 2012), but with a population of about 2.6 million in 2003, around 25% of the total population of Senegal lives in this region (ANTEA, 2003, Vol. env.).

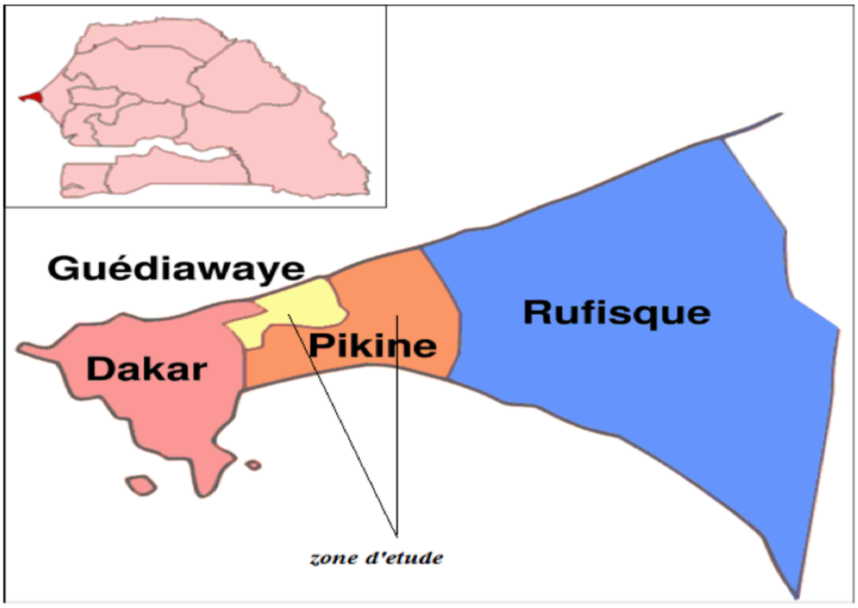

Figure 5.1: The four departments of the Dakar Region (Okuda, 2012)

As a fast growing city, shantytowns[4] were established around the city centre of Dakar in the middle of the 20th century. To gain a modern image, a "slum clearance" policy was conducted between 1952 and 1972. Slums and shantytowns were relocated to a place around 15 km outside of the city. This area includes today's Pikine Ancien, Pikine Loti, Pikine Extension and Guédiawaye. Parallel with the planned settlements, Pikine and Guédiawaye became the site of informal settlements and slums, a pattern that still continuous today (Okuda, 2012).

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[4] Shantytown: a city district inhabited by people living in huts and shanties

One of the origins of the flooding in Dakar's suburban areas is related to the drought in the 1970's (Ndong & Royez, 2012). From the end of the 1960's, the amount of precipitation decreased and reached a minimum of 166.7 mm/y in 1972 (PDD no. 1, 2011). Rural agricultural lands became unproductive and caused a surge of migrants to the cities. Due to an increasing population, Dakar City started to pump the Thiaroye aquifer to meet the demands of drinking water. The drought and exploitation of the aquifer combined resulted in an important lowering of the water table. Depressions in Dakar's suburban areas dried up and became potential settlement sites for the poor immigrants (ANTEA, 2003, Vol. env.; Okuda, 2012). Figure 5.2 schematically presents the factors contributing to the informal settlements.

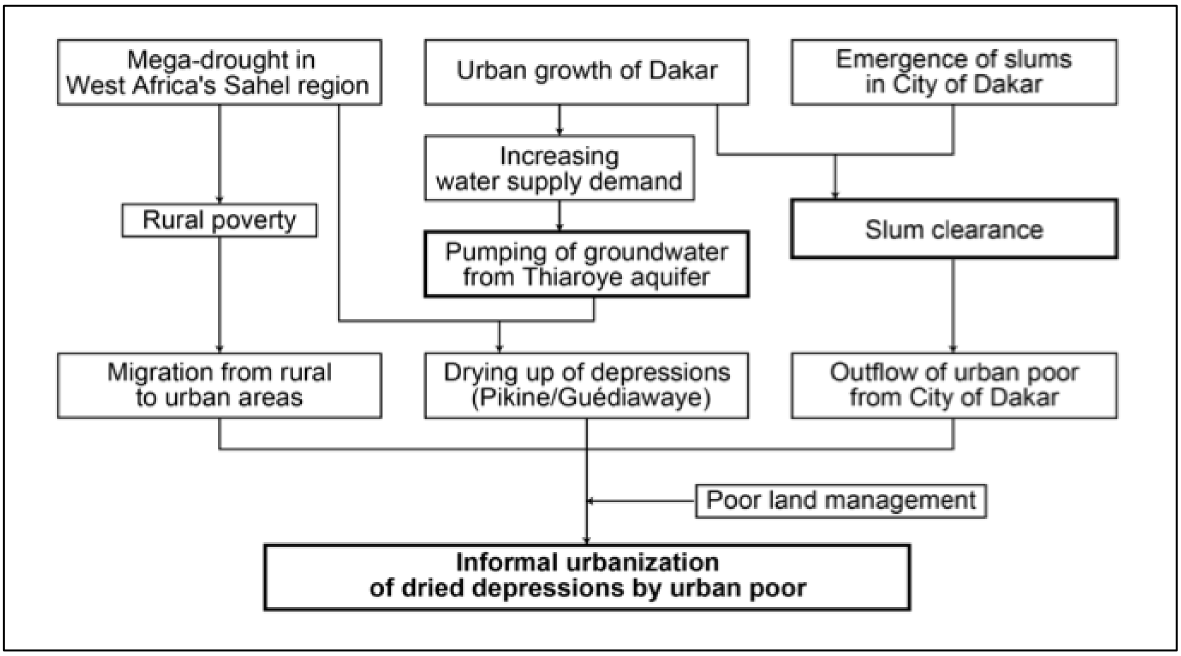

Figure 5.2: Informal urbanisation process in depressions in suburban Dakar (Okuda, 2012)

6 Exploitation of the Thiaroye aquifer

In 1950, the City of Dakar started pumping water from the Thiaroye aquifer to use as drinking water. An exploitation field in Thiaroye was developed (cf. Figures 4.1 and 6.1), extracting water at 25-40 m depth. Until 1959, water was pumped at a rate of 17,000 m^3/d. This resulted in an important lowering of the groundwater level. Because the aquifer is in direct contact with the Atlantic Ocean the lowering of the water table created a risk of saltwater intrusion. For this reason, the pumping was reduced to 2,000 m^3/d in the years 1960-1962. But to meet the water needs of the growing city of Dakar, exploitation was increased again in 1962 to a rate of 10,000 m^3/d. This seemed to keep the risk of saltwater intrusion at an acceptable level. The aquifer was pumped at this rate until 1988. (von Gunten, 2012; Cabinet Merlin 2007)

Figure 6.1: Thiaroye well field (PDD no. 1, 2011)

The population growth in the suburban areas was neither planned nor controlled. Public wastewater and sanitary systems were not developed and the Thiaroye aquifer became highly polluted with nitrate. The most densely populated area is around the wells of the Thiaroye capture zone, which has made this part of the aquifer the most polluted. Today, the groundwater cannot be used as drinking water on its own, mainly because of the high levels of nitrate (up to several hundreds of mg-NO_3/L). The Thiaroye wells are today pumped at a negligible rate of 1,200-1,300 m^3/d and the water is mixed with water of better quality to dilute the salts and nitrate.

Another area of the Thiaroye aquifer, the area of Beer-Thialane further east (Figure 4.1), was exploited for irrigation purposes. Five wells (F1 to F5), situated along a 2 km long line, were drilled and water extracted at a depth of 25-40 m from 1972. F5 was abandoned in 1987 due to high salt content. The other four wells experienced corrosion and were either repaired or replaced several times. The Beer-Thialane well field was exploited at a rate of 6,090–11,160 m^3/d until it was abandoned in 1999 due to improper maintenance of the wells (Cabinet Merlin, 2007). There are plans to reactivate these wells for agricultural purposes (Ndong & Royez, 2012).

7 Flooding in Dakar

7.1 Introduction

Most African coastal cities face a growing risk of urban flooding. The causes are complex, being a mixture of climate change, rapid urbanisation, poverty, and poor land management, amongst others. Flooding has been identified as one of the major factors preventing Africa's growing urban population from escaping poverty (Okuda, 2012). In Dakar, an estimated 400,000 to 600,000 people are each year affected by the flooding. Only in 2009, about 360,000 people were directly affected, and the cost of the flooding was assessed to 104 million USD (Okuda, 2012). The flooding creates significant damage to the infrastructure, public and private property and destruction of urban agricultural land and crops. The stagnant water is polluted and creates bad odour and a habitable environment for insects and microbes, which in turn increase the risk of malaria, cholera, diarrhoea and other illnesses and epidemics. The commune of Medina Gounass in Guédiawaye is one of the areas most affected by flooding. In addition, it is one of the most densely populated areas (261 habitants/km^2 against 45 habitants/km^2 in average in Dakar). In this commune, the rate of hospitalisation is 10 times greater than in the rest of Dakar, which supports the theory of a correlation between flooding and negative health effects. (ANTEA, 2003, Vol. env.)

Figure 7.1: Flooded zone with algae growth on the water. Tomatoes and other vegetables are grown around the flooded area (photo: author)

7.2 Causes

7.2.1 General considerations

Urban floods in Dakar can be separated into groundwater floods, due to a rising water table, and pluvial floods, a result of increased surface runoff. The problem of flooding in Dakar, although triggered by natural events in the form of water table rise and intense precipitation, is mainly a result of anthropic activities. The following paragraphs describe each of the processes related to the flooding occurrences and Figure 7.2 schematically presents the chain of causation.

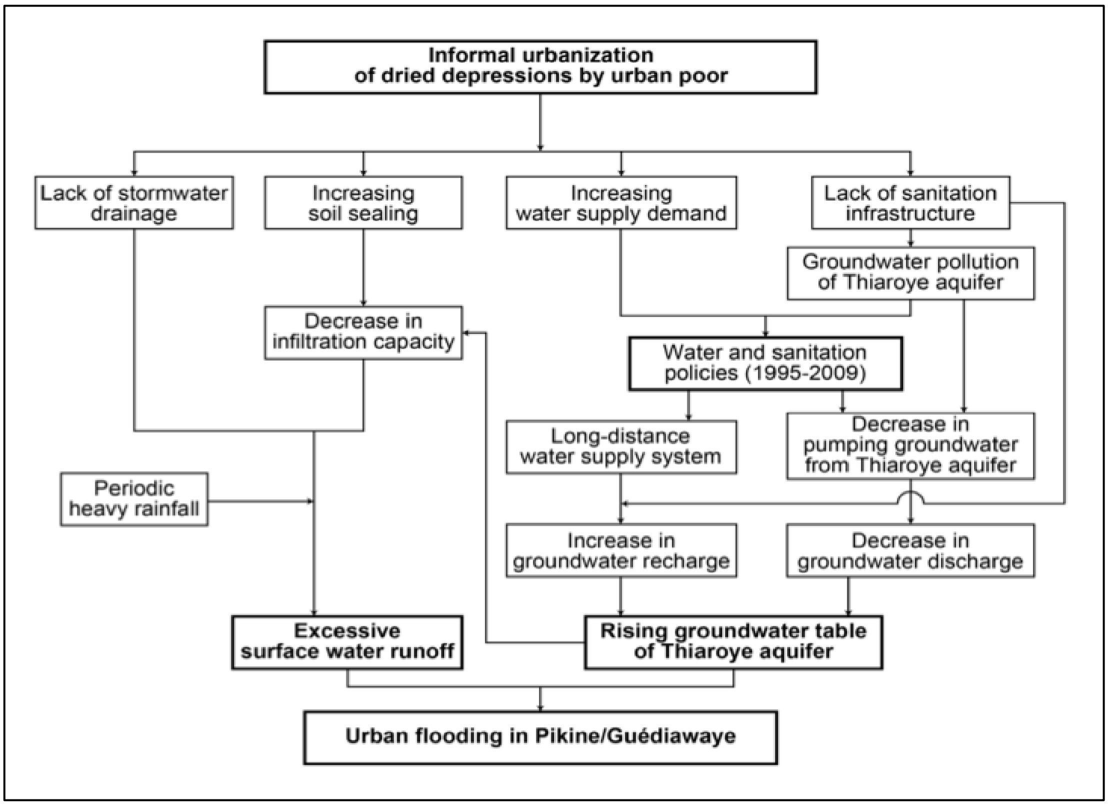

Figure 7.2: Urban flood occurrences in suburban Dakar (Okuda, 2012)

7.2.2 Increased anthropogenic recharge

To provide water to the whole region of Dakar, the SDE (Sénégalaise des Eaux) transports water from Lake Guiers, situated 250 km north of Dakar in the region of St. Louis. Along with the informal urbanisation in the 1970's and 1980's, a public wastewater drainage and treatment system failed to be developed. Even today, most houses have personal septic tanks or pit latrines, which allow seepage to the groundwater. An estimated 52,000 m^3/d of water is today distributed to the suburban region. Between

75-95% of this water can be expected to infiltrate down to the groundwater. An additional 15% of the distributed water must also be included in the anthropogenic recharge due to leakage from the distribution system. As a result of the reduced exploitation of the aquifer, the added recharge due to infiltration of domestic water, wastewater and leakage, together with the tendency of increased precipitation, the water table increases by about 15 cm every year. The dried up depressions have again become flooded and other areas are now regularly flooded during the rainy season (von Gunten, 2012; Ndong & Royez, 2012).

7.2.3 Urbanisation and reduced soil infiltration

Increased urbanisation results in expansion of built-up areas with more houses and roads and a general compaction of the soil. The surface where rainwater can infiltrate becomes gradually decreased and the surface runoff equally increased. Due to the topography of the region of Dakar, there is no natural drainage pathway out of the area and surface runoff flows towards the depressions

Figure 7.3: Water from the hand-operated Diambar pumps is used for domestic activities like washing and given to animals. The photo is of the site DP9. (Photo: author)

7.3 Current strategies and their limitations

7.3.1 Generalities

The problems related to flooding in Dakar are complex and there are many actors involved (Amiguet, 2013). Several solutions have been proposed, including pumping of the aquifer, construction of retention pools, construction of drainage pathways and development of a public wastewater system. Each of the strategies plays an important role, but if developed independently of each other, new problems may arise. Reduction of the groundwater table is inevitable to reduce the risk of flooding, but at the same time, the “Niayes” are important to the region as urban agricultural land. Too deep groundwater will have negative effects on the urban agriculture and enhance the risk of saltwater intrusion. A coordinated development of the strategies is essential to achieve a sustainable, long-term management of the groundwater. The following paragraphs describe the current strategies, with their positive sides and their limitation.

7.3.2 Groundwater management

Wastewater and sanitation systems: This strategy is called the Plan Directeur d’Assainissement (PDA) and is proposed by the organisation ONAS (Office National de l’Assainissement du Sénégal). The goal is to improve the wastewater and sanitation systems in the suburban areas of the Dakar Region during the period of 2010-2025 (von Gunten, 2012). Developing a public wastewater system is unavoidable both from a social, environmental, political and economic point of view. The anthropogenic recharge to the aquifer is the main cause of the rising water table. During 2003, the water table increased by 0.5-1m in the DTK community (von Gunten, 2012). Developing sanitary systems will also have an impact on the water quality, as the lack of such a system is the reason for the high levels of nitrate. Unfortunately, the region is densely populated and the social-economic situation complicates the construction of a complex wastewater system. It will also take many years before such a system is ready. Construction of a public wastewater system is the most important strategy in a long-term perspective, but for immediate action other solutions against the flooding must be found.

Exploitation of the aquifer: It is the “Programme de Développement des Marchés Agricoles” (PDMAS) that is in charge of providing sufficient water for irrigation for the agricultural activities in the Dakar Region. The Beer-Thialane wells (cf. Figure 4.1) are planned reactivated in the near future (Hitz, 2012). The participants of the round table seminary of Nov. 2012 (Ndong & Royez, 2012) proposed to do the same for the Thiaroye wells. Extraction of groundwater will give immediate results in the areas most prone to flooding. The extracted water can be used as irrigation water for the agricultural areas of

Rufisque (Figure 5.1) and would thus become a valuable resource for the community. Other potential usages of the water from Thiaroye include different industrial activities in the region. The constraints related to the pumping strategy are the deteriorated water quality, the area where the pumping has an effect being limited to the Thiaroye capture zone, and the risk of saltwater intrusion if overexploited.

7.3.3 Surface water management

Lowering of the water table is important to clear areas that are flooded throughout the year, but it is not sufficient to cope with the intense rainfall during the wet season. There are two main strategies to control the surface runoff:

Drainage system: The “Programme de Gestion des Eaux Pluviales dans la Zone Périurbaine de Dakar” (PROGEP) forsees a horizontal drainage system that will affect both the groundwater level and the regions sensitivity to intense rainfall events. In areas close to the drainage pathways, the water table will be kept at a maximum level and less water will contribute to the natural recharge of the aquifer. Surface runoff will be collected and lead towards retention pools, lakes or the ocean, and thus reduce the flooding. The drainage strategy is limited in that the lowering of the water table will only be effective in areas close to the drainage pathways (PDD no. 1 & 3, 2011).

Plan Jaxaay and retention pools: After the event of major flooding in 2005, the Senegal government reacted by creating the “Plan Jaxaay”. The goal of this urgency plan was to relocate the people living in flooded zones to the periphery of Dakar City. Retention pools were constructed in the evacuated zones. However, because the pools are located where the groundwater is already at the surface, their retention capacity is limited. To increase the capacity, the pools were drained before and during the rainy season with motor pumps and the water rejected to the ocean. Nevertheless, this did not prove sufficient around the currently existing retention pools during the flooding of 2009 (von Gunten, 2012). Today there are several existing retention pools. The three most important are situated in the neighbourhood of Medina Gounass, Bagdad and Nietty Mbar (Figure 10.2). Plan Jaxaay is under operation, but the relocation of thousands of people living in flood prone areas has proven to be very difficult (Amiguet, 2013).

Figure 7.4: Retention pool Nietty Mbar (photo: author)

Figure 7.5: Retention pool and Bagdad (photo: author)

Theoretical Background

8 Nitrate in the environment

8.1 Introduction

Nitrogen, N, is an abundant element, constituting 78.1 vol% of the atmosphere in the form of N_2 gas. All forms of life incorporate nitrogen in their cell structure. It is a major component in amino acids, nucleic acids and phospholipids. Nitrogen is essential to life, but various nitrogen compounds can also be poisonous at high concentrations. The European Union and the World Health Organization have both set the maximum concentration for nitrate in drinking water at 50 mg-NO_3/L, or 11.3 mg-N/L (Rivett et al., 2008, WHO, 2006). Above this value, the nitrate interferes with the O_2-carrying capacity of haemoglobin in infants, and may result in methemoglobinemia, commonly known as blue-baby syndrome. Nitrate can also be implicated in the formation of carcinogenic nitrosamine compounds in humans. As ammonium (NH_4^+), it is toxic to aquatic life and contributes to oxygen demand. Most ecotoxicological studies on the toxicity of inorganic nitrogen indicate LC_{50}-limits[5] of about 100 mg/L for amphibians and about 1000 mg/L for fish (CAN, 2003). However, the indirect toxic effects of high NO_3^--concentrations in water, through depletion of O_2 due to excessive algae growth (limit of about 5 mg/L O_2), is probably much more important. In addition to the direct hazard of nitrate contamination, values of nitrate content may serve as an indicator of faecal pollution when microbiological data are lacking. Other environmental problems related to high concentration of nitrate include eutrophication of surface waters, often followed by fish-death due to oxygen depletion. Emissions of both nitric oxide (NO) and nitrous oxide (N_2O), which are intermediate products of denitrification, result in acidification of ecosystems by acid rain, destruction of ozone and global warming (Clark & Fritz, 1997; Rivett et al., 2008).

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[5] Lethal concentration 50 %: Concentration required to kill half the member of a tested population after a specified test duration (Wikipedia).

The main sources of nitrate in the environment are biological fixation and nitrification of atmospheric N_2, precipitation, manure and fertilizers, sewage, human and animal wastes, mine waste dumps, and leachates from landfills.

Human waste contains significant amounts of nitrogen in the form of soluble inorganic compounds like nitrate, nitrite and ammonia, and organic compounds like proteins and peptides. Jacks et al. (1998) propose that around 95 % of the total nitrogen in human excreta is present in the urine, while Höglund (2001) found that 80% of the nitrogen in Swedish domestic wastewaters comes from urine and around 12 % from faeces. Urine also contains other nutrients like sulphate, phosphorus and potassium, but very little heavy metals, which makes it a good fertiliser. Today, the alternatives to a conventional wastewater system include systems that separate or divert urine and faeces in order to use the nutrients more efficiently. In regions without piped sewerage, like the suburbs of Dakar, nutrient utilisation as well as improved sanitation is possible to achieve by avoiding mixing urine and faeces. If the faecal fraction is kept dry there will be less leaching from, for example, pit latrines and in many places the faeces are also reused. Thus, the two main reasons to separate urine and faeces are to recycle the plant nutrients in urine and to obtain a faecal fraction that is more practical and safer to handle. Fresh urine contains around 7 g/L of nitrogen, mostly in the form of urea, and has a pH between 4.8 and 7.5. However, urea is usually quickly degraded to ammonium, e.g. in pipes, and increases the pH up to 9 (Höglund, 2001).

Nitrogen exists in oxidation states -3 (NH_4^+), 0 (N_2), +1 (N_2O), +2 (NO), +3 (NO_2^-), and +5 (NO_3^-). The only two forms of N that plants and algae can assimilate are nitrate and ammonium. Organisms adapted to low pH and reducing conditions tend to favour ammonium over nitrate. In soils or waters with high pH and more aerobic conditions, nitrate is the preferred species of N (Figure 8.1). Other forms must either be oxidised to nitrate or reduced to ammonium before plants or algae can assimilate the nitrogen (e.g.,

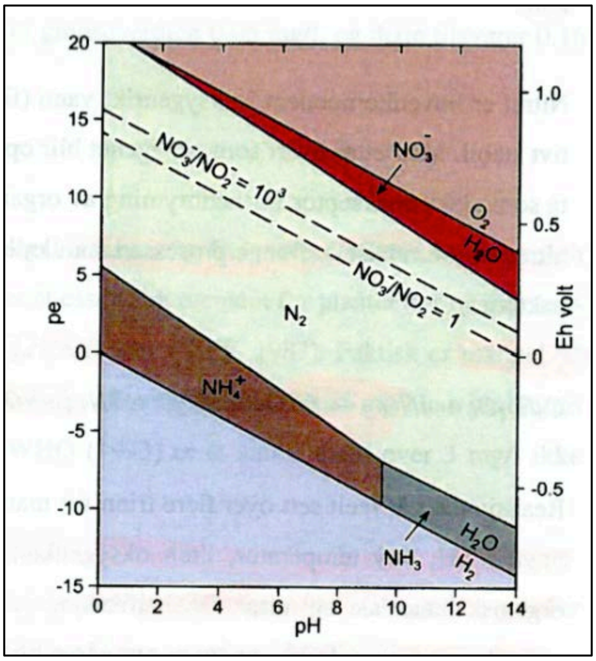


Figure 8.1: Eh-pH diagram for nitrogen (Brattli, 2009)

Clark & Fritz, 1997; Kendall & McDonnell, 1998). Nitrate is very soluble and usually exhibits a conservative behaviour, i.e. it does not form precipitates, nor is it easily adsorbed. It is stable and mobile in oxygenated waters and can therefore be easily leached out from agricultural soils to the groundwater. The main process that reduces the nitrate concentration in groundwater is the reduction of NO_3^- to $N_{2(g)}$, a process called denitrification. (Brattli, 2009; Rivett et al., 2008)

8.2 Processes

The nitrogen cycle is a complex system of many different processes, involving all environmental compartments (Figure 8.2).

8.2.1 Biological nitrogen fixation

Dinitrogen is an odourless, colourless, and inert gas at standard conditions. The triple bond between the nitrogen atoms in $N_{2(g)}$ is extremely strong and requires high energy-input to be broken (bond energy = 945 kJ/mol, www.webelements.com). Biological nitrogen fixation refers to the process where $N_{2(g)}$ is changed into ammonia. The process must be mediated by microorganisms. Only certain prokaryotes of bacteria, algae, and Archaea, so called nitrogen fixers, are able to perform this reduction of N_2. They employ the specific Fe- and Mo-bearing enzyme nitrogenase, which catalyses the following reaction (Sigel et al., 2005):

$$N_2 + 8e^- + 8H^+ \rightarrow 2NH_3 + H_2 \tag{8.1}$$

Nitrogenase is rapidly, and irreversible, deactivated by oxygen. Therefore, only those organisms that live in anoxic conditions, or that can locally create such an environment, are able to perform nitrogen fixation (Sigel et al., 2005).

8.2.2 Ammonia assimilation

Assimilation refers to the incorporation of N-bearing compounds into organisms. Ammonia uptake is a process where ammonium is transferred to organic nitrogen-containing compounds. This direct assimilation into the biomass has energetic advantages for those organisms. The process is mainly present under anoxic conditions where nitrification does not occur (Kendall & McDonnell, 1998).

8.2.3 Nitrification

Nitrification is a two-step process where ammonium is oxidised to nitrite and then further to nitrate. Aerobic, chemoautotroph bacteria mediate the processes, but no known organism is able to perform both steps simultaneously. *Nitrosomonas*, which is very common in soils, is the most important type of bacteria during the first stage; oxidation to nitrite (equation 8.2). *Nitrobacter* is the representative bacteria that oxidises nitrite to nitrate (eq. 8.3) (Knowles and Blackburn, 1993):

$$NH_4^+ + 3/2\,O_2 \rightarrow NO_2^- + H_2O + 2\,H^+ \qquad \Delta G^0 = -290\text{ kJ/mol} \qquad (8.2)$$

$$NO_2^- + ½\,O_2 \rightarrow NO_3^- \qquad \Delta G^0 = -82\text{ kJ/mol} \qquad (8.3)$$

The nitrification process requires oxygen and is thus only possible under aerobic conditions. The optimal pH range is 7 to 9.

8.2.4 Assimilatory nitrate reduction

This process is a biologically fundamental process defined as the reduction of nitrate and uptake of the nitrate-derived ammonia into the biomass. Bacteria, fungi, algae and higher plants have the ability to assimilate nitrate. Assimilatory nitrate reduction is the main source of nitrogen for many microorganisms, whereas plants can often assimilate both nitrate and ammonium. Ammonia assimilation, with NH_4^+ derived from fixation of N_2, is more energetically favourable for many organisms. Nitrate assimilation is therefore mostly prevalent in aerated waters and soils, where the amount of ammonium is originally low (Guerrero et al., 1981).

For this study, the uptake of N by phytoplankton present in the eutrophic lakes and retention pools is an important process. According to Colles & Berges (2013), the major part is nitrate assimilation.

8.2.5 Ammonification

Degradation of organic matter releases nitrogen to the environment. The initial stage is the breaking down of particulate organic nitrogen (PON) to dissolved organic compounds (DON). Heterotrophic bacteria transform the DON to ammonium in the process “ammonification” (eq. 8.4). The resulting ammonium can then be assimilated or microbially oxidised to nitrate (Kendall & McDonnell, 1998):

$$\text{organic-N} \rightarrow NH_4^+ \qquad (8.4)$$

8.2.6 Denitrification

Denitrification is the biologically facilitated reduction of nitrate to N_2 and other intermediate compounds (eq. 8.5). Microorganisms, mostly anaerobic heterotroph bacteria like *Pseudomonas denitrificans*, but also autotrophs and fungi, are able to oxidise organic matter (simplified as HCHO) by using nitrate as electron acceptor (eq. 8.6, Appelo & Postma, 1993; Kendall & McDonnell, 1998):

$$NO_3^- \rightarrow NO_2^- \rightarrow NO_{(g)} \rightarrow N_2O_{(g)} \rightarrow N_{2(g).} \qquad (8.5)$$

$$5HCHO + 4\,NO_3^- \rightarrow 2\,N_2 + 5\,HCO_3^- + H^+ + H_2O \qquad (8.6)$$

An important rate-limiting factor is the presence of available organic carbon. The relative concentrations of nitrate and organic carbon appear to control whether nitrate is depleted by denitrification or by dissimilatory nitrate reduction to ammonium (Rivett et al., 2008).

Depending on the redox conditions, organisms will use different oxidised compounds as electron acceptor in the preferred order: O_2, NO_3^-, SO_4^{2-}. Oxygen is thus a competing electron acceptor, and denitrification does not occur in the presence of high concentration of dissolved oxygen. The maximum amount of dissolved oxygen present during denitrification is often assumed to be 2 mg/L, but it has been observed up levels of 4 mg/L (Rivett et al., 2008). Denitrification can also occur in anaerobic pockets within an otherwise oxygenated soil or water body. In addition to being an electron acceptor, key enzymes of the denitrification processes are inhibited by the presence of oxygen (Kendall & McDonnell, 1998). Optimal conditions for denitrification are a pH between 5.5 and 8.3 and a relatively low salt content. When the pH becomes more basic than 8.3, denitrification is inhibited, while at pH lower than 5, the process stops at the N_2O step, which may be released to the atmosphere and contribute to the greenhouse effect (Rivett et al., 2008).

Seo & DeLaune (2010) found that denitrification might occur over a large interval of redox conditions; with Eh ranging from -100 mV to +400 mV. In an ideal system, bacterial denitrification can occur in conditions with a redox potential of maximum +250 mV. This corresponds to the findings of Fukada et al. (2004). However, Seo & DeLaune (2010) also showed that denitrification by fungi occur up to +400 mV. The maximum rate of denitrification mediated by both bacteria and fungi is around 0 mV. Under strongly reducing conditions (e.g. -200 mV) bacteria are responsible for most of the denitrification. Between -100 to +100 mV, fungi and bacteria were found to be equally important, while in slightly oxidising conditions (+250 to +400 mV), fungi is the most efficient denitrifier (Seo & DeLaune, 2010). Both the presence of NO_2^-, N_2O and increased amounts of bicarbonate (eq. 8.6) may indicate that denitrification is taking place (Appelo & Postma, 1993; Rivett et al., 2008).

Denitrification can also be mediated by chemo-autotrophic respiration of *Thiobacillus denitrificans*, which uses sulphur as electrone donor (Kendall & McDonnell, 1998).

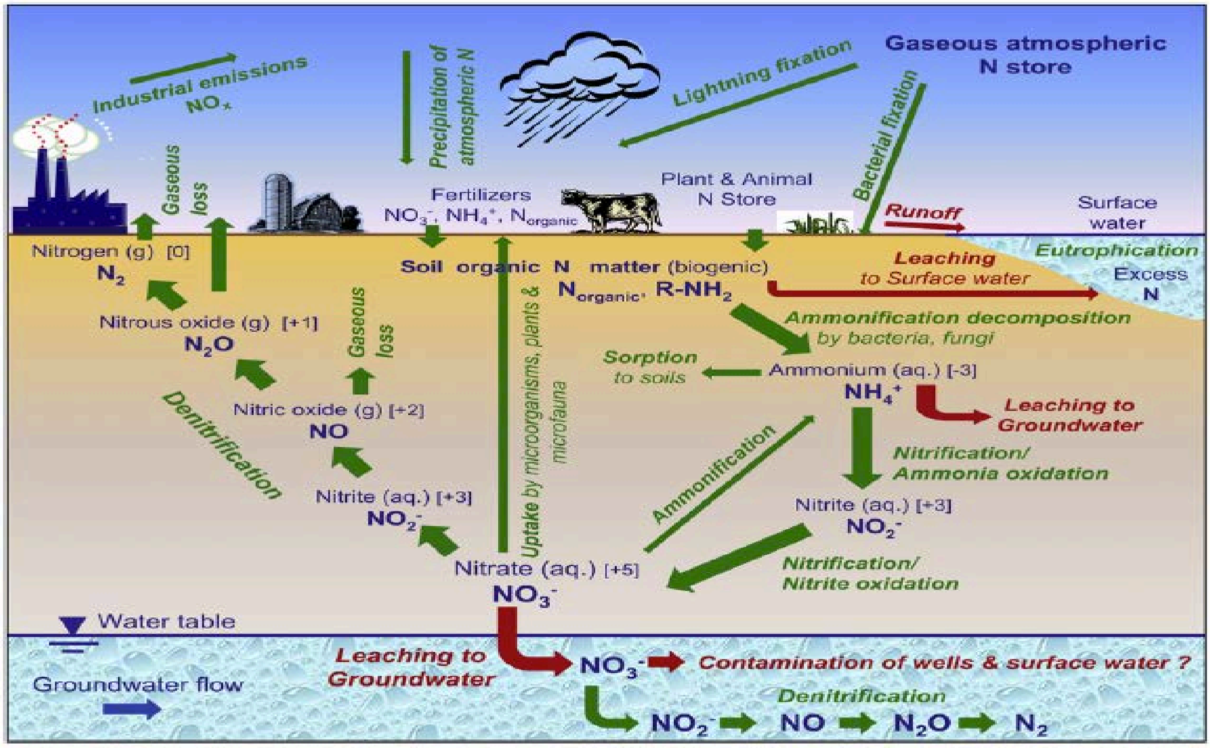


Figure 8.2: Schematic figure of the nitrogen cycle (Rivett et al., 2008)

9 Environmental isotopes in hydrogeology

9.1 Fundamentals of isotope geochemistry

Protons and neutrons make up the nuclide of an atom. Isotopes of an element have the same number of protons and electrons, but different number of neutrons and therefore different atomic weight. For example, most oxygen has 8 protons and 8 neutrons, giving an atomic mass of approximately 16. However, 0.04% of all oxygen atoms contains 9 neutrons and has an atomic mass of 17, while 0.2% has 10 neutrons and a mass of 18. The chemical properties of molecules with the same chemical composition, but with different isotopic composition, are essentially the same. However, the properties related to their mass (physical-chemical properties) change for the different isotopologues (same molecules but made up by different isotopes). Some nuclides have either too many or too few neutrons creating an unstable isotope or a radioactive nuclide. Stable isotopes, on the other hand, do not decay. Figure 9.1 shows the abundance of some light element isotopes. (Clark & Fritz, 1997)

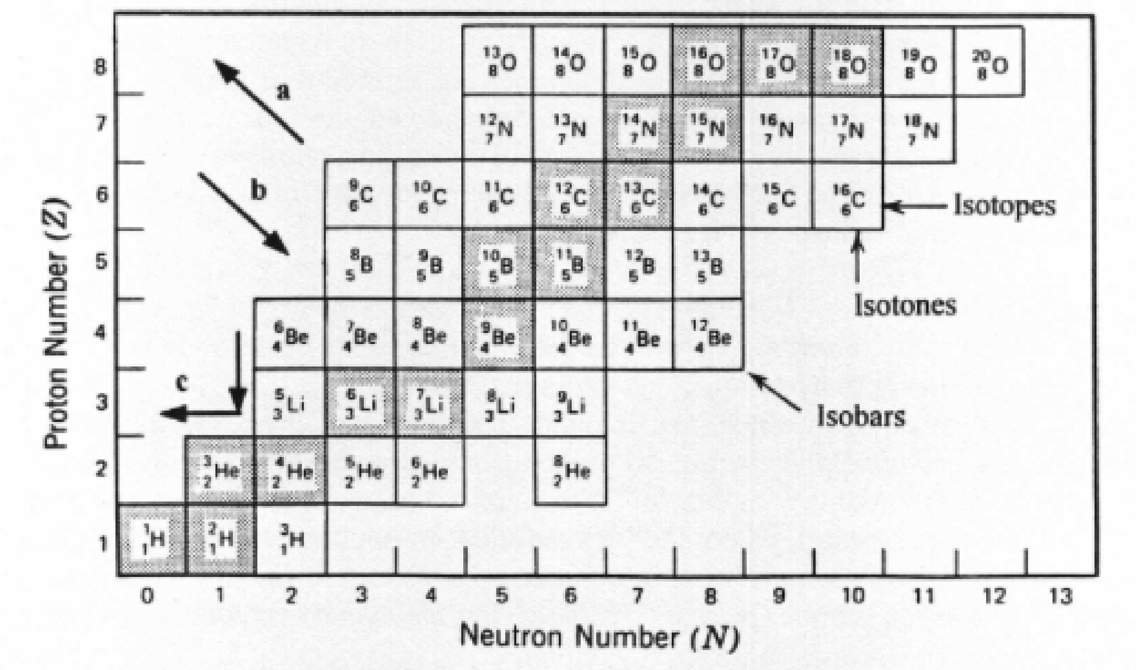


Figure 9.1: Partial chart of some light elements and their isotopes. Shaded squares are stable isotopes; white squares are unstable or radioactive nuclides (Kendall & McDonnell, 1998)

The variation in the number of neutrons in elements results in different masses of the molecules of which they are a part. Molecules with differences in mass have different reaction rates. This leads to isotope partitioning or fractionation. The delta (δ) notation, expressed in permil (‰) difference from a reference, is used to define the isotopic composition of a material (Kendall & McDonnell, 1998):

$$\delta = (\frac{Rx}{Rs} - 1) * 1000 \text{ (‰)} \qquad (9.1)$$

where R denotes the ratio of the heavy to light isotope (e.g. $R_{oxygen} = {}^{18}O/{}^{16}O$). R_x and R_s are the ratio in the sample and the standard respectively. This gives the relationship (Clark & Fritz, 1997):

$$\delta^{18}O_{sample} = (({}^{18}O/{}^{16}O)_{sample} / ({}^{18}O/{}^{16}O)_{standard} - 1)*1000 \text{ (‰)} \qquad (9.2)$$

(Vienna Standard Mean Ocean Water (VSMOW))

A positive delta value represents enrichment of the heavy isotope in the sample; the isotopic ratio of the sample is higher than that of the standard. A negative value means a depletion of the heavy isotope compared to the standard.

In hydrogeology and environmental geology, only certain isotopes are of practical importance. Amongst the stable isotopes, abundant light elements like H, C, N, O, and S are the most important. These are principal elements in hydrological, geological, and biological systems. Stable environmental isotopes are now used to trace groundwater provenance, recharge processes, subsurface processes, geochemical reactions and reaction rates. Some radioactive environmental isotopes are also important in hydrogeology. For example, radionuclides such as ^{14}C and ^{3}H can be used to estimate the age or circulation of groundwater (Clark & Fritz, 1997).

9.2 Isotopic fractionation

During physical, chemical and biological processes, the isotopic composition of a medium gets altered. Thermodynamic fractionation is a fundamental process and is due to differences in the reaction rates for different molecular species. Isotopic fractionation can happen by physicochemical reactions under equilibrium conditions or non-equilibrium (kinetic) conditions or by molecular diffusion (also kinetic). The fractionation factor, α, is the ratio of the isotope ratios of the reactant to that of the product (Clark & Fritz, 1997):

$\alpha_{s-p} = R_{substrate} / R_{product}$ (9.3)

where R is the ration of each compound (e.g. $R_{O2} = {}^{18}O/{}^{16}O$)

Reactions can be a physical change of state:

$H_2O_{water} \leftrightarrow H_2O_{vapour}$ (9.4)

$\alpha^{18}O_{water\text{-}vapour} = ({}^{18}O/{}^{16}O)_{water} / ({}^{18}O/{}^{16}O)_{vapour}$ (9.5)

or a chemical or biological transformation:

$CO_2 + H_2O \leftrightarrow H_2CO_3$ (9.6)

$\alpha^{13}C_{CO2\text{-}H2CO3} = ({}^{13}C/{}^{12}C)_{CO2} / ({}^{13}C/{}^{12}C)_{H2CO3}$ (9.7)

The basis of physical-chemical fractionation is the difference in the bond strength formed by the light vs. heavy isotope of a given element. The strength of chemical bonds involving different isotopic species will usually be different (Figure 9.2). Molecules containing heavy isotopes are more stable than molecules with lighter isotopes; they have higher dissociation energy and lower zero-point energy (ZPE). ZPE is the minimum potential energy of a molecular bond in a vibrating atom (Clark & Fritz, 1997; Kendall & McDonnell, 1998).

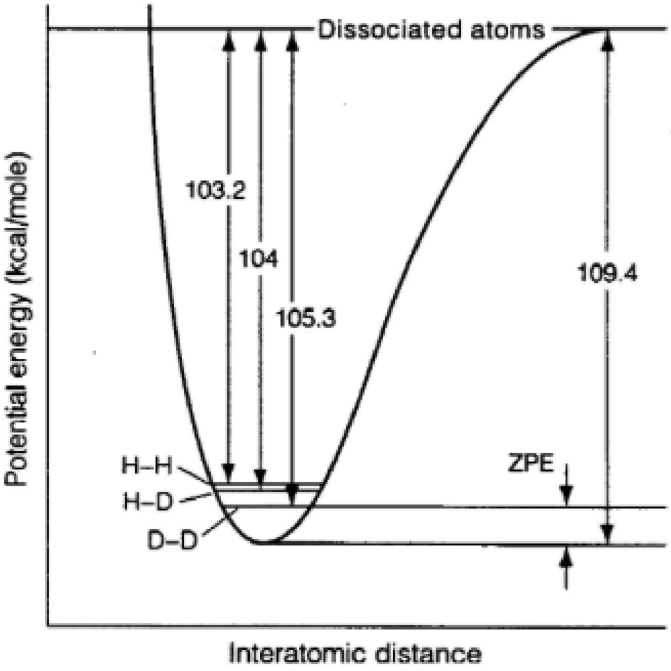


Figure 9.2: The potential energy/atomic distance relationship for stable hydrogen isotopes of a molecule. Higher ZPE (distance from curve minimum to bond energy) results in a molecule being less stable (Kendall & McDonnell, 1998)

9.2.1 Equilibrium fractionation

Isotopic fractionation at equilibrium is the process of isotope-exchange in a closed, well-mixed system at chemical equilibrium. At isotopic equilibrium, the forward and backward reaction rates of any particular isotope being exchanged are identical. This means that the ratios of the different isotopes in each compound are constant at a specific temperature (Kendall & McDonnell, 1998).

During equilibrium reactions, the heavy isotope usually has a slight tendency to accumulate in the compound with the higher oxidation state. For example, nitrate (+5) becomes more enriched with ^{15}N compared to nitrite (+3), and sulphate (+6) contains more of the heavy isotope, ^{34}S, than sulphide (-2). Among the different phases of a compound, the most solid phase is normally the most enriched in heavy isotopes. For the various phases of water at equilibrium $\delta^{18}O_s > \delta^{18}O_l > \delta^{18}O_g$. Similarly, the $\delta^{13}C$ and $\delta^{18}O$ values of $CaCO_{3(s)} > HCO_3^- > CO_{2(g)}$. The condensation of water vapour to precipitation is an equilibrium reaction (Kendall & McDonnell, 1998).

9.2.2 Non-equilibrium fractionation

A sudden change in temperature or the addition or removal of a reactant can move a system far from thermodynamic equilibrium and the forward reaction rate accelerates. The reversed reaction will by consequence diminish. This creates kinetic fractionation conditions. The rate of the reaction influences the amount of fractionation. For example, calcite gets enriched by about 1 ‰ over bicarbonate in solution during precipitation. However, if the rate of precipitation is accelerated, the difference decreases towards 0. Similarly, if water freezes very rapidly, the 3 ‰ equilibrium enrichment of oxygen-18 in ice with respect to water is reduced towards 0. Kinetic effects are affected by the surface temperature, wind speed, salinity, and most importantly, humidity. Evaporation at humidities lower than 100% is a non-equilibrium fractionation reaction (Clark & Fritz, 1997).

9.2.3 Diffusive fractionation

Isotopic fractionation can occur due to concentration gradients. This can be diffusion within another medium (e.g. CO_2 diffusing through a static air column, or Cl^- diffusion through clay) or diffusion of a gas into vacuum. Fractionation happens because of the differences in diffusive velocities between isotopes. It is possible to establish a steady-state diffusion regime, but not equilibrium, as this would be a completely mixed system with no fractionation. Thus, diffusion is a kinetic fractionation process (Clark & Fritz, 1997).

9.2.4 Rayleigh equation

For many isotopic fractionation processes, the Rayleigh equations describe the partitioning of isotopes between two reservoirs (compounds or species) as one reservoir decreases in size. It can only be used to describe an isotopic fractionation if 1) the material is continuously removed from a mixed system containing molecules of two or more isotopic species, 2) the fractionation accompanying the removal process at any instance is described by the fractionation factor α, and 3) α does not change during the process. Under these conditions, the evolution of the isotopic composition in the residual material is described by (Kendall & McDonnell, 1998):

$$R = R_o f^{(\alpha - 1)} \qquad (9.8)$$

where R is the isotope ratio in a diminishing reservoir, R_o the initial isotope ratio in the bulk water, f the remaining water fraction of the reactant and α the fractionation factor between the two phases or compounds.

Using eq. 9.1, the Rayleigh equation can be expressed as:

$$\frac{\delta + 1000}{\delta_o + 1000} = f^{\alpha - 1} \qquad (9.9)$$

which is valid for δ_o near 0, α near 1, and $\varepsilon < 10$ (see next paragraphs)

The Rayleigh equation can be applied to physical-chemical processes like evaporation and condensation and biological processes like nitrification and denitrification. For example, during evaporation, light isotopes are removed and the remaining water becomes increasingly enriched in heavy isotopes. As will be seen in the following paragraphs, the humidity, h, affects this progressive enrichment of the bulk water. The smaller the humidity is, the greater the fractionation will be (Figure 9.3, eq. 17 and 18) (Kendall & McDonnell, 1998).

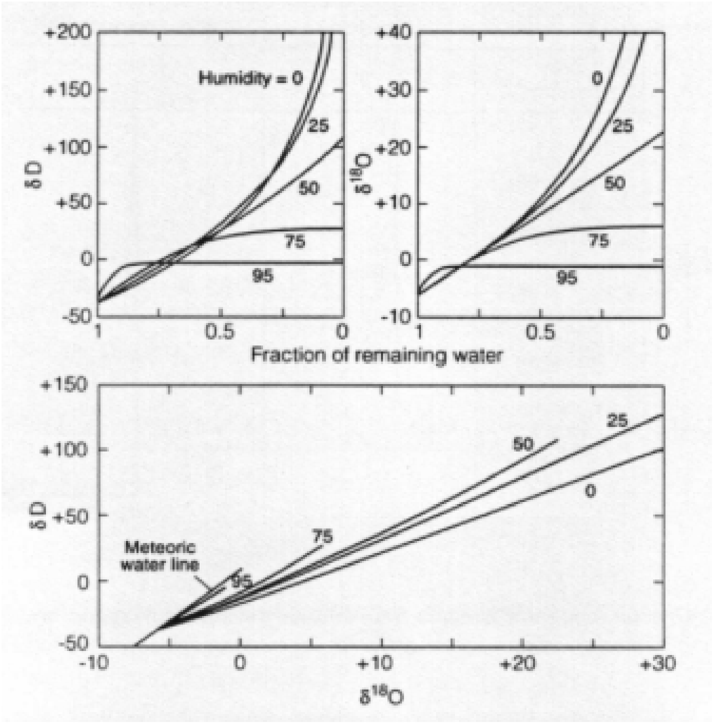


Figure 9.3: The effect of humidity on the δ^{18}O and δ^{2}H values of the residual water fraction during evaporation. Higher humidities result in less fractionation because the back exchange between the water and the vapour, and evaporation lines with higher slopes (Kendall & McDonnell, 1998)

9.2.5 Other useful parameters and relationships

The isotopic difference or isotopic separation, Δ, between two compounds in an isotopic exchange reaction, whether or not they are co-reacting, is:

$$\Delta_{A\text{-}B} = \delta_A - \delta_B \qquad (9.10)$$

The fractionation factor for isotope exchange between these two compounds is derived from the δ-‰ values according to:

$$\alpha_{A\text{-}B} = (1000 + \delta_A) / (1000 + \delta_B) \qquad (9.11)$$

The corresponding fractionation factor for the reversed reaction is the inverse:

$$\alpha^*_{B\text{-}A} = 1/\alpha_{A\text{-}B} \qquad (9.12)$$

The enrichment factor, ε, can be used to express this isotopic difference in ‰ notation (Clark & Fritz, 1997; Kendall & McDonnell, 1998):

$$\varepsilon_{A\text{-}B} = (\alpha_{A\text{-}B} - 1)\, 1000\ ‰ \qquad (9.13)$$

For small values of epsilon, $\varepsilon_{A\text{-}B} \approx \delta_A - \delta_B$. The relationship can be simplified to:

$$\varepsilon_{A\text{-}B} \approx 1000 \ln \alpha_{A\text{-}B} \approx \Delta_{A\text{-}B} \qquad (9.14)$$

9.3 Isotopes of H and O

9.3.1 Introduction

The isotopic composition of materials is usually reported relative to an international reference standard. Samples are either analysed at the same time as this reference standard and/or with an internal laboratory standard that has been calibrated relative to the international standard. Different standards are used for the different elements. Due to its abundance and because its values are relatively constant all around the world, seawater is used as the basis for the hydrogen and oxygen isotopes. The H and O isotopes of water are compared to the reference Vienna Standard Mean Ocean Water (VSMOW) with δ^2H = 0 ‰ and $\delta^{18}O$ = 0 ‰ (Clark & Fritz, 1997; Kendall & McDonnell, 1998).

Evaporation from the oceans, rainout, runoff, re-evaporation, snow and ice accumulation and melting vary under different climatic regimes. Each step in the hydrologic cycle partitions oxygen-18 (^{18}O) and deuterium (^2H or D) relative to the light isotopes of ^{16}O and protium, ^1H, amongst the different freshwater reservoirs. However, in spite of all these complex processes, the relationship between the isotopes of the two elements behaves rather predictably. The meteoric relationship for $^{18}O/^{16}O$ and $^2H/^1H$ in precipitation is represented by the global meteoric water line (GMWL) (Figure 9.4, Clark & Fritz, 1997):

$$\delta^2H = 8.17\ (\pm 0.07)\ \delta^{18}O + 11.27\ (\pm 0.65) \qquad (9.15)$$

This relationship is an average of many local or regional meteoric water lines. It is based on measurements of the isotopic composition of precipitation around the globe and adjusted from the line $\delta^2H = 8\ \delta^{18}O + 10$ ‰ initially proposed by Craig (1961), which was based on surface water measurements. Local and regional meteoric water lines may differ from GMWL both in slope and in deuterium intercept. This is due to varying climatic and geographic parameters.

According to Travi et al. (1987) the local meteoric water line for Dakar is:

$$\delta^2H = 7.93\ \delta^{18}O + 10.09 \qquad (9.16)$$

The slope of meteoric water lines is related to the ratio of the equilibrium fractionation (s = $\alpha^2H_{l\text{-}v}/\alpha^{18}O_{l\text{-}v}$. The fractionation between the isotopes of a light element is greater than that for a heavy element. Under equilibrium conditions (100 % humidity) and temperatures of around 25 °C, the ^2H enrichment in water would be roughly 8 times greater than that for ^{18}O, due to the difference in mass for the H and O atoms ($\Delta m/m = (^2H\text{-}H)/H = 1$; $\Delta m/m = (^{18}O\text{-}^{16}O)/^{16}O = 1/8$). The slope of the GMWL is for this reason around 8. The deuterium intercept, *d*, also called the deuterium excess or d-excess, is a result of evaporation at humidities less than 100% (non-equilibrium fractionation). The GMWL plots on a line displaced from seawater by approximately +10 ‰ along the δ^2H axis (Figure 9.4). The deuterium excess varies due to differences in humidity, wind speed and sea surface temperatures. It decreases with increasing humidities. At $h = 1$, the d-excess would be zero.

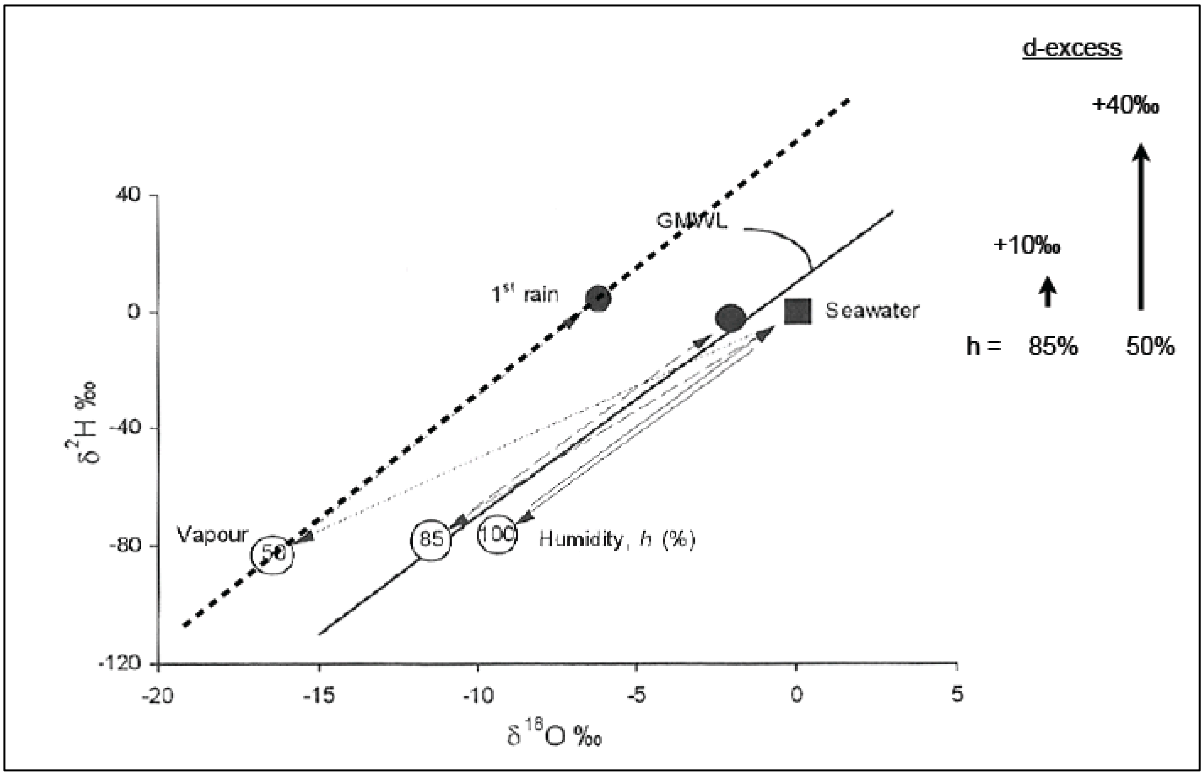


Figure 9.4: Kinetic isotope effects during evaporation of seawater to form vapour (open circles with *h* in %) for various humidities at 25 °C. The first rain formed by equilibrium condensation is shown in filled circles. When humidity is less than 100%, deuterium excess is found in the rain (Clark & Fritz, 1997)

9.3.2 Evaporation

The isotopes of hydrogen and oxygen in water react differently on a phase change. $H_2{}^{18}O$ and ^2HHO have different vapour pressures that result in a disproportional enrichment during evaporation. As shown in Figure 9.5, the water-air interface consists of a boundary layer (with a thickness of a few micrometres), with water-saturated air (h = 100 %), and a transition zone, where the humidity decreases away from the interface (h < 100 %). Isotopic fractionation during evaporation is thus a combination of a thermodynamic equilibrium process in the boundary layer and kinetic diffusive fractionation in the transition zone. Hence the atmospheric vapour changes in isotopic composition with increasing altitude away from the liquid water surface.

The humidity greatly affects the kinetic partitioning; the lower the humidity, the larger the fractionation. Vapour formed at lower humidities is more depleted than that formed at higher humidities. Precipitation from water vapour formed at a humidity of 85 % plots very close to the global meteoric water line (Figure 9.4). This means that in average, global water vapour forms at humidities slightly higher than 85 % (Clark & Fritz, 1997).

The kinetic enrichment during evaporation as a function of humidity can be determined from the following relationships (Gonfiantini, 1986):

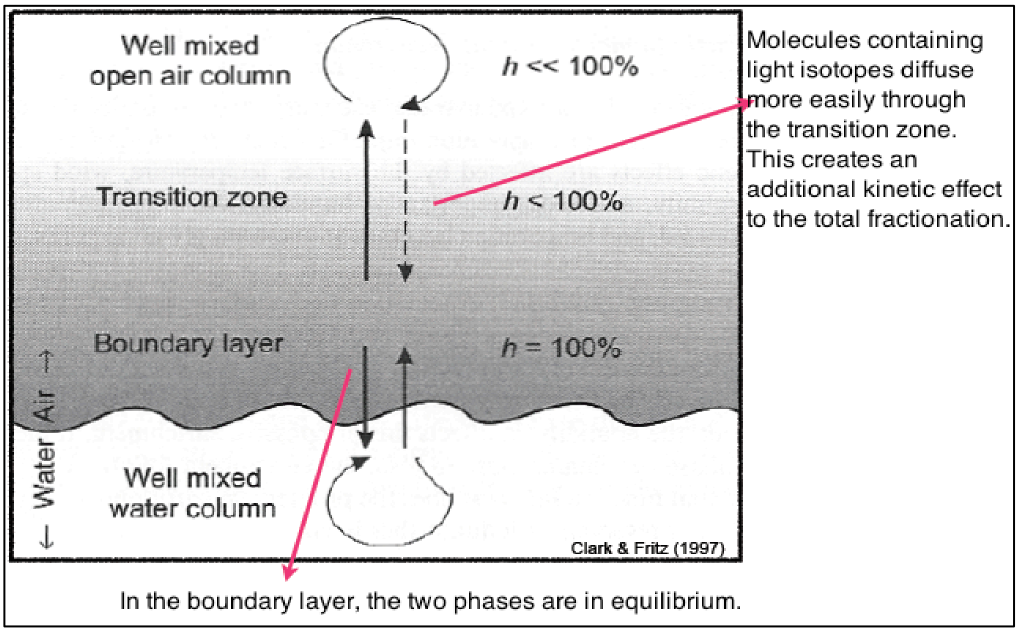
$$\Delta\varepsilon^2H_{\text{BoundaryLayer-vapour}} = 12.5\ (1-h)\ ‰ \qquad (9.17)$$

$$\Delta\varepsilon^{18}O_{\text{BoundaryLayer-vapour}} = 14.2\ (1-h)\ ‰ \qquad (9.18)$$

The total fractionation during evaporation between the bulk water and the atmosphere ($\varepsilon_{l-v} > 0$) is the sum of the fractionation factor for the equilibrium water-vapour exchange (ε'_{l-v}) and the kinetic factor ($\Delta\varepsilon_{bl-v}$). For ^2H this becomes:

$$\delta^2H_l - \delta^2H_v = \varepsilon'^2H_{l-v} + \Delta\varepsilon^2H_{bl-v} \qquad (9.19)$$

This equation describes the enrichment of the water with respect to the vapour. The depletion in the vapour with respect to the water is the reciprocal or negative enrichment ($\varepsilon^*_{v-l} < 0$) (Clark & Fritz, 1997).



Molecules containing light isotopes diffuse more easily through the transition zone. This creates an additional kinetic effect to the total fractionation.

In the boundary layer, the two phases are in equilibrium.

Figure 9.5: Schematic figure of the water-air interface with relative humidities. Adapted from Clark & Fritz (1997)

Generally, rainwater in cold regions is depleted in heavy isotopes, whereas rainwater associated with warmer climates is more enriched in ^{18}O and ^{2}H compared to that of the colder climate zones. This was early on, in isotopic research, recognised as a tool for characterising groundwater recharge environments and is now the basis for groundwater provenance studies. Although the humidity is never exactly 100 % during evaporation, calculations of the equilibrium process are instructive to understand the relationship between fractionation and temperature.

Majoube (1971) described the fractionation factor as a function of temperature with the equations:

$$\ln(\alpha^2 H_{l-v}) = \frac{24.844\times10^3}{T^2} - \frac{76.248}{T} + 52.612\times10^{-3} \qquad (9.20)$$

$$\ln(\alpha^{18} O_{l-v}) = \frac{1.137\times10^3}{T^2} - \frac{0.4156}{T} - 2.0667\times10^{-3} \qquad (9.21)$$

For oceans at 25°C, the equilibrium isotopic composition of water vapour would be (Clark & Fritz, 1997):

$$\delta^{18}O_{vapour} = \delta^{18}O_{ocean} + \varepsilon^{*18}O_{v\text{-}l} = 0.0 + (-9.3) = -9.3\text{ ‰} \qquad (9.22)$$

$$\delta^{2}H_{vapour} = \delta^{2}H_{ocean} + \varepsilon^{*2}H_{v\text{-}l} = 0.0 + (-76) = -76\text{ ‰} \qquad (9.23)$$

In cooler regions (e.g. 10 °C), equilibrium water vapour would have an isotopic composition of $\delta^{18}O$ = -10.6 ‰ and $\delta^{2}H$ = -93 ‰ (Figure 9.6).

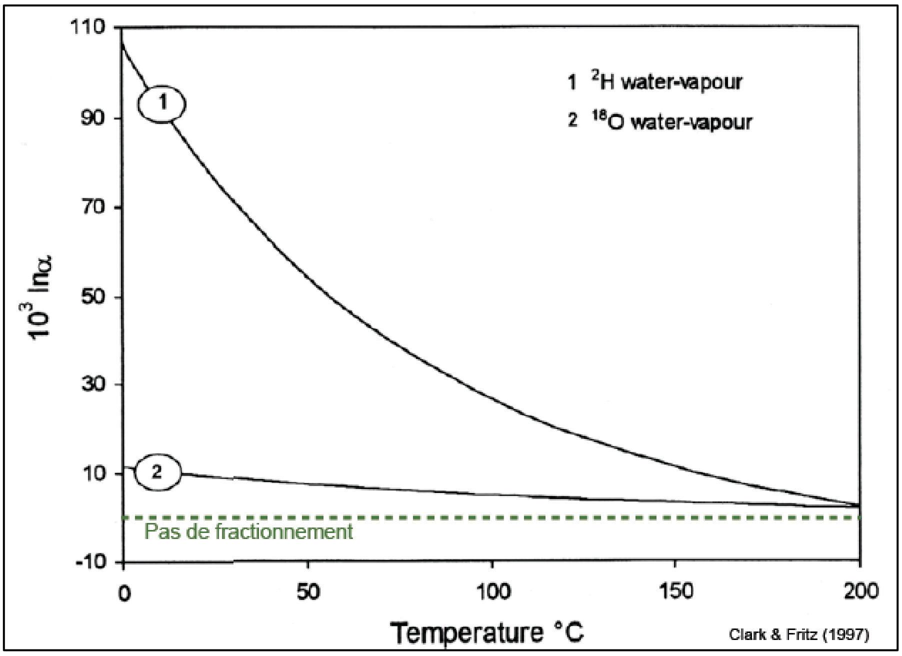


Figure 9.6: The amount of fractionation during evaporation depends on temperature (Clark & Fritz, 1997)

When plotting the isotopic composition of waters (surface- or groundwater) in a $\delta^{2}H$ vs. $\delta^{18}O$ diagram, deviations from the GMWL suggest that evaporation has occurred (Figure 9.8). The difference in atomic weight between H_2O and $H_2{}^{18}O$ is 2 amu (atomic mass units), while between H_2O and H^2HO it is 1 amu. The kinetic effect is therefore more important for $H_2{}^{18}O$ and evaporation lines for the residual water will have a slope smaller than the GMWL (Kendall & McDonnell, 1998).

9.3.3 Condensation and precipitation

Condensation, in contrast to evaporation, is an equilibrium process where the humidity necessarily is 100 %. The isotopic evolution of precipitation during rainout is largely controlled by temperature. Dansgaard (1964) established a linear relationship between surface air temperatures and isotopic composition:

$$\delta^{18}O = 0.695\ T_{annual} - 13.6\ ‰ \qquad (9.24)$$

$$\delta^{2}H = 5.6\ T_{annual} - 100\ ‰ \qquad (9.25)$$

A 1 ‰ decrease in mean δ^{18}O-value corresponds to a decrease of about 1.1 to 1.7 °C in the mean annual temperature. The global δ^{18}O-T relationship is only an approximation, and several other phenomenon affect the isotopic composition of meteoric water on a regional level. Figure 9.7 shows the relationship between δ^{18}O, temperature, remaining vapour content and the enrichment factor during precipitation.

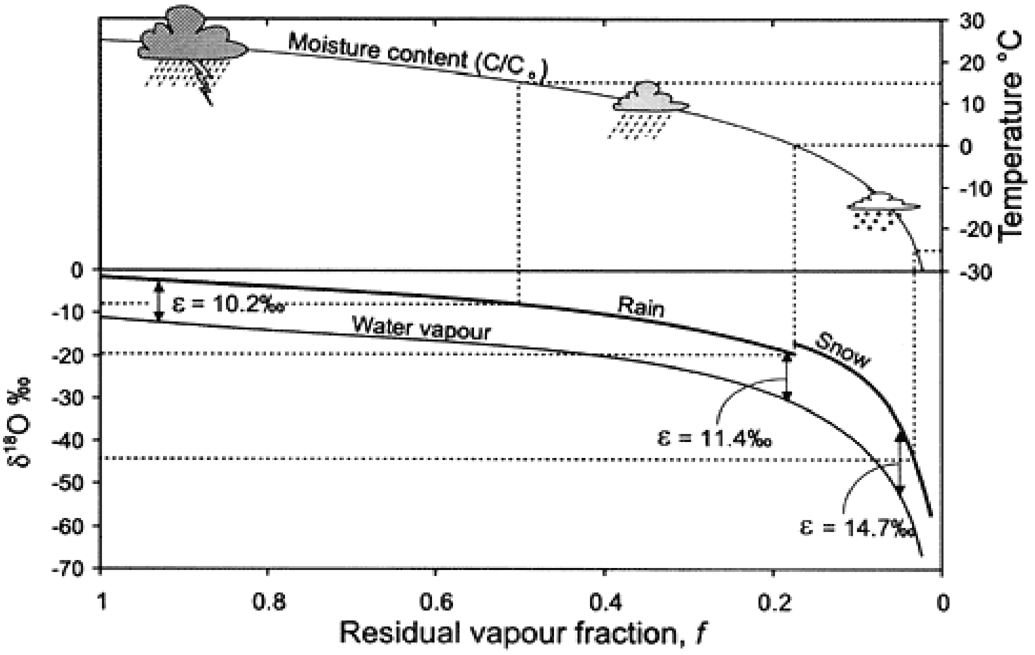


Figure 9.7: The ^{18}O content of rainfall decreases with the fraction precipitated. The fraction remaining as vapour has been calculated from the decrease in moisture carrying capacity of air at lower temperatures. Dashed lines link δ^{18}O of precipitation with temperature of condensation (Clark & Fritz, 1997)

9.3.4 Variations of water isotopes over the continents

Latitude effect

In general, the isotopic composition of meteoric water is more depleted at higher latitudes. This effect is caused by increased rainout at higher latitudes and by greater isotopic fractionation at cooler temperatures. Lesser amounts of enriched evaporated vapour are recycled back to the air mass further away from the equator. Thus, precipitation close to the poles will be lighter than precipitation at the equator. In tropical areas the correlation between fractionation and temperature is rather small. Polar regions, however, are situated at the end of the Rayleigh rainout process, so the δ^{18}O-T gradients become increasingly steep at higher latitudes (Kendall & McDonnell, 1998).

Continental effect

Observations that meteoric water far away from the oceans is more depleted than at marine areas are called the continental effect. As an air mass travels inland, precipitation will remove the heavy isotopes and the remaining vapour becomes gradually lighter. This is due to topographic and climatic changes across the continent. Also, inland regions experience more seasonal variations in temperature, which is reflected in the isotopic composition of precipitation (Kendall & McDonnell, 1998).

Altitude effect

As an air mass rises it is cooled by adiabatic expansion. The vapour condensates and precipitates. At higher altitudes, where temperatures are lower, and the air has already lost some mass to precipitation, the remaining vapour is depleted in heavy isotopes. For oxygen, the depletion of ^{18}O is about -0.15 to -0.5 ‰ per 100 m rise in altitude. Deuterium decreases correspondingly with -1 to -4 ‰. The altitude effect is important in hydrogeological studies as it distinguishes groundwaters recharges at different altitudes (Clark & Fritz, 1997).

Amount effect

The intensity of the rain affects the fractionation. Gentle rainfall or rain from the early part of the storm will be more enriched than heavy rain or the rain that falls at the end of a rainfall event. This is because the evaporation from the raindrops during precipitation is more important under gentle rainout conditions. Small amounts of rain over a longer period of time will therefore be more fractionated due to evaporation during precipitation (Kendall & McDonnell, 1998).

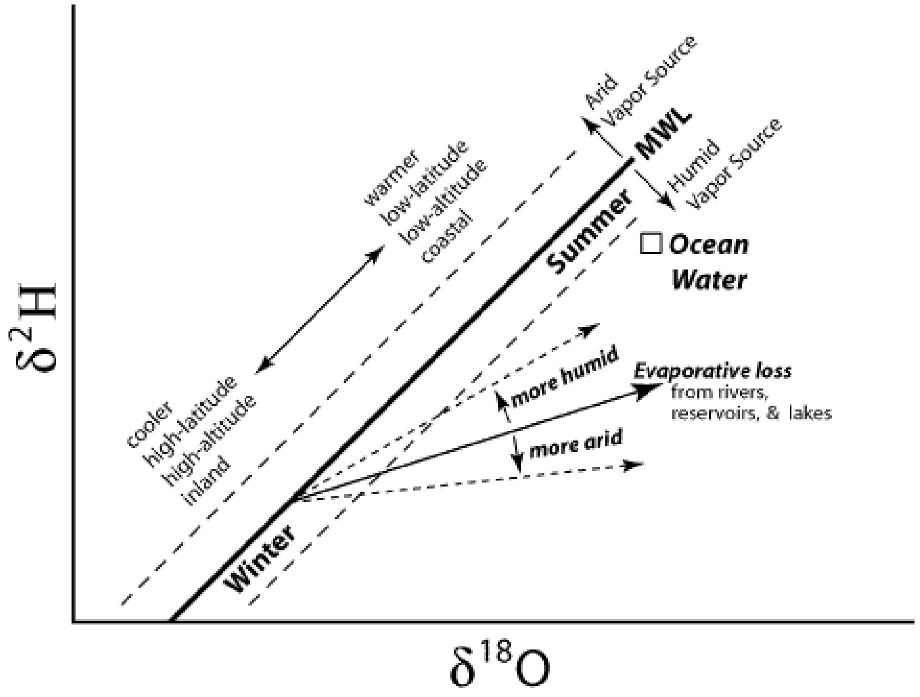


Figure 9.8: Summary diagram of how hydrologic processes affect oxygen and hydrogen isotopic composition of water (http://web.sahra.arizona.edu/programs/isotopes/oxygen.html)

9.4 Isotopes of nitrate

Within the nitrogen cycle, both kinetic and thermodynamic processes fractionate the isotopes of N, $^{15}N/^{14}N$, has been used for some time in hydrogeological and biological studies, particularly for insights to sources and fate of nitrate and other N-contaminants in groundwaters and to trace biological reactions. Analytical precision of the isotopic analysis of nitrate reflects the complicated preparation procedures and is usually not better than about ± 0.5 ‰. In recent years, the use of $^{18}O/^{16}O$ in nitrate has been developed as a complementary tool in hydrogeological studies. The oxygen of nitrate is converted to CO_2 for isotopic measurements and is referenced to VSMOW. The combination of $^{15}N/^{14}N$ and $^{18}O/^{16}O$ in nitrate is useful to distinguish between nitrates of different origins, to recognise denitrification processes and to discuss the N-budget in the soil-water system (Clark & Fritz, 1997).

9.4.1 Isotopic composition of nitrate

Atmospheric nitrogen has a constant ratio between the heavy and the light isotope: $^{15}N/^{14}N = 1/272$. N_2 of the atmosphere is therefore set as the reference standard (AIR) and $\delta^{15}N_{N2}$ of air is thus 0.00 ‰ (Kendall & McDonnell, 1998). Other N compounds are either enriched or depleted in ^{15}N, depending on the source and the fractionation process having affected them.

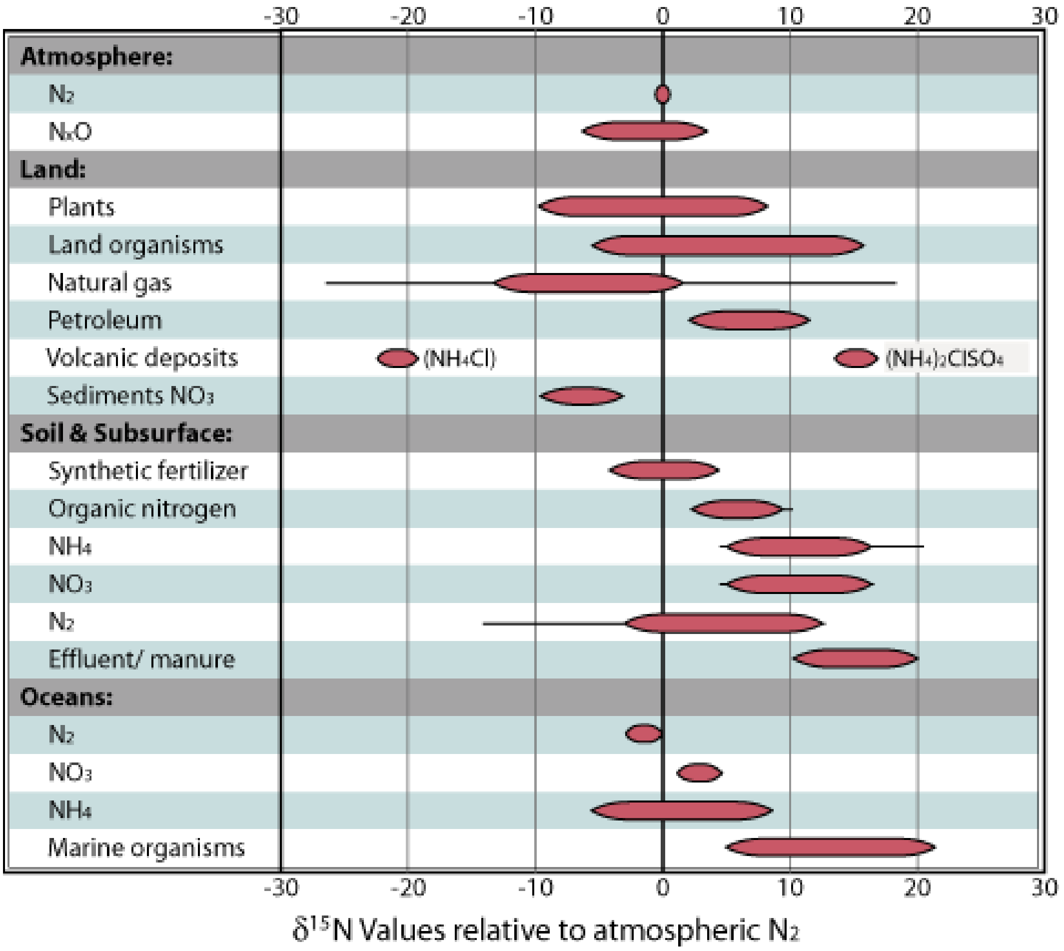


Figure 9.9: Range of $\delta^{15}N$ values of different natural N-species.
http://web.sahra.arizona.edu/programs/isotopes/nitrogen.html

9.4.2 Fractionation processes

Isotopic fractionation of nitrogen trough the food web is proportional to the trophic level of the organism. Initially low ^{15}N contents in algae and other primary producers are increased by over 10‰ at each level of consumers in the food chain. The catabolic reaction of amino acids in soils and in animals produces ammonium, which is depleted in ^{15}N by several permil. This results in an enrichment of ^{15}N in the remaining solid waste, e.g. manure. Volatilisation of NH_3 has also a fractionation effect because the compounds containing the light isotopes are more volatile. Microorganisms prefer the lighter isotopes to the heavy ones. Products from biological transformations will therefore always be depleted in the heavy isotopes (Clark & Fritz, 1997).

Processes that do not result in significant fractionation of nitrogen include manufacturing of urea fertilizers from atmospheric N_2 and biologic nitrogen fixation. Results on the fractionation during ammonification/mineralisation are variable. Möbius (2012) found that remineralisation of organic matter could result in a depletion of ^{15}N in the decayed matter, with a corresponding enrichment of ^{15}N in the remaining organic matter. The difference between the decay and remaining organic matter were found to be around 2 to 4 ‰, and possibly up to 7 ‰ in some cases (Möbius, 2012). Isotopic fractionation during assimilation of nitrate or ammonium is found to be more important in water bodies than in soils. More fractionation during assimilation is observed for higher algae growth rates and for lower NO_3^- and NH_4^+ concentrations. A general rule is that fractionation is caused by a "rate-determining step", which is the slowest step (Kendall & McDonnell, 1998).

Volatilisation

The loss of ammonia gas to the atmosphere from surficial soils and waters results in an enrichment of the residual ammonium. There are several steps during volatilisation that can create fractionation; (1) equilibrium fractionation between ammonium and ammonia in solution, and between dissolved and gaseous ammonia, or (2) kinetic fractionation caused by diffusive loss of ^{15}N-depleted ammonia. Volatilisation in farmlands with application of manure may result in an enrichment of the residual organic matter with more than 20 ‰ (Kendall & McDonnell, 1998).

Nitrification

The nitrification process results in isotopic fractionation of mainly the nitrogen in nitrate, where the produced nitrate is lighter than the original ammonium. The oxidation from nitrite to nitrate (eq. 8.3) is usually rapid, and generally not the rate-determining step. Most of the N-fractionation is caused by the slow oxidation of ammonium by *Nitrosomonas* (eq. 8.2). In soils, the overall fractionation of nitrogen during nitrification range between 1.012 and 1.029, the enrichment factor for the produced nitrate being -12 to -29 ‰ (Kendall & McDonnell, 1998). It also depends on the amount of ammonium available. When the amount of ammonium is limited, the fractionation is minimal. If there is a large amount of ammonium available (e.g. after fertilisers have been applied) nitrification is stimulated. In the beginning fractionation is high, but as the ammonium is being used, the overall fractionation decreases.

Denitrification

Denitrification causes the $\delta^{15}N$ of the residual nitrate to increase. Measurements of enrichment factors associated with denitrification ($\varepsilon^{15}N_{N2\text{-}NO3}$) range from -40 to -5 ‰; hence, the produced N_2 contains much more ^{14}N that the residual nitrate. The enrichment of heavy isotopes in the nitrate follows a Rayleigh equation and is in proportion to the natural logarithm of the remaining nitrate fraction (Kendall & McDonnell, 1998):

$$\delta^{15}N = \delta^{15}N^0 + \varepsilon \ln(NO_3/NO_3^0) \qquad (9.26)$$

where $\delta^{15}N$ is the composition of the reactant nitrate at time t, $\delta^{15}N^0$ the initial composition of the nitrate, and $\varepsilon < 0$.

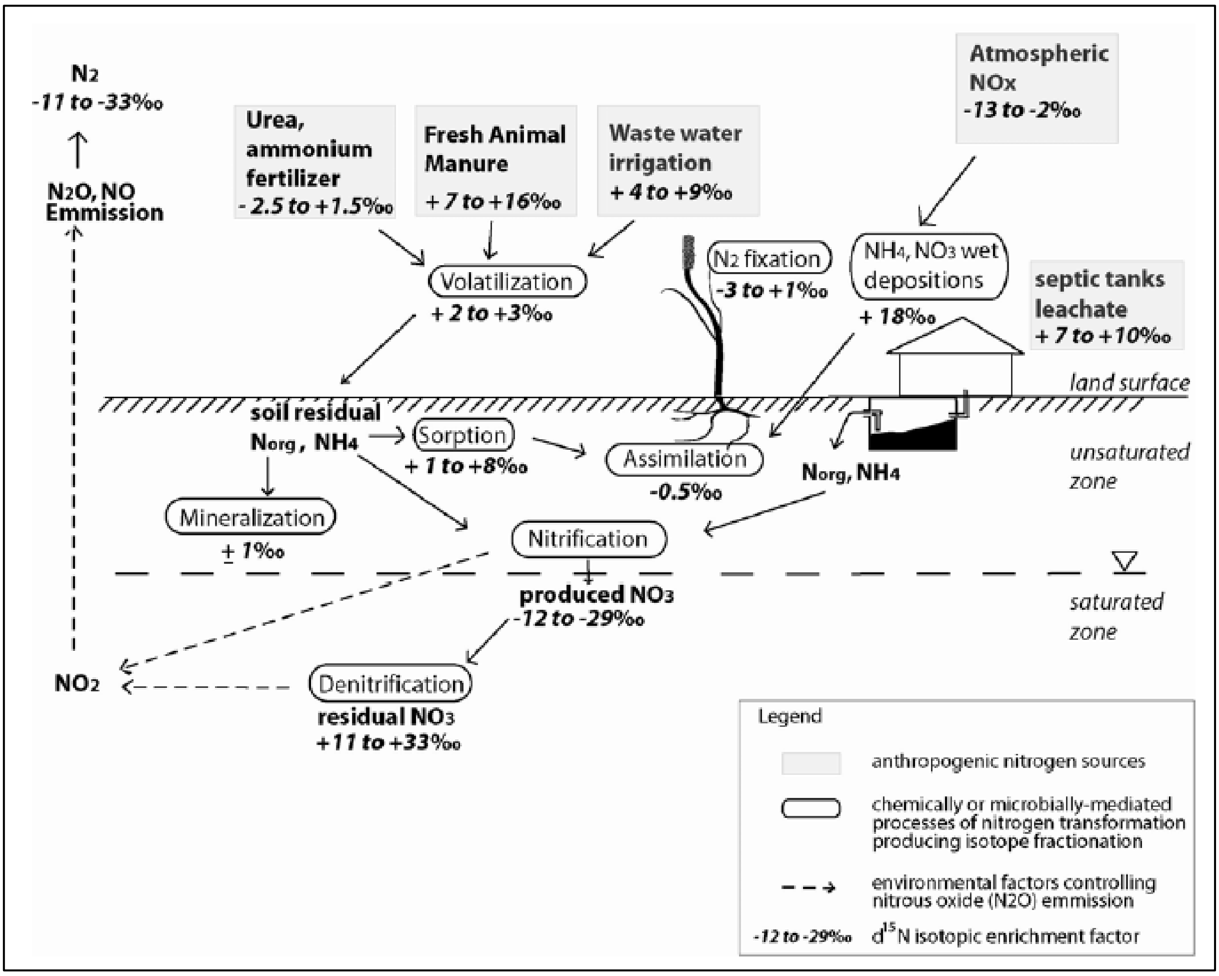


Figure 9.10: Nitrogen cycle with processes that result in fractionation of $^{15}N/^{14}N$ (Gueye-Girardet, 2010)

Isotopes of oxygen in the nitrate

The $\delta^{18}O$ of nitrate adds another perspective on the origin of the NO_3^-. During the biological formation of a NO_3-molecule, two molecules of oxygen derive from H_2O and one from atmospheric O_2. Contrarily, synthetic fertilisers received its oxygen mainly from atmospheric O_2. O in water is considerably more depleted in ^{18}O than O in the atmosphere, which makes it relatively easy to trace if the nitrate originates from synthetic or organic (mineralised) fertilisers (Figure 9.11). Denitrification fractionates the ^{18}O in nitrate in the same manner as the ^{15}N; the residual nitrate becomes enriched in ^{18}O ($\varepsilon^{18}O_{product\text{-}substrate}$ = -8 ‰). The combined study of $\delta^{18}O$ and $\delta^{15}N$ of nitrate, called the dual-isotope method, is a useful tool to distinguish the sources of nitrate and to determine if denitrification processes happen in groundwaters (Clark & Fritz, 1997).

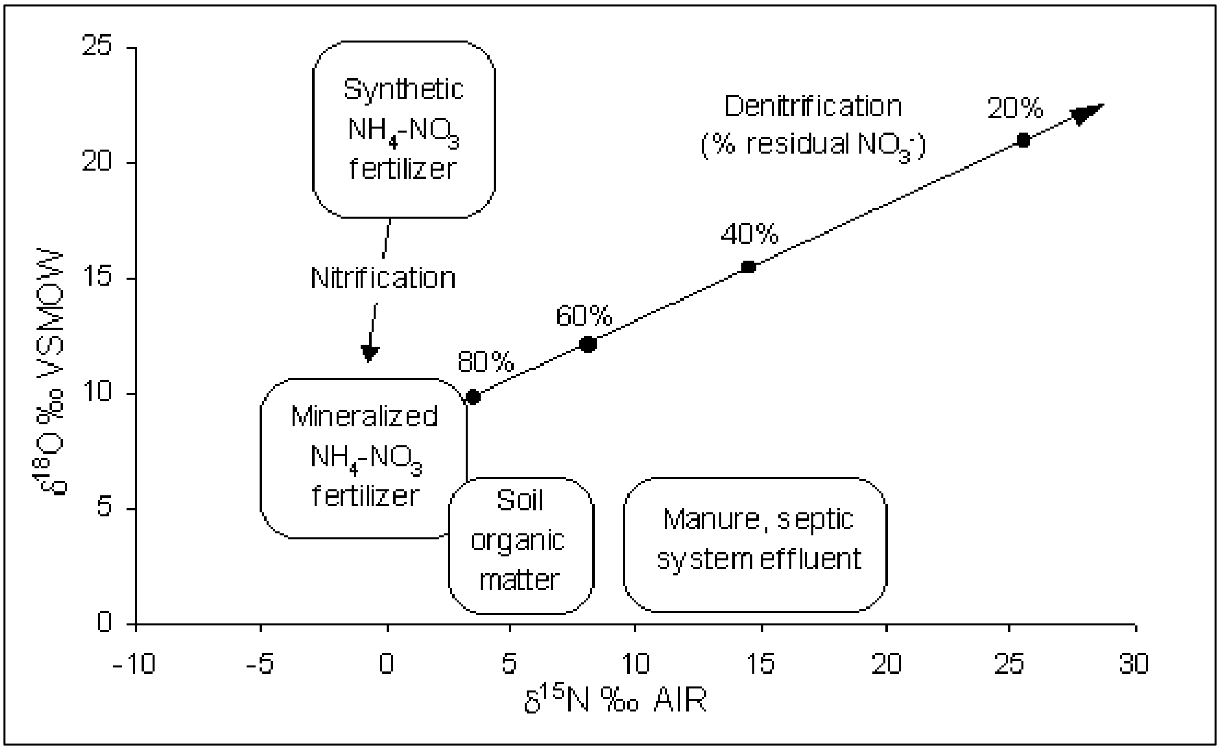


Figure 9.11: The isotopic composition of various sources of nitrate. The enrichment trend for NO_3^- during denitrification with % of original amount remaining (Clark & Fritz, 1997)

Materials & Investigations

10 Fieldwork

The water samples were taken in the period between January 28th and February 10th, 2013. The weather was clear and sunny, with air temperatures of around 25 °C, most days. Appendix II contains a list of the sample sites, including GPS-coordinates, type of sample and description of the site. In total 34 sites were sampled and their position mapped with the GPS Garmin E-trex Vista HCx. Different environments were sampled:

- Retention pools: 12 samples
- Flooded areas of the suburb: 3 samples
- Niayes (wetland/agricultural zones): 4 samples
- Dug wells: 2 samples
- Diambar pumps: 13 samples

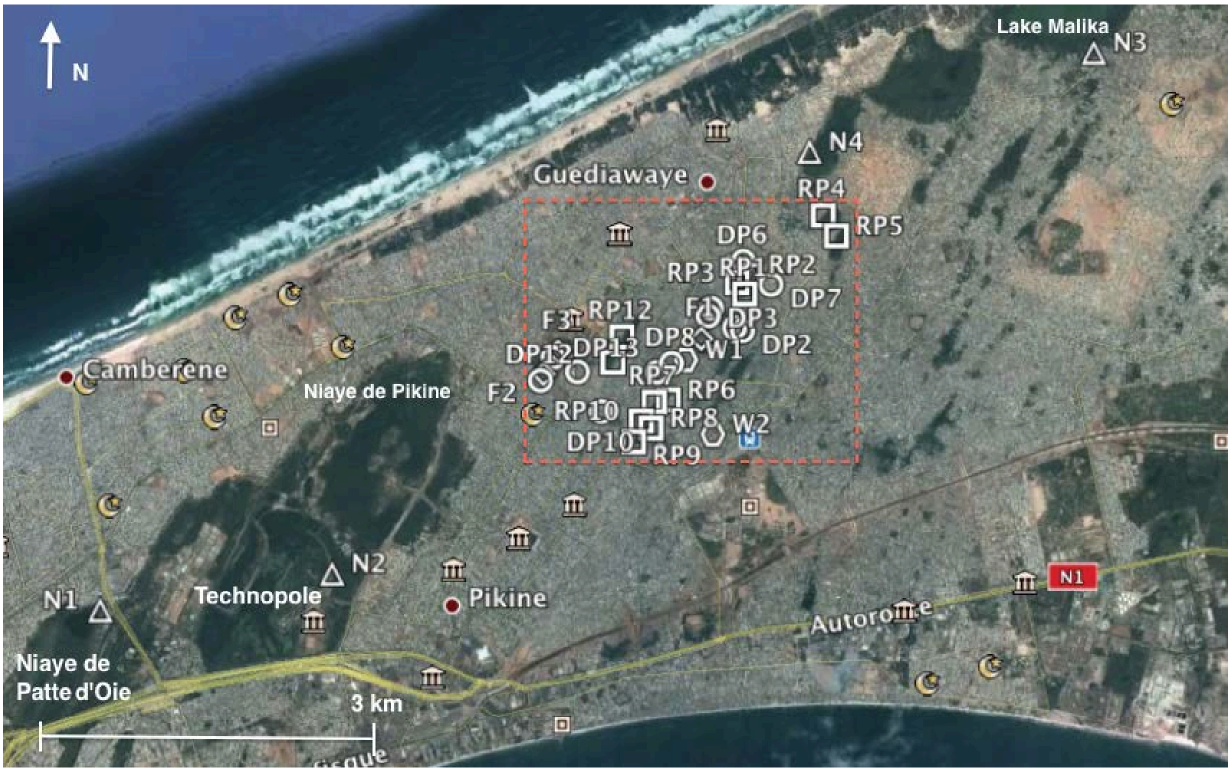


Figure 10.1: Overview map of the suburban parts of the Dakar Region with the location of all sample sites. Red, dashed square is magnified in Figure 10.2. Circles = Diambar pumps (DP), squares = retention pools (RP), diamonds = flooded zones (F), triangles = "Niayes" (N), and hexagons = dug wells (W).

Figure 10.2: Satellite image of Pikine and Guédiawaye with sample sites.

At all the sites, 3 sterile polyethylene (PE) bottles of 30 mL were filled with filtered water. The filtration was done with a combination of two of the three nylon filters: 1 μm (pre-filter), 0.45μm and 0.2 μm. These bottles were designated to the analysis of carbon, anions, cations and isotopes of water. In the bottle for the cation analysis, two drops of 65 % nitric acid (HNO_3) were added to obtain a pH around 2. Additionally, a 1.5 L plastic bottle, previously used for Kirène bottled water, was filled with non-filtered water at each site. Duplicates of the sites were not taken due to lack of time and space to store samples. However, for some of the retention pools, several samples were taken from the same pool around 100 m apart. These samples can be regarded as approximate duplicates.

The water samples were stored in a refrigerator between sampling and laboratory analysis.

In the field, several physical and chemical properties were measured:

- The temperature and conductivity of the water was measured with the conductivity meter WTW 315i, which normalised values to 25 °C.

- The concentration of dissolved oxygen was measured with the oximeter WTW Oxi 3205 and the probe CellOX 325.
- The pH and Eh were measured by the same meter (WTW pH 323), with two different probes (pH-Electrode SenTix 41 and Electrode SenTix ORP-Ag/AgCl for the Eh). The Eh values measured on the field had to be converted to values corresponding to the standard hydrogen electrode, normally used in the literature (addition of around 200 mV, Norstrom & Wilde, 2005)
- To obtain an approximate value of the concentration of nitrate, a Reflectoquant (MERCK RQflex plus) with nitrate-test strips was used.
- The concentration of NH_4^+ was estimated roughly by a Merckoquant 110024 Ammonium test with colorimetric strips.

A short interview of the owners of the Diambar pumps and dug wells were held. The answers on the questionnaire can be found in Appendix VIII.

11 Laboratory work

11.1 Anions and Cations

The concentration of anions and cations of the waters were measured by ionic chromatography (IC). An ionic chromatograph, DIONEX ICS-1100-2100, at ISTE-UNIL, Switzerland, was used for both the anions and the cations. In addition, duplicates of the cation samples were analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), type Perkin Elmer – Elan DCR II, at the Chemical-Mineralogical Laboratory of NTNU, Norway.

The ion chromatograph requires conductivities between 200-500 µS/cm. All samples were diluted with deionized water by either 1/4, 1/8, 1/10 or 1/20, according to the conductivity.

Standards with known concentrations were analysed at the same time to verify that the error of the results was smaller than 10%.

11.2 Carbon

The total dissolved inorganic carbon (TIC) and the total dissolved organic carbon (TOC) were analysed at the ISTE-UNIL with an Elementar LiquiTOC. The samples were analysed without any pre-treatment. Standards of 100 mg/L and 20 mg/L of both TIC and TOC, were used to calibrate the results.

11.3 Isotopes of water

The isotopes of hydrogen and oxygen of water were analysed with a PICARRO WS-CRDS (Wavelength Scan – Cavity Ring-Down Spectrometer) L2130-i at the ISTE-UNIL. The analyser is sensitive to very high conductivities. 11 of the samples, those with the highest conductivity, were distilled before the analysis. Three different standards were used to correct the results. Repeated measurements of samples and standards gave a one-sigma error of better than ±0.5 ‰ and ±0.1 ‰ for the H- and O-isotope measurements, respectively.

11.4 Isotopes of nitrate

11.4.1 Pre-treatment

1-2 days after sampling, water from the 1.5L Kirène bottles were filtered with a vacuum pump and 1µm glass microfiber filters. The water was afterwards passed in small values through columns containing a nitrate-absorbing resin (Bio-Rad AG1-X8, 200 - 400 mesh, Cl^- form). Depending on the concentration of nitrate, estimated by the Reflectoquant in the field, between 15-300 mL of filtered sample were used to concentrate an amount of approximately 9 mg of nitrate in the columns. The columns can easily be transported or stored in a refrigerator for several weeks.

NB! Due to a mistake done at the laboratory of the ISTE-UNIL, approximately half the samples were passed through columns with a cation-exchange resin (Bio-Rad 100 - 200 mesh AG 50W X8, H^+ form) instead of an anion-exchange resin. For these samples, nitrate did not become accumulated and only very small amounts of $AgNO_3$ were available for the analyses.

11.4.2 Analyses

The preparation and analyses of the isotopic composition of nitrate were done according to the method described by Silva et al. (2000). Due to the long amount of time it takes for the preparation of the N- and O-isotope analyses, 10 samples were chosen; RP3, RP4, RP5, F1, N3, W1, W2, DP1, DP6 and DP8. These were chosen based on their relative high nitrate content, location and type of sample. All 5 types of sample sites (retention pool, flooding, Niaye, dug well and Diambar pump) were represented.

At the end of the preparation, nitrate was in the form of $AgNO_{3(s)}$. Around 9 mg of nitrate were supposedly kept in the columns, but the samples that were passed through the cation-resin contained very little solids. This concerned RP3, RP4, RP5, F1, W1 and W2, which were nevertheless analysed. Duplicates of DP1, DP6, DP8 and N3 were analysed.

The nitrogen isotope compositions were analysed with an Elemental Analyser (EA) linked to a Thermo-Fisher Delta-V Plus mass spectrometer, while the isotopes of oxygen were analysed with a High-Temperature Conversion Elemental Analyser (TC-EA) linked to a Delta-Plus XL mass spectrometer. Analytical error for the nitrogen isotope measurements is about ±0.2 ‰ while for oxygen it is ±0.5 ‰, based on repeated measurements of the standards analysed together with the samples.

11.5 Algae

The water samples from the retention pools, Niayes and flooded zones contained various amounts of algae. In total 19 surface water samples were filtered and the algae analysed for theirs N-isotope composition.

11.5.1 Pre-treatment in Dakar

To concentrate the amount of algae, Whatman filters of glass microfiber 1 μm (diameter 47 mm) were used. The following steps were done in the LTEU-laboratory of UCAD:

1. The filters were filtered with 100 mL of distilled water using a vacuum pump.
2. They were then placed in aluminium petri dishes and dried at 55 °C for 3 hours*.
3. A volume between 100 mL and 500 mL of the samples, depending on the amount of algae and suspended solid, were filtered.
4. The filters were dried again at 55 °C for 3 hours.

5. Once dry, the filters were each placed in a 30 mL plastic (PE) bottle and stored in the fridge.

* NB! Some of the samples were dried at 45 °C for 1 hour 20 min after filtration with distilled water and 1 hour 20 min at 45 °C + 15 min at 60 °C after filtration with the sample. Even then, they were not completely dry when they were placed in the plastic bottle. It is recommended to dry the filters for at least 3h at 55 °C.

11.5.2 Pre-treatment in Lausanne

The samples of the algae needed to be washed of any traces of carbonate. The filters were thus rinsed with 10% HCl and left flat for 1 minute before being filtered with 100 mL of deionised Millipore® water. They were put in glass petri dishes and covered with aluminium foil. The foil was perched and the petri dishes placed in a freeze-dryer overnight. Once freeze-dried the filters were placed in small glass bottles, closed with a tight cap, and stored in a freezer.

11.5.3 Analysis

The filters being very thick, a thin layer with the algae on had to be scraped off and placed in small tin capsules. These were further analysed at the ISTE-UNIL for the N-isotope composition of algae by the same elemental analyser and mass spectrometer as for the nitrogen in nitrate. Duplicates of the samples RP3, RP4, RP9, RP10 and RP12 were analysed.

Results & Discussion

12 Results

12.1 Results from the field measurements

Table 12.1 summarises the results of the field measurements done during the sampling period in Senegal. Surface water temperatures vary between 19.9°C and 28.7°C, with an average of 24.4°C, while the groundwater samples have a mean temperature of 28.0°C, with the lowest temperature being 24.9°C and the highest 30.7°C. The pH is slightly basic for the surface waters, with an average of 8.02 and a standard deviation of 0.56. The groundwater is more acidic with an average pH 6.15 and a standard deviation of 0.55 (Table 12.1 and Figure 12.1).

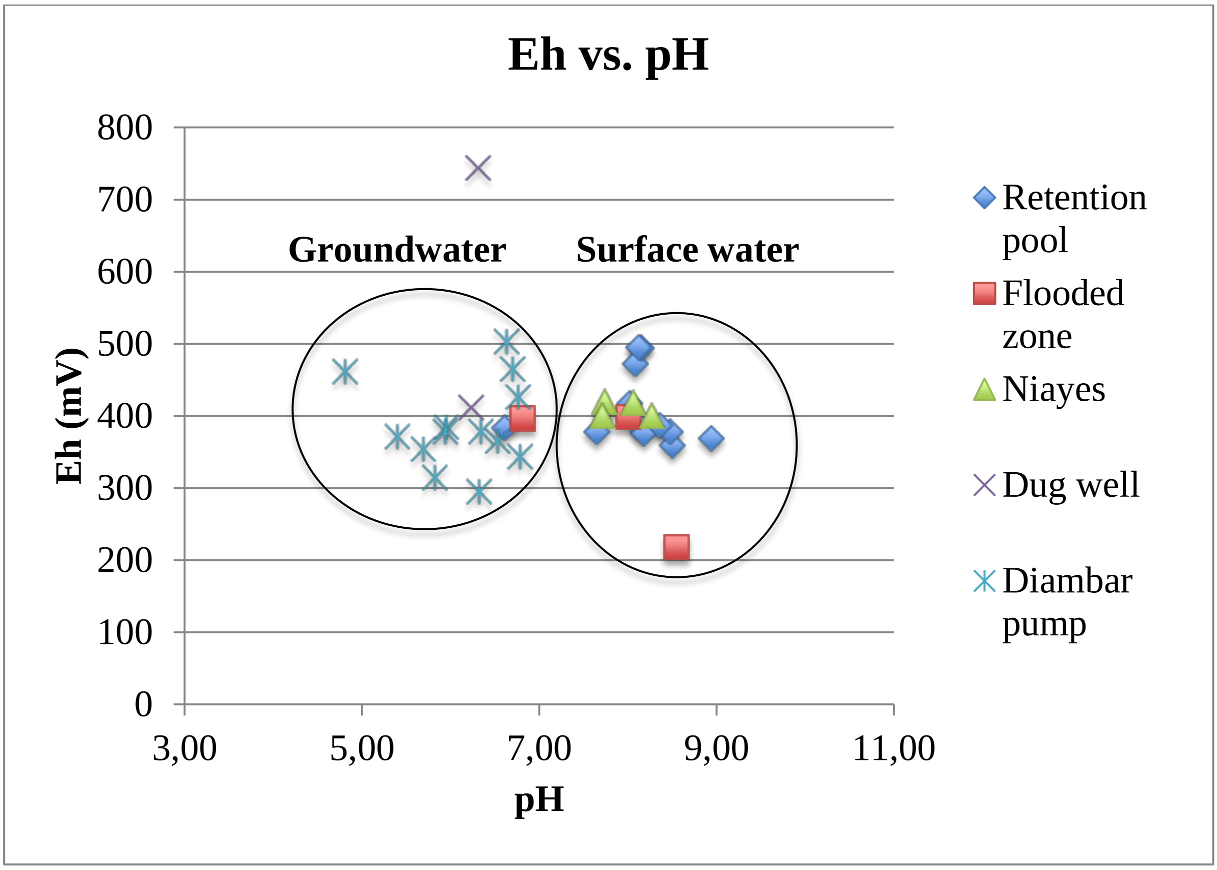


Figure 12.1: Eh-pH diagram of the field measurements. Two surface water samples, F2 and RP4, plot in the typical groundwater range. W2 and F3 stands out with very high and very low Eh.

Table 12.1: Values of the field measurements. Eh values are corrected relative to standard electrode H_2/H^+ (Norstrom & Wilde, 2005), while pe[6] is derived from the corrected Eh. O_2-saturations are calculated according to APHA (1992).

Type	Sample	Date	Temp (°C)	pH	Eh (mV)	pe (V)	Conductivity µS/cm	O2 (mg/L)	O2-saturation (%)
Surface water	RP1	30. jan	22.10	8.08	473	8.08	3020	5.90	68
	RP2	30. jan	22.60	8.15	494	8.44	3010	7.75	90
	RP3	30. jan	23.20	8.12	495	8.44	3010	6.40	75
	RP4	5. feb	25.00	6.61	384	6.50	2730	3.65	44
	RP5	5. feb	25.20	7.65	378	6.40	2750	3.36	41
	RP6	5. feb	26.00	8.02	418	7.06	3140	11.70	145
	RP7	5. feb	25.20	8.13	386	6.53	3010	10.14	124
	RP8	5. feb	24.90	8.18	376	6.38	2870	10.63	129
	RP9	5. feb	26.00	8.94	369	6.23	2840	17.70	219
	RP10	5. feb	24.60	8.50	360	6.10	2860	9.06	109
	RP11	31. jan	25.90	8.48	379	6.39	2910	13.50	167
	RP12	31. jan	24.70	8.36	387	6.56	2860	14.40	173
	F1	31. jan	19.90	8.01	399	6.87	4600	3.60	40
	F2	1. feb	25.00	6.81	397	6.72	2800	1.52	18
	F3	1. feb	28.70	8.55	218	3.65	7380	12.40	161
	N1	3. feb	22.40	7.74	420	7.17	3970	1.43	17
	N2	3. feb	22.80	8.27	401	6.84	9230	5.20	61
	N3	3. feb	24.90	8.06	419	7.09	3590	15.20	184
	N4	5. feb	25.10	7.71	401	6.79	2520	3.10	38
Ground-water	W1	31. jan	24.90	6.23	412	6.97	3190	3.04	37
	W2	5. feb	27.20	6.31	744	12.51	2780	2.14	27
	DP1	30. jan	28.20	6.70	466	7.80	1270	3.60	46
	DP2	30. jan	26.90	6.63	504	8.48	2740	1.78	22
	DP3	30. jan	28.00	6.34	379	6.35	1744	3.30	42
	DP4	30. jan	26.90	6.53	366	6.16	2190	2.66	33
	DP5	31. jan	27.00	6.76	426	7.17	3130	1.70	21
	DP6	31. jan	27.10	5.95	385	6.47	1178	3.04	38
	DP7	31. jan	28.90	4.81	462	7.73	2780	3.78	49
	DP8	31. jan	28.80	6.78	344	5.75	2560	4.30	56
	DP9	31. jan	29.60	5.82	315	5.25	3050	1.74	23
	DP10	31. jan	28.60	5.94	379	6.34	2210	1.30	17
	DP11	1. feb	30.70	6.32	296	4.91	3970	1.47	20
	DP12	1. feb	28.70	5.69	354	5.92	1602	2.11	27
	DP13	1. feb	28.60	5.40	372	6.22	1088	1.66	22
Statistics									
Surface water	Min		19.90	6.61	218	3.65	2520	1.43	17
	Max		28.70	8.94	495	8.44	9230	17.70	219
	Mean		24.43	8.02	398	6.75	3637	8.24	100
	St. dev.		1.91	0.56	59	1.02	1743	4.98	62
Ground-water	Min		24.90	4.81	296	4.91	1088	1.30	17
	Max		30.70	6.78	744	12.51	3970	4.30	56
	Mean		28.01	6.15	414	6.93	2365	2.51	32
	St. dev.		1.39	0.55	108	1.82	849	0.95	12

The Eh measured in the field (Eh_f) with a Pt-electrode, must be corrected relative to a hydrogen electrode. The difference between these two electrodes, ΔEh, which can be found in Table 12.2, depends on the temperature and must be added to Eh_f to obtain the real redox potential, $Eh = Eh_f + \Delta Eh$ (Norstrom & Wilde, 2005).

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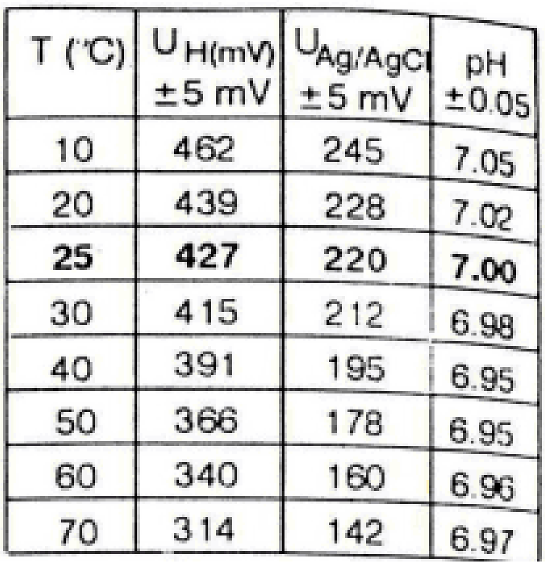
[6] pe = F/(2.3*R*T)*Eh (lecture notes from H.-R. Pfeifer) where F (Faradays constant) = 96485 J/mol, R (ideal gas constant) = 8.3144621 J/(K*mol), T = temperature in Kelvin

Table 12.2: The difference between U_H and $U_{Ag/AgCl}$ must be added to the Eh_f measured in the field to obtain the real Eh (from etiquette belonging to the redox buffer solution of the Eh-measurement probe, distributor Mettler-Toledo, Switzerland)



T (°C)	$U_{H(mV)}$ ±5 mV	$U_{Ag/AgCl}$ ±5 mV	pH ±0.05
10	462	245	7.05
20	439	228	7.02
25	**427**	**220**	**7.00**
30	415	212	6.98
40	391	195	6.95
50	366	178	6.95
60	340	160	6.96
70	314	142	6.97

The correlation between the amount of dissolved oxygen and the redox potential (Eh) is very poor (Figure 12.2). The corrected redox potential ranges from 218 mV to 495 mV for the surface waters and from 296 mV to 744 mV for the groundwater. Dissolved oxygen is fairly constant for the groundwater samples, with values from 1.3 to 4.3 mg/L, while the surface waters vary between 1.4 and 17.7 mg/L. The saturation of oxygen is in the range of 17-219 % with a mean of 100% for the surface waters, and between 17-56 % with a mean of 32% for the groundwater (Table 12.1).

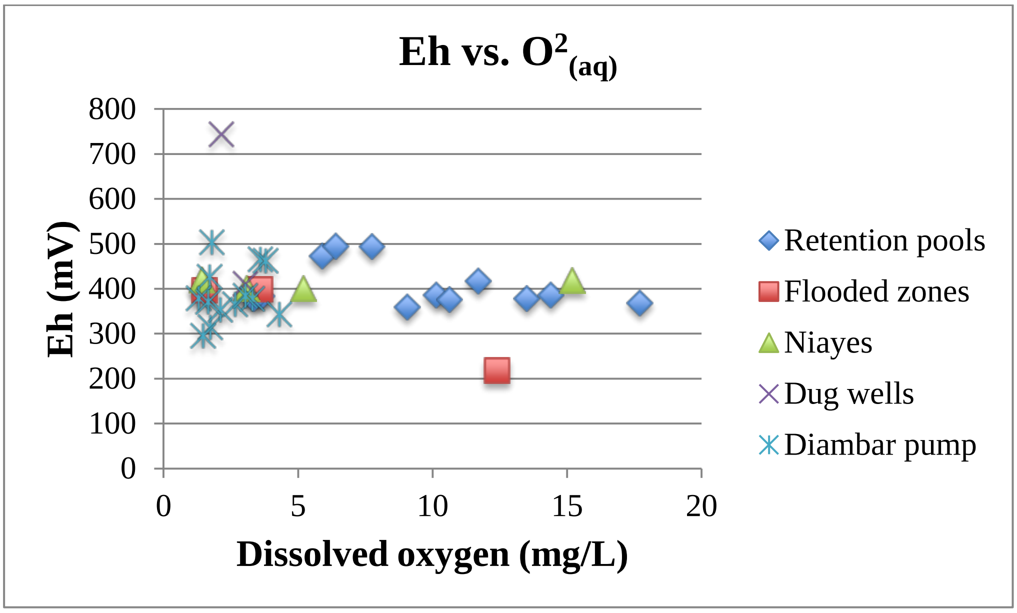


Figure 12.2: Field measurements show poor correlation between Eh and amount of dissolved oxygen.

The electrical conductivity reflects the total amount of ions in the water. The surface water samples have conductivities between 2.52-9.23 mS/cm, while the groundwater has a range from 1.09-3.97 mS/cm. Three surface water samples stand out with very high values: F1 has a conductivity of 4.6 mS/cm (suspected outlier, Figure 12.3), F3 has 7.38 mS/cm and N2 has 9.23 mS/cm (outlier, Figure 12.3). When excluding these three samples, the surface waters have very similar conductivities. The groundwater samples have in general lower conductivities. There are no outliers, but the samples cover a larger range. The boxplot in Figure 12.3 shows this variability.

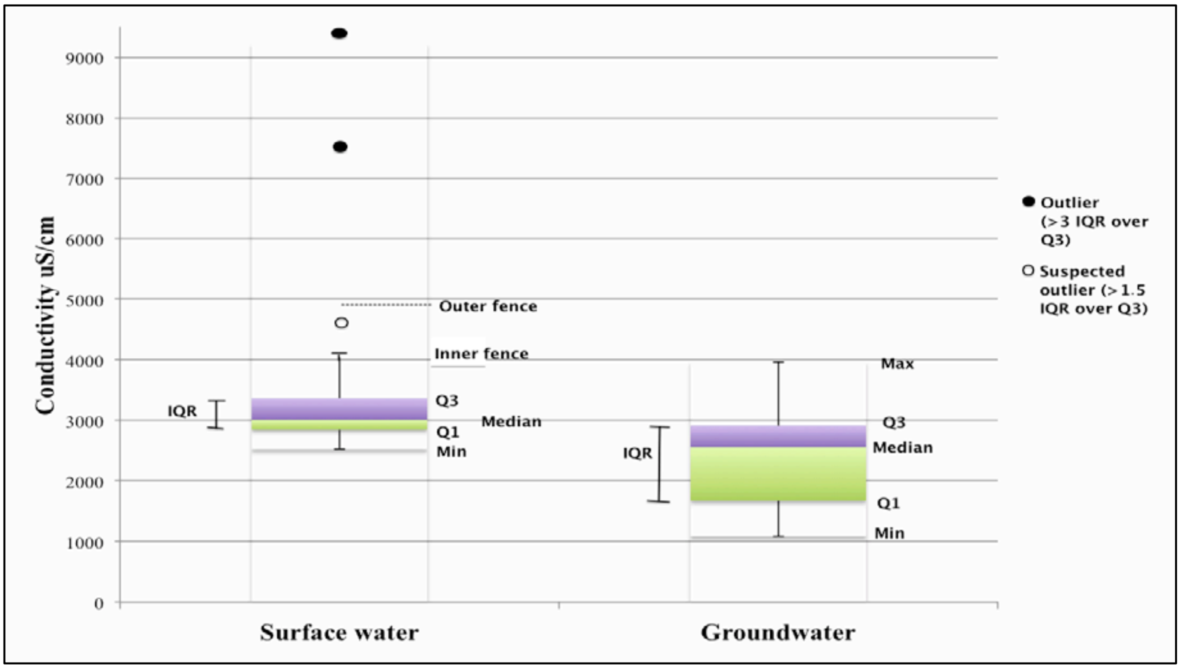


Figure 12.3: Boxplot of the conductivity from the field measurements. Surface water includes retention pools, Niayes and flooded zones, groundwater includes dug wells and Diambar pumps. (Instructions on boxplot after http://www.physics.csbsju.edu/stats/box2.html)

12.2 Results from laboratory analyses

12.2.1 Results for the concentrations of anions, cations and carbon

The complete results from the ion chromatography are found in Table 12.3. The results from the ICP-MS are presented in Appendix IV. In the following presentation of the results and discussions, values from the IC are used rather than those from the ICP-MS because the error of the ion balance proved to be smaller when using the IC-results and because the anions were analysed with the same IC instrument. Stiff diagrams for certain samples are shown in Figure 12.5, while the Stiff diagrams for all the 34 samples can be found in Appendix V.

Anions

The major anions present in the both the surface waters and in the groundwater are chloride, nitrate, sulphate and bicarbonate. In general, the surface waters contain more chloride, while the groundwater is richer in nitrate. Phosphate is a less abundant anion, while nitrite and bromide only occur in a few samples in negligible amounts.

The boxplot in Figure 12.4 presents some statistics on the concentrations of nitrate in the ground- and surface waters. The average concentration of nitrate in the groundwater is 371.5 mg/L and in the surface waters it is 97.1 mg/L. However, the average value is not very representative for the surface waters because most of these samples contain < 100 mg/L nitrate. Comparingly, the median nitrate concentration for surface waters is 3.7 mg/L. Two samples, the flooded house F1, with 708.6 mg/L nitrate, and the agricultural site N3, with 443.7 mg/L, increase this average considerably. These two sites are represented as an outlier and a suspected outlier in the Figure 12.4. The average nitrate concentration for the retention pools is 57.5 mg/L, which might be more representative of the surface waters in the region. For the groundwater, the Diambar pump DP7 has the highest value containing 784.9 mg/L nitrate. The median for the groundwater is 370.2 mg/L, which is practically equal to the average.

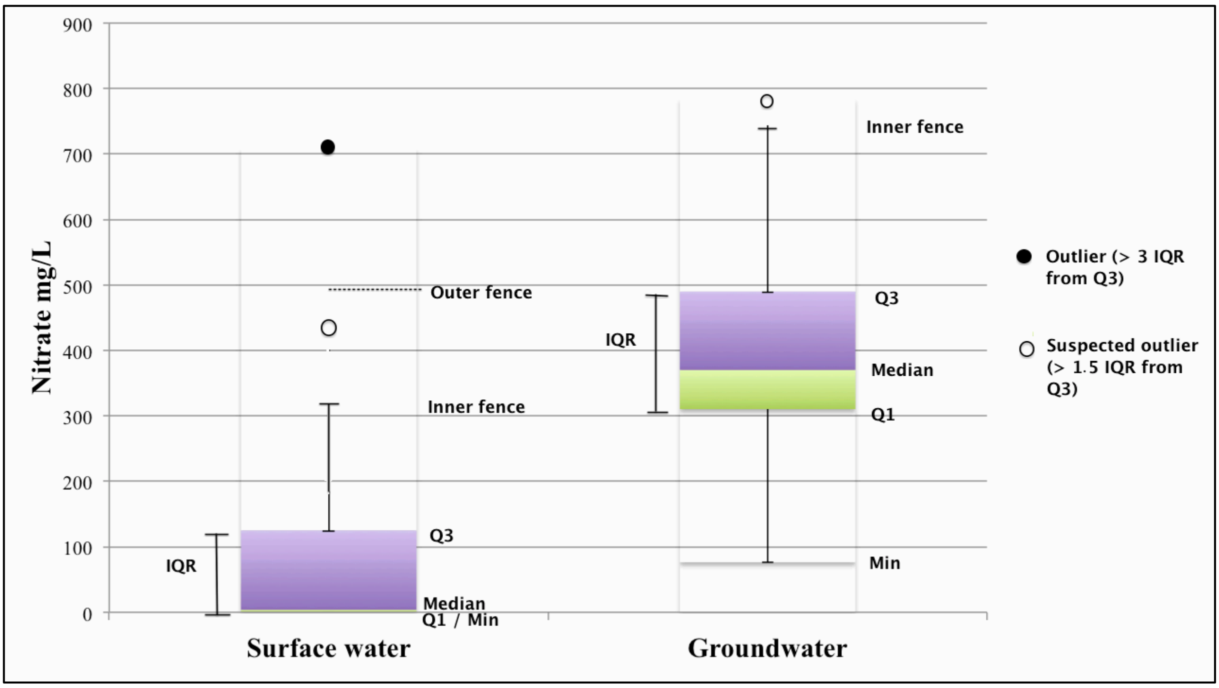


Figure 12.4: Boxplot of the nitrate concentration measured with IC. (Instructions on boxplot after http://www.physics.csbsju.edu/stats/box2.html)

Similar to the conductivity, the two surface water sites, F3 and N2, stands out with regard to the amount of chloride. They contain concentrations of respectively 2045.6 mg/L and 2749.6 mg/L of chloride, which is 3-4 times more than the other surface waters. The two samples are also richer than the others in bromide.

The amount of sulphate is slightly higher for the groundwater, ranging from 64.5 to 380.8 mg/L, with an average of 176.7 mg/L. The surface waters contain between 0 and 342.6 mg/L, averaging 159.2 mg/L. The SO_4^{2-} value of 1 mg/L for RP9 can be ignored, as it is drastically different from RP8 and RP10 (160 mg/L), which are taken from the same retention pool.

The content of total inorganic carbon (TIC) is very variable for both types of water. In general, the surface waters are richer in TIC, but one groundwater sample, DP5, far exceed any of the other samples (Figure 12.5). It contains 211 mg/L of TIC, compared to the average 46.8 mg/L for the groundwater. In the Stiff diagrams (Figure 12.5 and Appendix V) the TIC is represented as bicarbonate.

The surface water samples from the agricultural "Niayes" sites N1 and N3, in addition to the samples DP2 and DP3 from the groundwater, contain relatively more phosphate than other sites, with concentrations between 8.4-27.1 mg/L.

Cations

The surface water samples are very rich in sodium, having an average of 518.2 mg Na^+/L, compared to the samples from the groundwater, with an average of 245.6 mg Na^+/L. Calcium is the second most dominant cation for all the samples. The surface waters also contain more potassium and magnesium than the groundwater. The amount of ammonium in surface waters is relatively low, only 1.7 mg/L in average, compared to the groundwater, which have an average ammonium concentration of 12.4 mg/L and maximum concentration of 87.9 mg/L. As seen in Stiff diagram in Figure 12.5, DP5 stands out from the other groundwater samples, containing less nitrate but more ammonium.

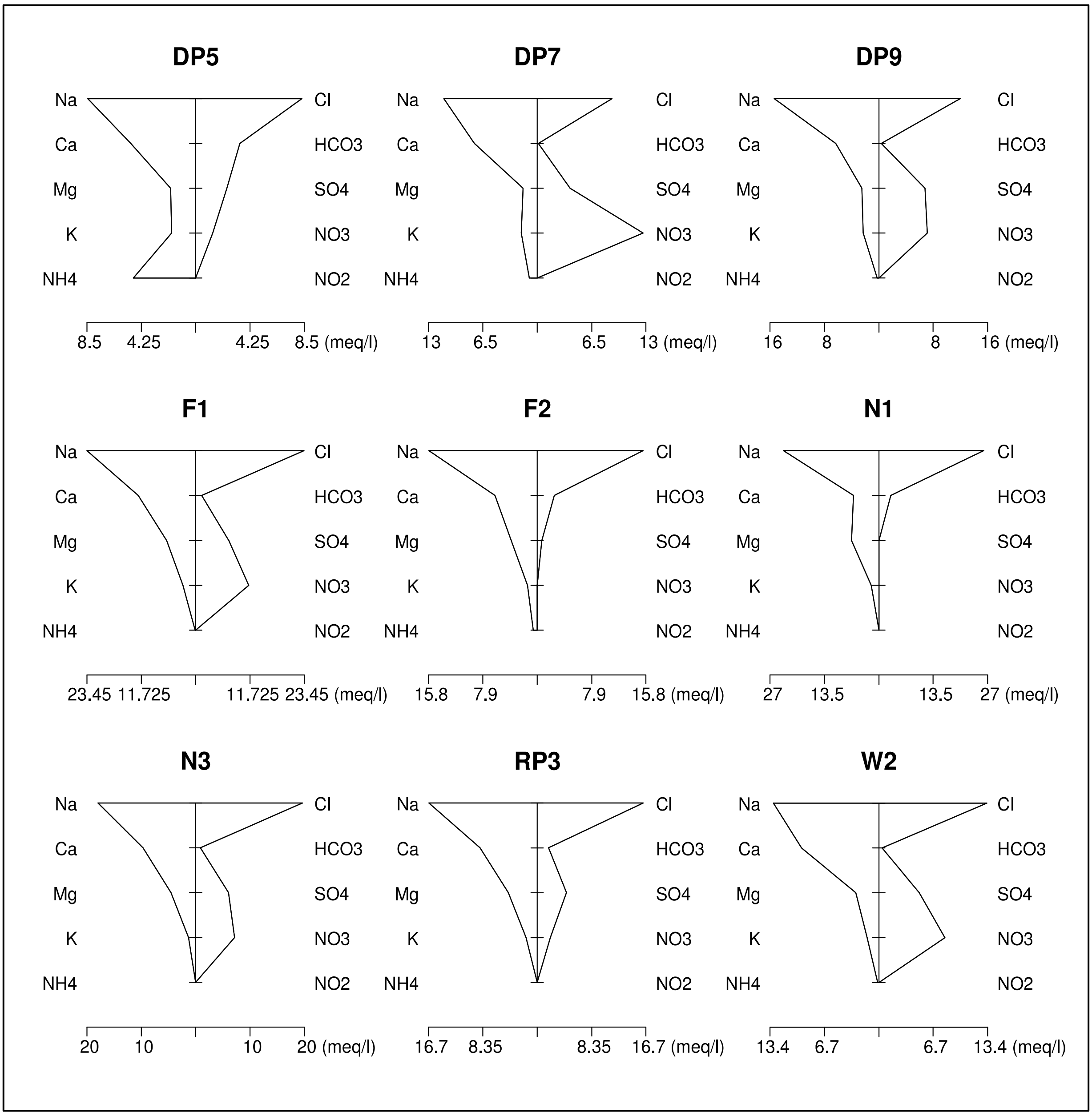
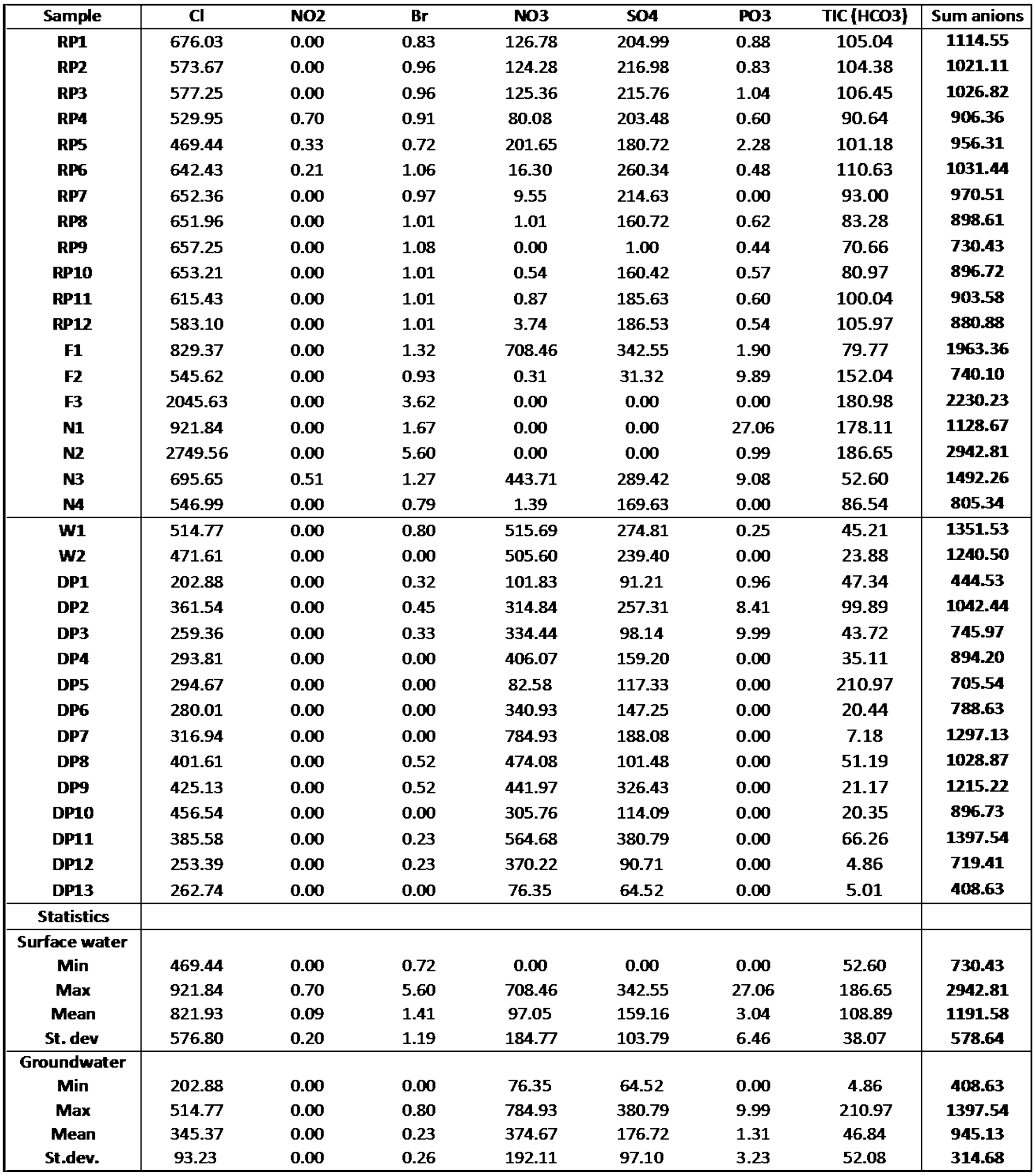
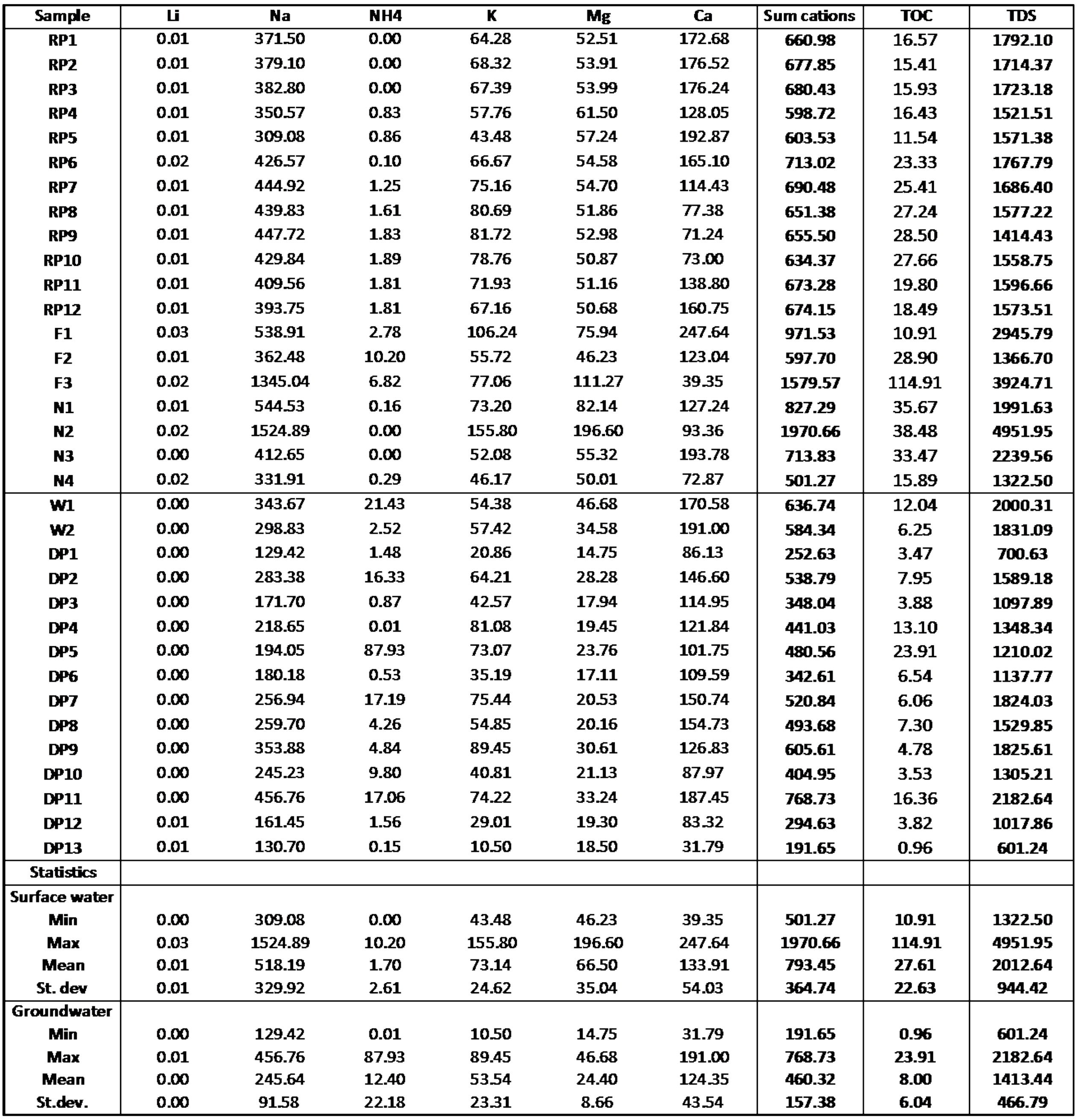


Figure 12.5: Stiff diagrams for some of the water samples. Note the difference in scale. For explanation of the samples names, see Figure 10.1 and Appendix II. Stiff diagrams for all the 34 samples are found in Appendix V.

Table 12.3: Complete results from the ion chromatography (IC) and LiquiTOC analyses. All values are in mg/L.



Sample	Cl	NO2	Br	NO3	SO4	PO3	TIC (HCO3)	Sum anions
RP1	676.03	0.00	0.83	126.78	204.99	0.88	105.04	**1114.55**
RP2	573.67	0.00	0.96	124.28	216.98	0.83	104.38	**1021.11**
RP3	577.25	0.00	0.96	125.36	215.76	1.04	106.45	**1026.82**
RP4	529.95	0.70	0.91	80.08	203.48	0.60	90.64	**906.36**
RP5	469.44	0.33	0.72	201.65	180.72	2.28	101.18	**956.31**
RP6	642.43	0.21	1.06	16.30	260.34	0.48	110.63	**1031.44**
RP7	652.36	0.00	0.97	9.55	214.63	0.00	93.00	**970.51**
RP8	651.96	0.00	1.01	1.01	160.72	0.62	83.28	**898.61**
RP9	657.25	0.00	1.08	0.00	1.00	0.44	70.66	**730.43**
RP10	653.21	0.00	1.01	0.54	160.42	0.57	80.97	**896.72**
RP11	615.43	0.00	1.01	0.87	185.63	0.60	100.04	**903.58**
RP12	583.10	0.00	1.01	3.74	186.53	0.54	105.97	**880.88**
F1	829.37	0.00	1.32	708.46	342.55	1.90	79.77	**1963.36**
F2	545.62	0.00	0.93	0.31	31.32	9.89	152.04	**740.10**
F3	2045.63	0.00	3.62	0.00	0.00	0.00	180.98	**2230.23**
N1	921.84	0.00	1.67	0.00	0.00	27.06	178.11	**1128.67**
N2	2749.56	0.00	5.60	0.00	0.00	0.99	186.65	**2942.81**
N3	695.65	0.51	1.27	443.71	289.42	9.08	52.60	**1492.26**
N4	546.99	0.00	0.79	1.39	169.63	0.00	86.54	**805.34**
W1	514.77	0.00	0.80	515.69	274.81	0.25	45.21	**1351.53**
W2	471.61	0.00	0.00	505.60	239.40	0.00	23.88	**1240.50**
DP1	202.88	0.00	0.32	101.83	91.21	0.96	47.34	**444.53**
DP2	361.54	0.00	0.45	314.84	257.31	8.41	99.89	**1042.44**
DP3	259.36	0.00	0.33	334.44	98.14	9.99	43.72	**745.97**
DP4	293.81	0.00	0.00	406.07	159.20	0.00	35.11	**894.20**
DP5	294.67	0.00	0.00	82.58	117.33	0.00	210.97	**705.54**
DP6	280.01	0.00	0.00	340.93	147.25	0.00	20.44	**788.63**
DP7	316.94	0.00	0.00	784.93	188.08	0.00	7.18	**1297.13**
DP8	401.61	0.00	0.52	474.08	101.48	0.00	51.19	**1028.87**
DP9	425.13	0.00	0.52	441.97	326.43	0.00	21.17	**1215.22**
DP10	456.54	0.00	0.00	305.76	114.09	0.00	20.35	**896.73**
DP11	385.58	0.00	0.23	564.68	380.79	0.00	66.26	**1397.54**
DP12	253.39	0.00	0.23	370.22	90.71	0.00	4.86	**719.41**
DP13	262.74	0.00	0.00	76.35	64.52	0.00	5.01	**408.63**
Statistics								
Surface water								
Min	469.44	0.00	0.72	0.00	0.00	0.00	52.60	**730.43**
Max	921.84	0.70	5.60	708.46	342.55	27.06	186.65	**2942.81**
Mean	821.93	0.09	1.41	97.05	159.16	3.04	108.89	**1191.58**
St. dev	576.80	0.20	1.19	184.77	103.79	6.46	38.07	**578.64**
Groundwater								
Min	202.88	0.00	0.00	76.35	64.52	0.00	4.86	**408.63**
Max	514.77	0.00	0.80	784.93	380.79	9.99	210.97	**1397.54**
Mean	345.37	0.00	0.23	374.67	176.72	1.31	46.84	**945.13**
St.dev.	93.23	0.00	0.26	192.11	97.10	3.23	52.08	**314.68**



Sample	Li	Na	NH4	K	Mg	Ca	Sum cations	TOC	TDS
RP1	0.01	371.50	0.00	64.28	52.51	172.68	660.98	16.57	1792.10
RP2	0.01	379.10	0.00	68.32	53.91	176.52	677.85	15.41	1714.37
RP3	0.01	382.80	0.00	67.39	53.99	176.24	680.43	15.93	1723.18
RP4	0.01	350.57	0.83	57.76	61.50	128.05	598.72	16.43	1521.51
RP5	0.01	309.08	0.86	43.48	57.24	192.87	603.53	11.54	1571.38
RP6	0.02	426.57	0.10	66.67	54.58	165.10	713.02	23.33	1767.79
RP7	0.01	444.92	1.25	75.16	54.70	114.43	690.48	25.41	1686.40
RP8	0.01	439.83	1.61	80.69	51.86	77.38	651.38	27.24	1577.22
RP9	0.01	447.72	1.83	81.72	52.98	71.24	655.50	28.50	1414.43
RP10	0.01	429.84	1.89	78.76	50.87	73.00	634.37	27.66	1558.75
RP11	0.01	409.56	1.81	71.93	51.16	138.80	673.28	19.80	1596.66
RP12	0.01	393.75	1.81	67.16	50.68	160.75	674.15	18.49	1573.51
F1	0.03	538.91	2.78	106.24	75.94	247.64	971.53	10.91	2945.79
F2	0.01	362.48	10.20	55.72	46.23	123.04	597.70	28.90	1366.70
F3	0.02	1345.04	6.82	77.06	111.27	39.35	1579.57	114.91	3924.71
N1	0.01	544.53	0.16	73.20	82.14	127.24	827.29	35.67	1991.63
N2	0.02	1524.89	0.00	155.80	196.60	93.36	1970.66	38.48	4951.95
N3	0.00	412.65	0.00	52.08	55.32	193.78	713.83	33.47	2239.56
N4	0.02	331.91	0.29	46.17	50.01	72.87	501.27	15.89	1322.50
W1	0.00	343.67	21.43	54.38	46.68	170.58	636.74	12.04	2000.31
W2	0.00	298.83	2.52	57.42	34.58	191.00	584.34	6.25	1831.09
DP1	0.00	129.42	1.48	20.86	14.75	86.13	252.63	3.47	700.63
DP2	0.00	283.38	16.33	64.21	28.28	146.60	538.79	7.95	1589.18
DP3	0.00	171.70	0.87	42.57	17.94	114.95	348.04	3.88	1097.89
DP4	0.00	218.65	0.01	81.08	19.45	121.84	441.03	13.10	1348.34
DP5	0.00	194.05	87.93	73.07	23.76	101.75	480.56	23.91	1210.02
DP6	0.00	180.18	0.53	35.19	17.11	109.59	342.61	6.54	1137.77
DP7	0.00	256.94	17.19	75.44	20.53	150.74	520.84	6.06	1824.03
DP8	0.00	259.70	4.26	54.85	20.16	154.73	493.68	7.30	1529.85
DP9	0.00	353.88	4.84	89.45	30.61	126.83	605.61	4.78	1825.61
DP10	0.00	245.23	9.80	40.81	21.13	87.97	404.95	3.53	1305.21
DP11	0.00	456.76	17.06	74.22	33.24	187.45	768.73	16.36	2182.64
DP12	0.01	161.45	1.56	29.01	19.30	83.32	294.63	3.82	1017.86
DP13	0.01	130.70	0.15	10.50	18.50	31.79	191.65	0.96	601.24
Statistics									
Surface water									
Min	0.00	309.08	0.00	43.48	46.23	39.35	501.27	10.91	1322.50
Max	0.03	1524.89	10.20	155.80	196.60	247.64	1970.66	114.91	4951.95
Mean	0.01	518.19	1.70	73.14	66.50	133.91	793.45	27.61	2012.64
St. dev	0.01	329.92	2.61	24.62	35.04	54.03	364.74	22.63	944.42
Groundwater									
Min	0.00	129.42	0.01	10.50	14.75	31.79	191.65	0.96	601.24
Max	0.01	456.76	87.93	89.45	46.68	191.00	768.73	23.91	2182.64
Mean	0.00	245.64	12.40	53.54	24.40	124.35	460.32	8.00	1413.44
St.dev.	0.00	91.58	22.18	23.31	8.66	43.54	157.38	6.04	466.79

Ion balance

The concentrations of anions and cations in mg/L were converted to meq/L (the concentration of TIC must be divided by the molecular mass of carbon, 12 g/mol, not the mass of bicarbonate) and the ion balance (Σcations - Σanions) was calculated (Appendix III). The range of the ion balance error[7] for all the samples is -14% to +5 %. The error should preferably be < |5| when the analyses are complete. 14 samples exceed this error, predominantly samples from Diambar pumps, with the anions being overrepresented compared to the cations. Surface waters have a mean error of -0.6 %, while the groundwater samples average -6 % error. According to the carbon analyses, DP5 contains a lot more TIC than the other groundwater samples, while other elements are less abundant than samples with similar conductivities. The error in the ion balance for DP5, -14 %, together with the deviation in the total dissolved solids (TDS)/Conductivity relationship (Figure 12.6), may indicate that the carbon analysis of DP5 is not exact. Meanwhile, since the results from the ion chromatography have an average error of -10 %, an average error in the ion balance of -6 % is acceptable when regarding the results qualitatively. The correlation between the amount of TDS and the conductivity is good (R^2 = 0.95, Figure 12.6), which supports the exactitude of the results.

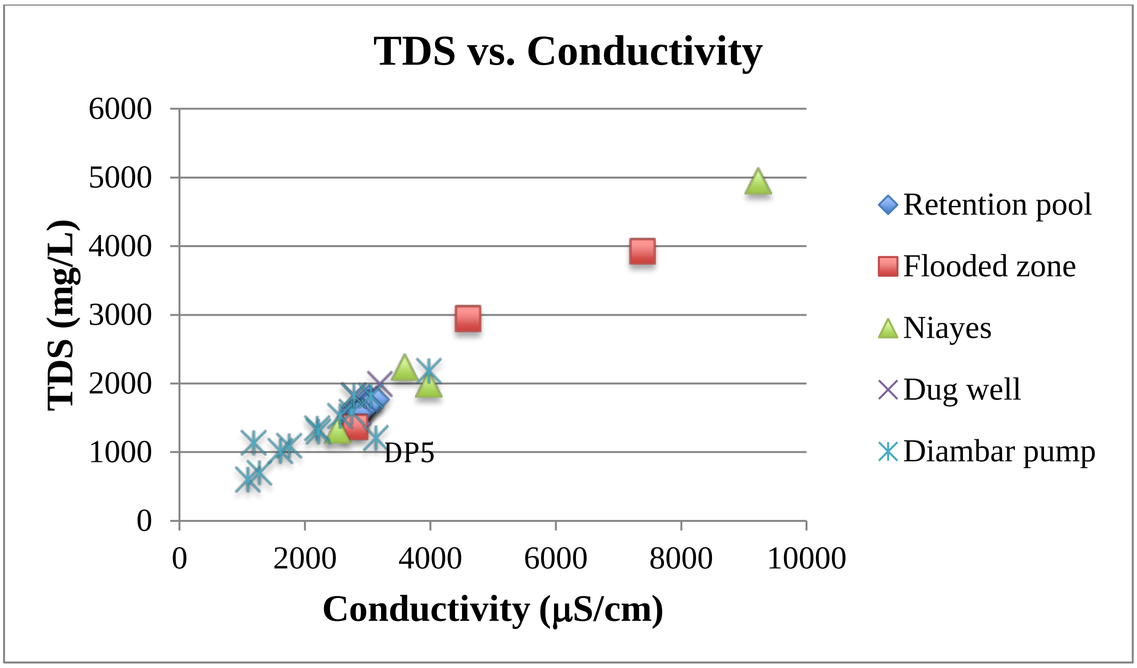


Figure 12.6: Good correlation between TDS and conductivity indicate that the results is evidence of the exactitude of the results.

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[7] Error (%) = (Σcations - Σanions) / (Σcations + Σanions)*100

The Piper diagram (Figure 12.7) shows that the samples can either be grouped as water of type sodium-chloride (surface waters), or of types sodium-chloride-sulphate/sodium-chloride-nitrate (predominantly groundwater samples). Samples N1 and F2 approach type sodium/chloride/carbonate. This corresponds to the findings of other studies (Finger, 2012; Gueye-Girardet, 2010; Tandia et al., 1999).

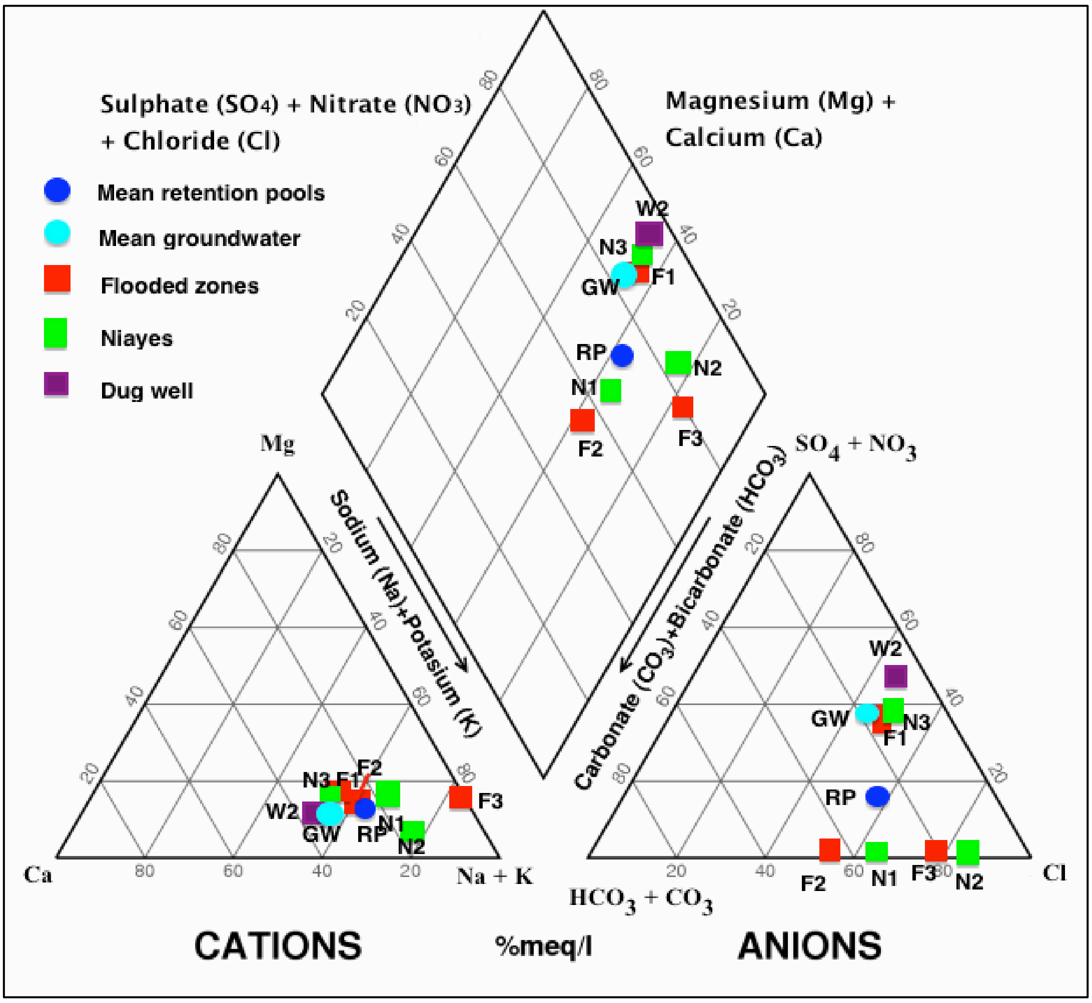

Figure 12.7: Piper diagram of selected samples from IC results.

The concentration of HCO_3^- represents in this study the amount of total inorganic carbon (TIC): that is the total concentration of $CO_{2(aq)}$ + HCO_3^- + CO_3^{2-}. Bicarbonate is the dominant species in the pH range of 6.4 to 10.3. In water with pH approaching 6.4, some of the TIC will be in the form of $CO_{2(aq)}$, while at pH more basic than 8.3, carbonate (CO_3^{2}) is often taken into account. The amount of bicarbonate may therefore be slightly overrepresented when assuming it equal to the TIC, and it may explain why the samples with acidic pH have a negative ion balance. However, the error as a result of this approximation is smaller than the error of the analyses and differentiating the TIC into

$CO_{2(aq)}$, HCO_3^- and CO_3^{2-} is therefore considered unnecessary. The concentration of bicarbonate (HCO_3^-) is assumed equal to the TIC in this study.

Surface waters, and especially the Niayes sites, contain slightly more organic carbon than the groundwater (Figure 13.4d). The average amount of dissolved organic carbon (TOC) for the surface waters is 28 mg/L, compared to the average 8 mg/L in the groundwater. Only one sample, F3 with a concentration of 115 mg/L, is extremely high compared to the other samples.

12.2.2 Isotopes of nitrate

Due to the error done during the pre-treatment for the isotopic composition of nitrate, only 4 samples for nitrogen and 3 samples for oxygen contained the preffered amount nitrate to be analysed for ^{15}N and ^{18}O. The other samples were nevertheless analysed. Table 12.4 and Figure 12.8 present the results. Numbers in red were analysed with very little sample and had correspondingly low signal in the mass spectrometer. The error of these results may be significant. A duplicate of N3 was analysed. N3a contained 1643 µg $AgNO_3$ (the preferred amount for the analysis) and N3b only 164 µg. The results show a 16 % difference (N3a = 25 ‰ vs. N3b = 21 ‰). As this error is much larger than the typical analytical error, the values for the small samples should be taken as rough estimates only or excluded from the discussion. The complete results of the isotope measurements of nitrate can be found in Appendix VI.

Table 12.4: Isotopic composition of nitrate in water samples. Red numbers represent analyses of very small samples.

Sample	d15N	d18O
RP3	29.9	23.9
RP4	30.8	34.2
RP5	30.4	32.8
F1	28.3	
N3	25.1	
W1	17.3	29.4
W2	14.4	19.7
DP1	12.7	10.3
DP6	12.6	6.3
DP8	11.4	6.8

The $\delta^{15}N_{NO3}$ value of the groundwater samples lies in the interval +11.3 to +17.3 ‰, which are typical values for human and animal wastes and manure (Figures 9.9 and 13.9). The surface water samples range from +25.1 to +30.8 ‰, being higher than any typical source of pollution. Groundwater samples from Diambar pumps are the most depleted in $^{18}O_{NO3}$, with values between +6.3 ‰ and +10.3 ‰, which lie in the range for human excreta. The dug wells and retention pools are more enriched in ^{18}O with values that exceed this source (+19.7 to +34.2 ‰).

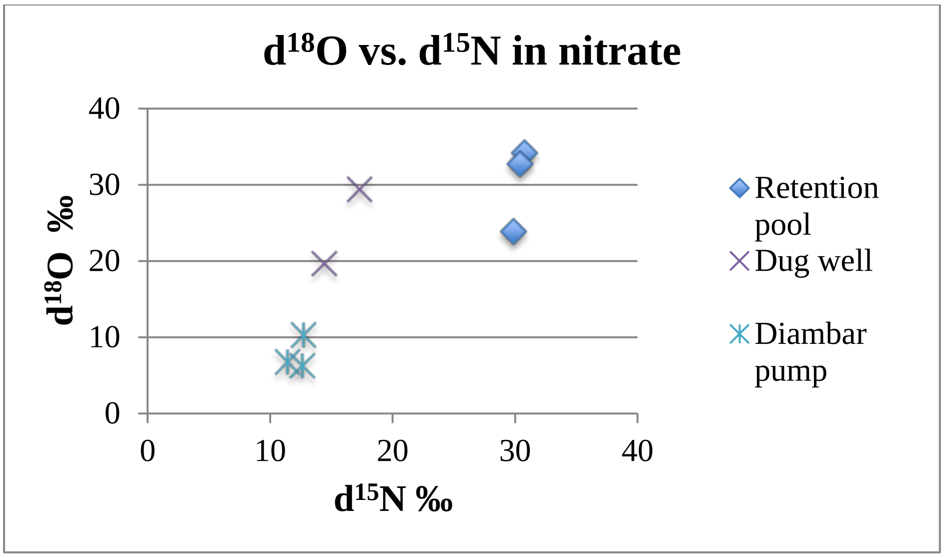

Figure 12.8: Combined plot of δ^{18}O and δ^{15}N.

12.2.3 Nitrogen isotopes of algae

The isotopic compositions of the algae, δ^{15}N$_{Algae}$, in the retention pools are between +18.2 and +25.5 ‰. The algae in the Niayes are slightly lighter and more variable, with δ^{15}N$_{Algae}$ ranging from +16.1 to +25.1 ‰. The flooded areas differ drastically; δ^{15}N$_{Algae}$ of F1 is +10.5 ‰, F2 has δ^{15}N$_{Algae}$ = +4.3 ‰, while F3 has a value of δ^{15}N$_{Algae}$ = +1.1 ‰. The results from the isotope analysis of the algae can be found in Appendix VI.

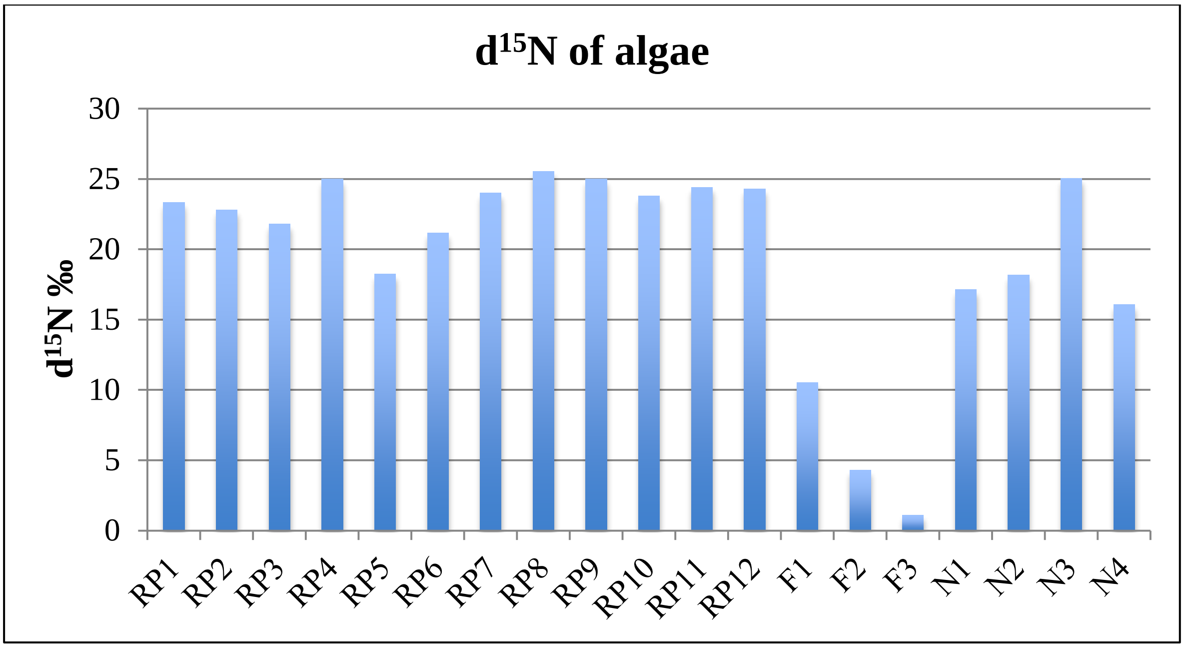

Figure 12.9: Isotopic composition of nitrogen in algae from surface waters.

12.2.4 Isotopic composition of water

The groundwater samples are in general more depleted in both deuterium and oxygen-18 than the surface water samples. δ^2H range from -34.3 ‰ to -13.3 ‰ for the groundwater and from -28.1 ‰ to +24.4 ‰ for the surface waters. The groundwater is correspondingly depleted in ^{18}O with values between -5.2 ‰ to -1.3 ‰ compared to -4.3 ‰ to +5.4 ‰ for the surface waters. The dug wells, W1 and W2, have values corresponding to the Diambar pumps. The Niayes and the flooded zones, except F2, plot in the same interval as the retention pools (Figure 12.10).

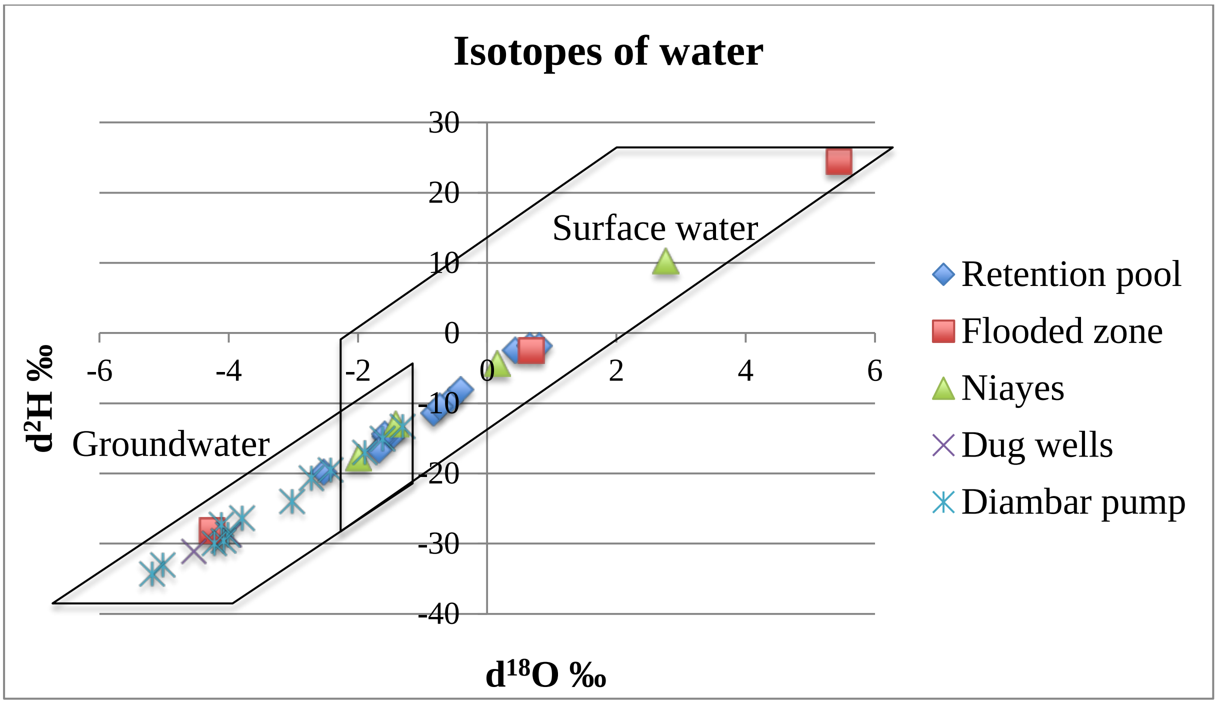

Figure 12.10: Linear relationship between δ^2H and δ^{18}O values of water samples.

13 Discussion

13.1 Temperature

The temperature of the surface water is lower than the groundwater because it is more sensitive to changes in the air temperature. The sampling was done during the cooler dry season. Surface water temperatures are similar to the ambient air temperature during sampling, while groundwater temperatures are higher, with values typical for the rainy season and closer to mean annual air temperatures.

13.2 Conductivity

Surface waters have, in general, higher conductivities than the groundwater due to more extensive evaporation. The samples F3 and N2 have the highest conductivities and highest concentrations of dissolved salts. These two sites are probably stagnant waters, where high evaporation and little mixing with the groundwater occur.

13.3 Eh and dissolved oxygen

The correlation between redox potential (Eh) and dissolved oxygen (Figure 12.2) can be affected by many factors. First, elevated concentrations of nitrate and sulphate have an impact on the correlation. Both compounds act as oxidising agents so that the redox potential may be high even though there is relatively little $O_{2(aq)}$. A second reason might be that measurements of both oxygen and Eh in the field are very approximate and may have been altered during the sampling. Eh measurements show qualitative trends, but generally cannot be interpreted as equilibrium values. On the other hand, the corrected Eh obtained in this study coincides with the observations of Re et al. (2011).

The saturation of oxygen is for many of the surface water samples greater than 100%. According to several studies (e.g. Oertli & Frossard, 2013; YSI, 2003), the supersaturation of oxygen may be a result of a very high photosynthetic activity of the algae in the water, and of a rapid increase in temperature due to solar radiation. Both processes create disequilibrium in the oxygen content, which in turn reduces the correlation with Eh. Both Oertli & Frossard (2013) and YSI (2003) report values exceeding 200 % in small ponds, where the algae content is very high. This means that the measurements of very high O_2-saturations in the surface waters in this study are plausible. However, since RP9 (with 219 % oxygen saturation) is taken from the same retention pool as RP8 and RP10 (with 129 and 109 % saturation respectively), this measurement is probably false. The other samples having very high values of oxygen saturation should be regarded as strictly indicative.

13.4 Variations in pH and TIC

The pH of around 8 to 9 of the surface waters is more basic than what is normal for precipitation. Rain is usually in equilibrium with the atmospheric $CO_{2(g)}$ and has a pH of 5 to 6 (Sigg et al., 2006; Elroy, 2002). A probable explanation is that the high photosynthetic activity of algae consumes dissolved CO_2 and the water becomes more basic. Surface water that infiltrates the ground is not aggressive so the dissolution of minerals is thought to be small. The groundwater, being recharged both by precipitation and by infiltration of domestic water transported from Lake Guiers and from the Sebikotane aquifer, is more acidic than the surface waters, but slightly more basic than rain. The increase in temperature in the groundwater might result in precipitation of calcite ($CaCO_3$), which occurs at higher pH, but shifts the reaction towards a more acidic pH (Wojtowicz, 1996). If precipitation of calcite has occurred (as suggested by Gueye-Girardet (2010)), it may explain the relatively low content of total inorganic carbon in the groundwater. The sites with the lowest pH (< 6) also contain the smallest amount of TIC (< 8 mg/L) (Figure 13.1). Acidic pH is normally associated with increased amounts of $CO_{2(aq)}$ with respect to HCO_3^-, but the overall capacity to dissolve inorganic carbon species is lower than at basic pH (Figure 13.2, Sigg et al, 2006).

The flooded zone F2, represents an urban agricultural site called Aïnoman. It is the only surface water site with an acidic pH of 6.8, and contrary to the trend described in the past paragraph, it contains relatively high amounts of TIC. A possible reason for this is that the rate of respiration of the plants and algae exceeds the rate of photosynthesis, keeping TIC at a high level and the pH low at the same time. This is supported by the observation that the amount of dissolved oxygen is only 1.52 mg/L, or 18 % saturation.

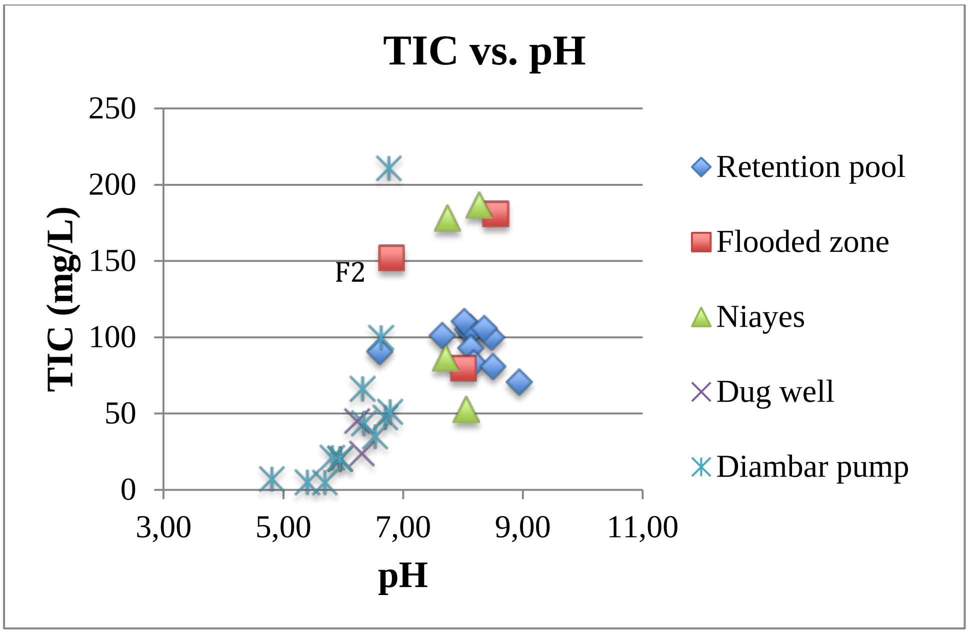

Figure 13.1: The relationship between TIC and pH for all the samples show a positive correlation ($R^2 = 0.37$).

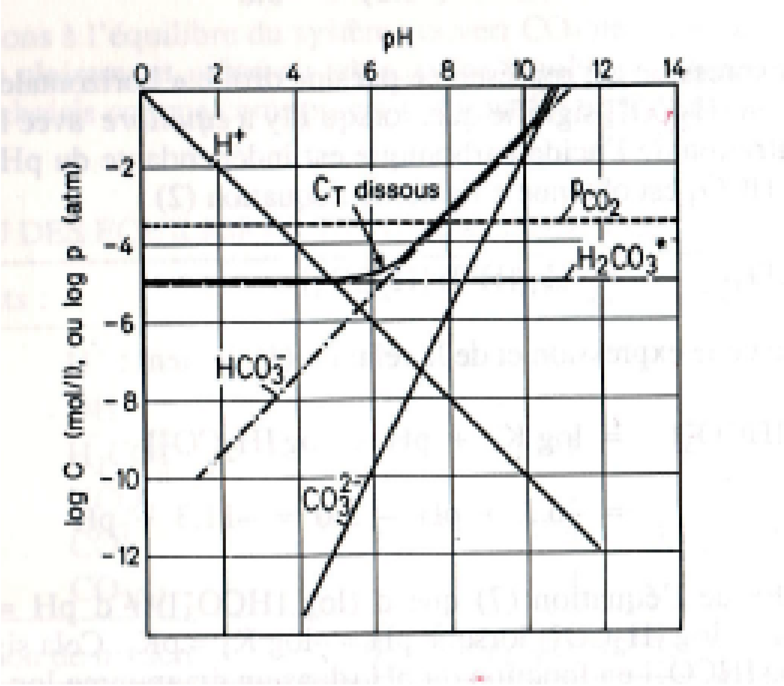

Figure 13.2: Carbonate species in an open system at equilibrium with atmospheric CO_2 (Sigg et al., 2006)

Water in equilibrium with carbonate-free silica rocks usually has a pH between 6.5 and 6.8 (Scheder et al. 1997). The measured pH for most of the groundwater samples is in accordance with this. The samples with a more acidic pH in the current study coincide with other authors working on the Thiaroye aquifer (Tandia et al, 1999; Tandia & Deme, 2003; Gueye-Girardet, 2010; Diouf et al., 2012), who found values as low as 3.5 often together with elevated Fe-concentrations (Niang et al., 2012). It is not easy to explain these findings. Three hypotheses exist, and all three could be active at the same time.

The first is related to the presence of peat and remnants of former mangrove vegetation in the Niayes areas (Lézine et al. 1985). The mangroves are known for their acidic pH conditions, often linked with authigenic pyrite (FeS_2) formation (Rampant 2003). If later exposed to oxygen-rich waters, the pyrite gets oxidised to jarosite ($KFe^{3+}{}_3(OH)_6(SO_4)_2$) by forming sulphuric acid and leading to acidic sulphate soils (Rampant 2003, Sadio & van Mensvoort 1993), comparable to the processes known from acid mine drainage.

The second hypothesis considers the fact that the Thiaroye aquifer seems to be dominated by quartz, Fe-hydroxide, halite and Mg-Ca-Na-sulphates, with some local clay beds (with possibly adsorbed SO_4^{2-} ions). Even if acidic rain water (pH around 5.6) percolates through the soil, the dissolution is not extensive and relatively few protons will be consumed, increasing the pH between 0.5 and 1.0 units at a maximum (pers. comm. H.-R.Pfeifer).

Third, since the water is polluted, the acidic pH may be a result of leakage of urine close to the Diambar pumps. As seen in Chapter 8, urine is originally acidic, but due to the degradation of urea into ammonium the pH usually increases. The water table in the region is very shallow and the Diambar pumps extract water from mainly 2 to 8 m depth, which is just below the normal depth of the pit latrines and septic tanks. The urine may easily mix with the groundwater, where urea is first degraded into ammonium but then rapidly nitrified into nitrate, which in turn reduces the pH. Results from DP7 show evidence of this. The owners of this Diambar pump reported that it is situated at only 2 to 3 m depth (Appendix VIII). The amount of nitrate in DP7 (785 mg/L) is by far the highest of all the samples, while the pH of 4.8 is the lowest. In addition, Eh and $O_{2(aq)}$ are relatively high compared to the other groundwater samples. Nitrification is inhibited at pH<6, but it is possible that the pH fluctuates with time according to the amount of leakage from the latrines and that nitrification occur when the pH is higher.

13.5 Macropollutants (nitrate, phosphate, sulphate and TOC)

All of the groundwater samples and several of the surface water samples, in total 22 of the 34 samples (65 %), have nitrate concentrations that exceed the WHO regulatory limit of 50 mg-NO_3/L for drinking water. Figure 13.3 shows the sites in red where this limit is exceeded.

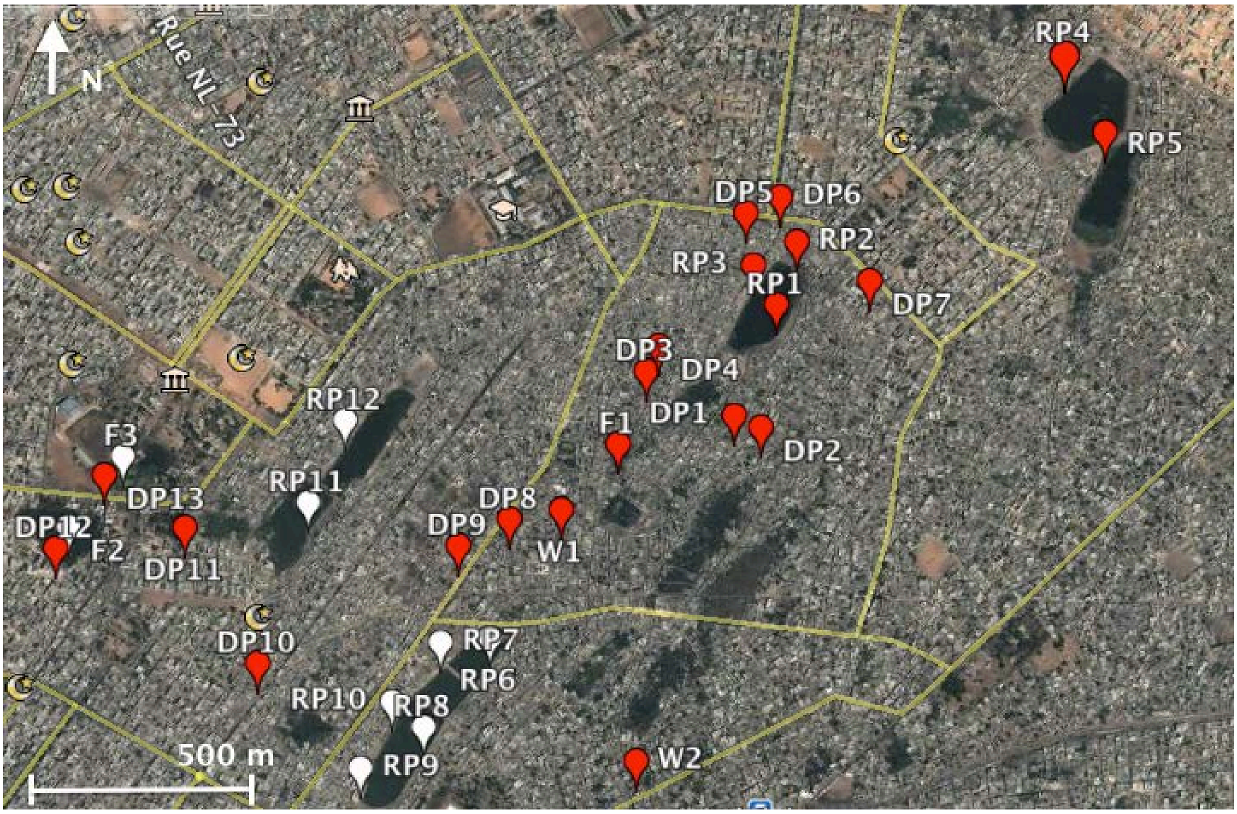

Figure 13.3: Map of the sample sites with relative values of nitrate concentration. Red markers indicate a site with a nitrate concentration > 50 mg/L, white markers are sites with < 50 mg/L nitrate.

The Niayes are areas of agriculture (Figure 1.1 and 10.1). The farmers at site N1 and N3 use organic fertilisers, like horse manure, which might add to the amount of phosphate. The phosphate in DP2 and DP3 originate probably from human excreta. It is not understood why DP2 and DP3 are richer in phosphate than the other groundwater samples. The amount of nitrate in N3 might also come from fertilisers, while in N1, N2, and N4 aquatic plants have probably consumed most of the nitrate. The same plants were not observed at the N3 site.

The sulphate in both the groundwater and surface waters could originate partly from marine aerosols and from the sedimentation of sand along the coast in earlier geologic times. It could also be a result of pollution from domestic wastes or be related to the dissolution of pyrite and jarosite in the soil (Gueye-Girardet, 2010). Since there is no correlation between Eh-sulphate (Figure 13.4c) or pH-sulphate (Figure 13.5c), it is not very likely that the sulphate originates from the oxidation of pyrite.

Some samples contain a significant amount of ammonium (Table 12.3 and Figure 13.4b). At these sites the redox potential and the amount of dissolved oxygen are relatively low. The samples with NH_4^+-concentrations > 9.8 mg/L contain between 1.3-3.8 mg/L of dissolved oxygen, while studies show that the oxygen concentration must be a minimum of above 2.5 mg/L for nitrification to occur at a significant rate (Garrido et al., 1996). Except F2, these are all groundwater samples and Figure 13.5b show that there is a slight negative correlation between pH and ammonium content. Acidic pH favours the formation of ammonium. The ammonium degraded from the urea in the sewage water is for this reason possibly nitrified into nitrogen oxides at a slower rate than at sites with more basic pH. When the pH increases, the Eh must be reduced for ammonium to form or for the oxidation of N to be inhibited (Figure 8.1). The surface waters with basic pH contain, for this reason, very little ammonium. The two dug wells have, in general, similar values for most parameters, except when looking at the redox conditions and ammonia content. The reason for this difference cannot be explained, but the result of very high Eh in W2 is reflected in the lack of ammonium in W2, while W1 contain the second most NH_4^+ of all the samples (21.4 mg/L), after DP5, but has less oxidising conditions than W2 (Table 12.3 and Figure 13.4b).

The combination of slightly acidic pH and very little dissolved oxygen in Aïnoman (F2), suggesting that nitrification may be inhibited, coincides with the presence of ammonium (10.2 mg/L) and the correspondingly low concentration of nitrate.

There seems to be a positive correlation between the pH and the amount of dissolved organic carbon (Figure 13.5d). Eutrophication of the surface waters is followed by a rapid growth of aquatic organisms. Degradation of this organic matter in the surface waters increases the TOC. At the same time, the TOC is related to the pH because the surface waters approach equilibrium with $CaCO_3$ and with atmospheric CO_2, which is consumed by plants and algae, shifting the pH to around 8-9.

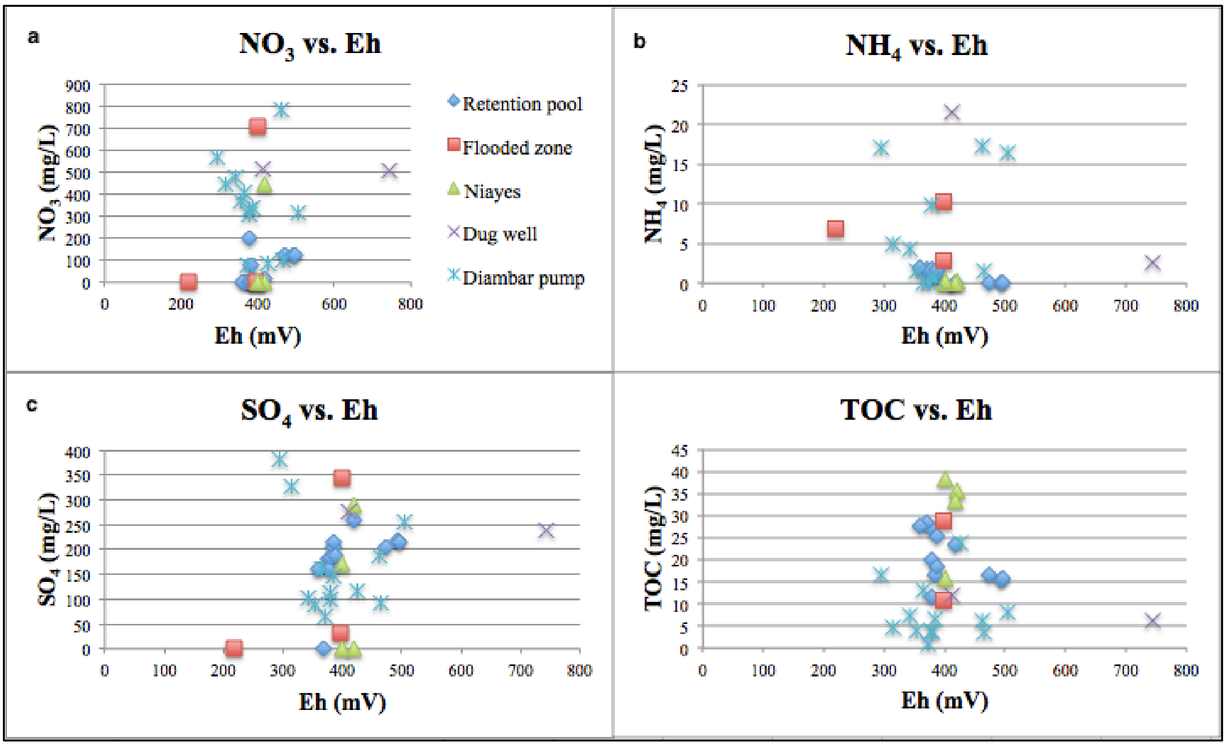

Figure 13.4: The relationship between different compounds and Eh. DP5 is excluded from the NH_4 vs. Eh diagram. F3 is excluded from the TOC vs. Eh diagram.

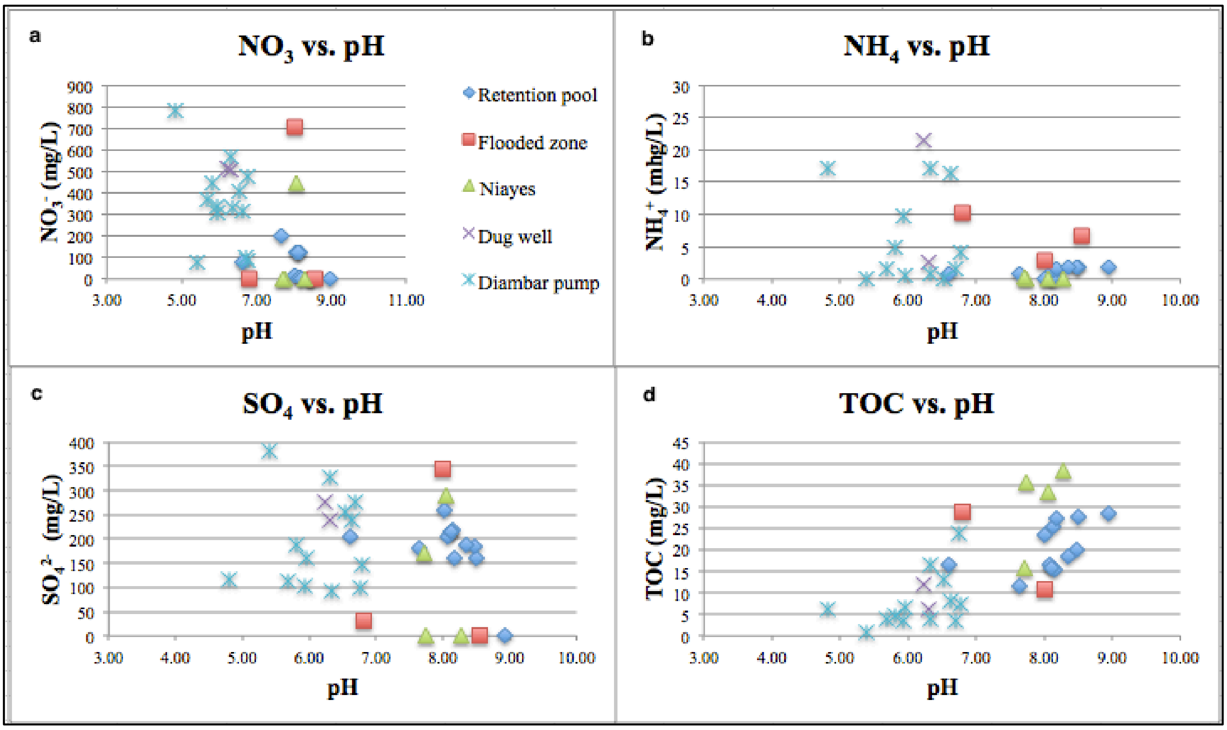

Figure 13.5: The relationship between different compounds and pH. DP5 is excluded from the NH_4 vs. pH diagram. F3 is excluded from the TOC vs. pH diagram.

13.6 Fate of the nitrate

Differentiating between the transformation processes that might reduce the concentration of nitrate is in this case very difficult because several processes may happen at the same site over a short time span. Also, the few samples and the possibly low accuracy of the results for the isotopic composition of nitrate further complicate the synthesis of the results. In the following paragraphs, different processes that might contribute to the reduced nitrate concentrations in the surface waters compared to the groundwater in Pikine and Guédiawaye are discussed.

13.6.1 Dilution

As suggested above, the retention pools and the other surface waters are recharged both by the groundwater and by precipitation. Due to surface runoff towards the depressions during the rainy season, the retention pools are recharged more by precipitation compared to the groundwater in terms of net volume, with the groundwater being mainly recharged by infiltration of polluted domestic water. One possible reason for the low nitrate content in the retention pools could, therefore, be dilution. In contrast, more extensive evaporation from the surface waters compared to the groundwater would concentrate the nitrate in the same manner as the other elements. A plot of NO_3^- vs. Cl^- (Figure 13.6) reveals that dilution is not an important cause for the reduced concentrations of nitrate in the surface waters. Dilution would result in a correlated decrease in both compounds, while Figure 13.6 shows that the concentrations of nitrate and chloride are independent of each other.

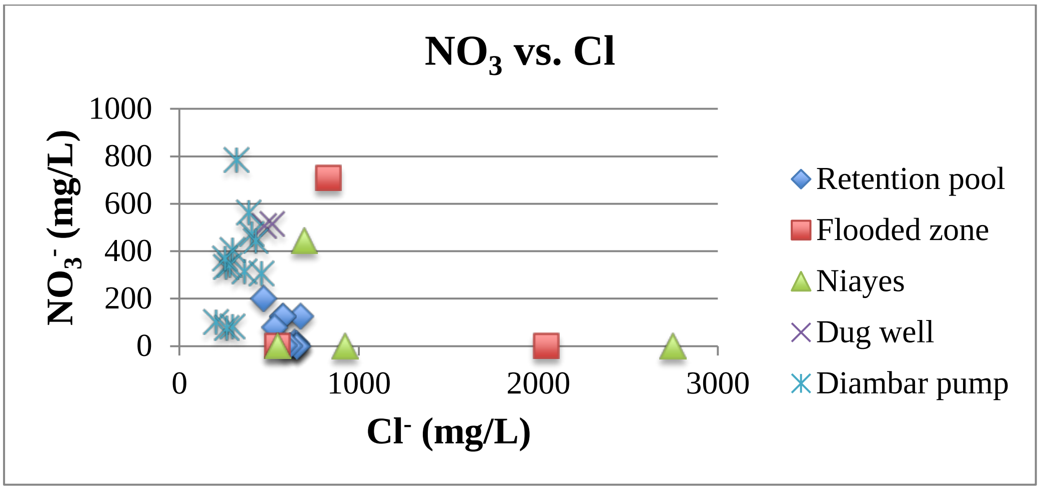

Figure 13.6: No correlation between the concentrations of nitrate and chloride suggests that dilution is not an important factor for the lowering of the concentrations of nitrate in surface waters.

13.6.2 Uptake of nitrate by aquatic plants and algae

There is strong evidence of nitrate uptake by aquatic plants and algae in the surface waters. This is first indicated by the very low nitrate concentrations in the surface waters compared to the high concentrations in the groundwater. Secondly, the surface waters that contain the most algae (observed in the field and during filtration) and the most TOC have the lowest concentrations of nitrate (Figure 13.7b). Analyses of the isotopic composition of nitrogen in the algae correspond to that of the nitrate in the surface waters (Figure 13.7a). The Niayes sample, N3, has an equal value of +25 ‰ in both the dissolved nitrate and in the algae. The other samples show that the nitrate in the water is generally more enriched in ^{15}N than the algae, but it is nevertheless enriched compared to the normal range for algae (Figure 9.9; according to Miyake & Wada (1967): phytoplankton [+3, +8] ‰ and algae [+5, +10] ‰). High $\delta^{15}N_{Algae}$-values of up to +25 ‰ measured for the algae are compatible with the assimilation of nitrate that originates from wastewater or human and animal wastes and where these sources have experienced some denitrification (e.g. Viana & Bode, 2012).

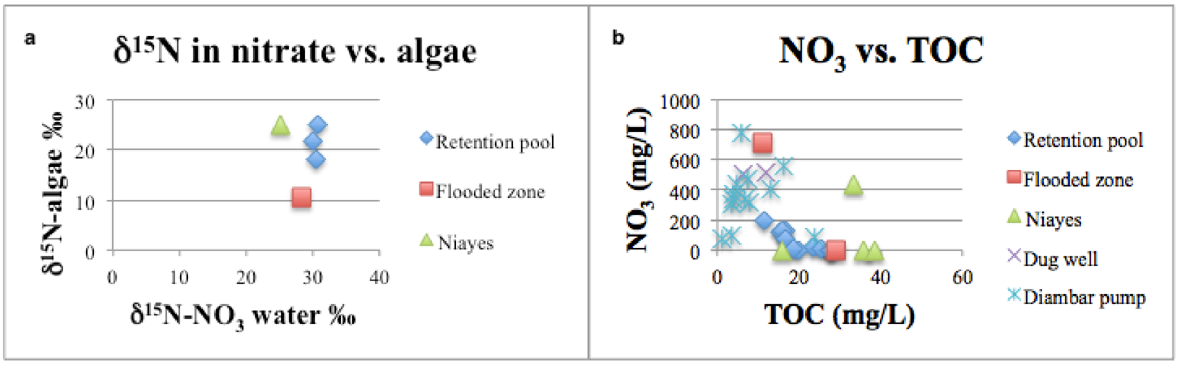

Figure 13.7: a) Correlation between δ^{15}N in nitrate and algae, b) correlation between nitrate and TOC.

Algae from the flooded zones are more depleted in heavy isotopes than algae from the Niayes and the retention pools. The water at these sites is brown and muddy, and contains relatively high amount of organic carbon. The nitrate may therefore originate from the degradation and ammonification of organic nitrogen, resulting in δ^{15}N between +2 to +9 ‰ (Chae et al., 2009). The very low δ^{15}N of the algae in F3 (1.1 ‰) might be a result of an additional fractionation during uptake of light nitrate and/or related to an uptake of dissolved ammonium.

13.6.3 Denitrification

Both Gueye-Girardet (2010) and Re et al. (2011) suggested that denitrification is taking place in the deeper parts of the Thiaroye aquifer, and in shallower areas of the groundwater under clayey soil or close to septic drain fields. The following paragraphs discuss the observations made in this study. The results are very ambiguous.

Denitrification can be indicated by an inverse relationship between $\delta^{15}N_{NO3}$ and NO_3^-; if denitrification occurs; decreased amounts of nitrogen should correspond to high values $\delta^{15}N_{NO3}$. There is little correlation between the concentration of nitrate and the isotopic composition of nitrogen when regarding all the samples (Figure 13.8). However, when just looking at the sites where denitrification is suspected (samples enriched with $\delta^{15}N_{NO3}$ > 15 ‰), thus excluding the Diambar pumps, the tendency of a negative correlation exists (R^2 = 0.3). Also, since the source of pollution is unevenly distributed and there is evidence of uptake by plants, as seen below, this relationship might be altered and the apparent correlation reduced. A good correlation can thus only be expected if the water is transported from the aquifer into a retention pool while denitrification is happening. Mixed sources or variable input as a function of time will weaken the correlation.

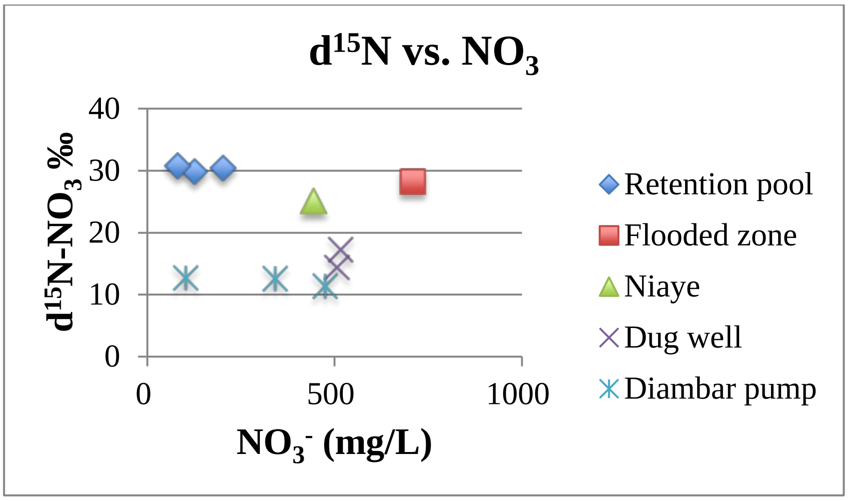

Figure 13.8: Slight negative correlation between isotopic composition of ^{15}N and nitrate concentration for the surface waters and dug wells.

The dual-isotope method, using a plot of $\delta^{18}O$ vs. $\delta^{15}N$, is a useful tool to detect if denitrification has occurred. Figure 13.9 shows that the nitrate, especially in the retention pools, but also in the dug wells, is enriched in the heavy isotopes of nitrogen as well as oxygen. There are no sources with an isotopic composition of $\delta^{18}O$ up to +35 ‰ and $\delta^{15}N$

up to +30 ‰, as measured in the retention pools, and denitrification is the most probable process for this extent of fractionation (cf. Figures 9.9-9.11). Denitrification usually results in a slope of 0.5-1 for the $\delta^{18}O/\delta^{15}N$ relationship (Itoh et al., 2011). The slope obtained in this study is 1.1 ($R^2 = 0.69$) is slightly larger than the normal range, but the difference is not significant enough for denitrification to be ruled out.

The redox potentials for the three retention pool sites in Figures 13.9 and 13.10 are 495 mV (corresponds to the lowest $\delta^{18}O$-value of the three), 384 mV and 378 mV. As seen in chapter 8.2.6, denitrification by bacteria is inhibited at Eh > +250 mV and by fungi at Eh > +400 m. It is therefore peculiar that the nitrate is so enriched in heavy isotopes. Possibly, the microorganisms and fungi are capable of creating a local microenvironment with more reducing conditions than the water body itself, and may in this way still perform the reduction of nitrate. There can also exist anaerobic pockets around the ground-/surface water interface or in the groundwater where denitrification may occur (as suggested by Gueye-Girardet (2010)). Another explanation is that denitrification happends at night, when respiration replaces the photosynthetic activity of the algae and the amount of dissolved oxygen assumingly is less than during the day. Alternatively, the nitrate is a residual nitrate that has experienced denitrification before it was admixed to the retention pools, with the latter being influenced by other surface waters (precipitation) with higher oxidation potentials but low nitrate concentrations. It might also be that either the Eh-measurements and/or the isotopic compositions of nitrate are incorrect.

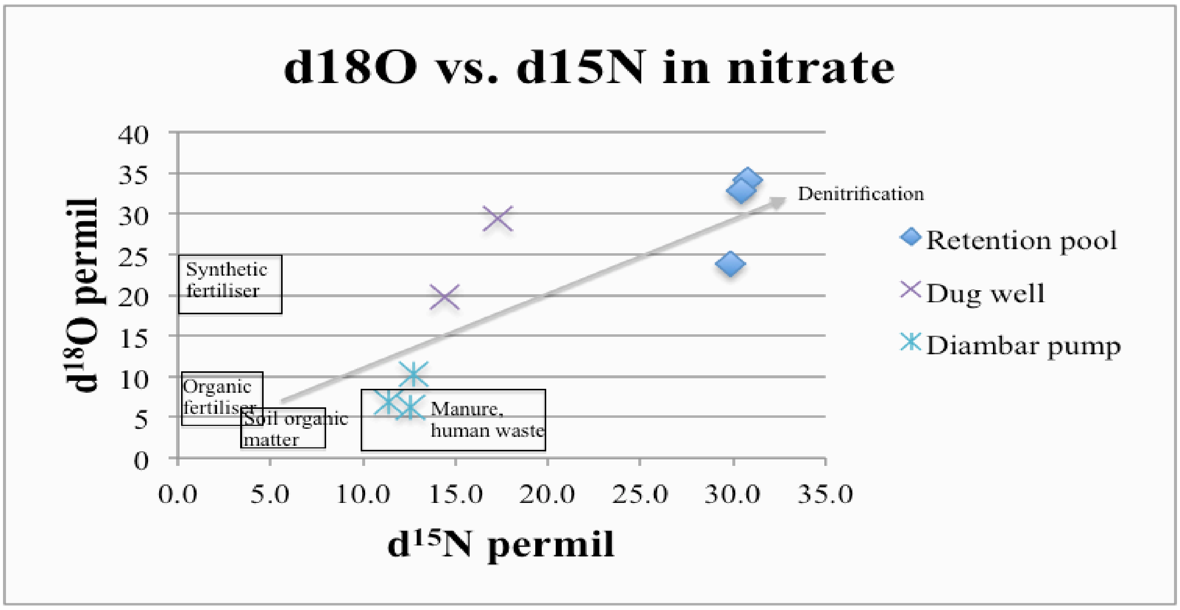

Figure 13.9: Dual-isotope method to determine the source of nitrate pollution and occurrence of denitrification.

However, decreasing Eh corresponds to increasing δ^{18}O-values for the potentially denitrified samples (Figure 13.10). This fact supports the possibility that denitrification is taking place, in spite of the apparent oxidising conditions.

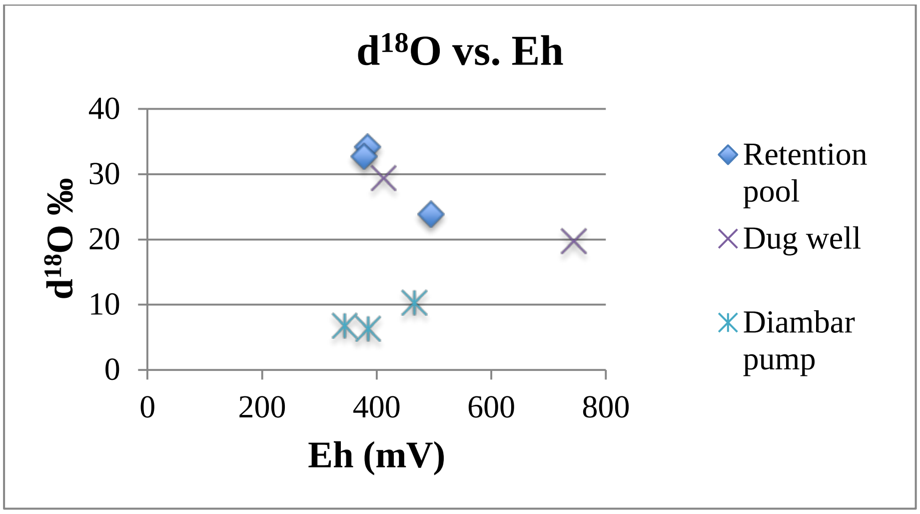

Figure 13.10: Isotopic composition of nitrate vs. Eh show a good negative correlation for dug wells and retention pools, which supports the possibility of denitrification at these sites.

The nitrate concentration is inversely related to the amount of inorganic carbon. Other factors may result in this relationshop, but after eq. 8.6, denitrification would contribute to this correlation and it is thus yet another indication that the nitrate is reduced by denitrification.

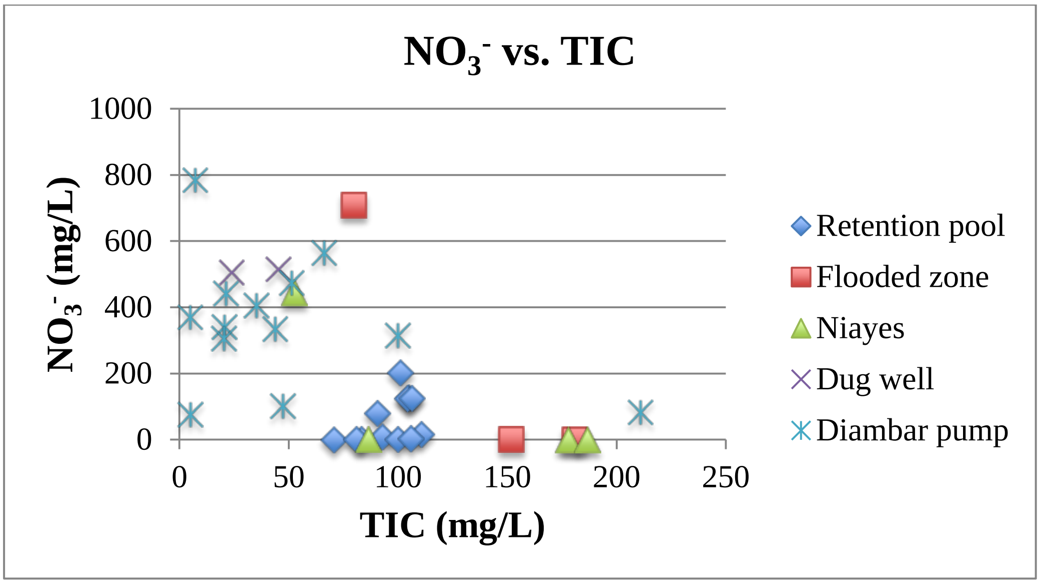

Figure 13.11: Relationship between nitrate concentration and total inorganic carbon. There is a negative correlation for all the samples combined (R^2 = 0.36).

In contrast, if denitrification is taking place, an inverse relationship should be observed between the nitrate and the sulphate, as this process does not affect sulphate. That is not the case in this study. Figure 13.12 shows that the two compounds are not dependent. Nitrate reduction normally precedes sulphate reduction, but the two can overlap, as often seen in the Baltic Sea for example (pers.comm. T.Vennemann), and, as mentioned in Chapter 8.2.6, some microorganisms are capable of reducing nitrate by the oxidation of sulphate.

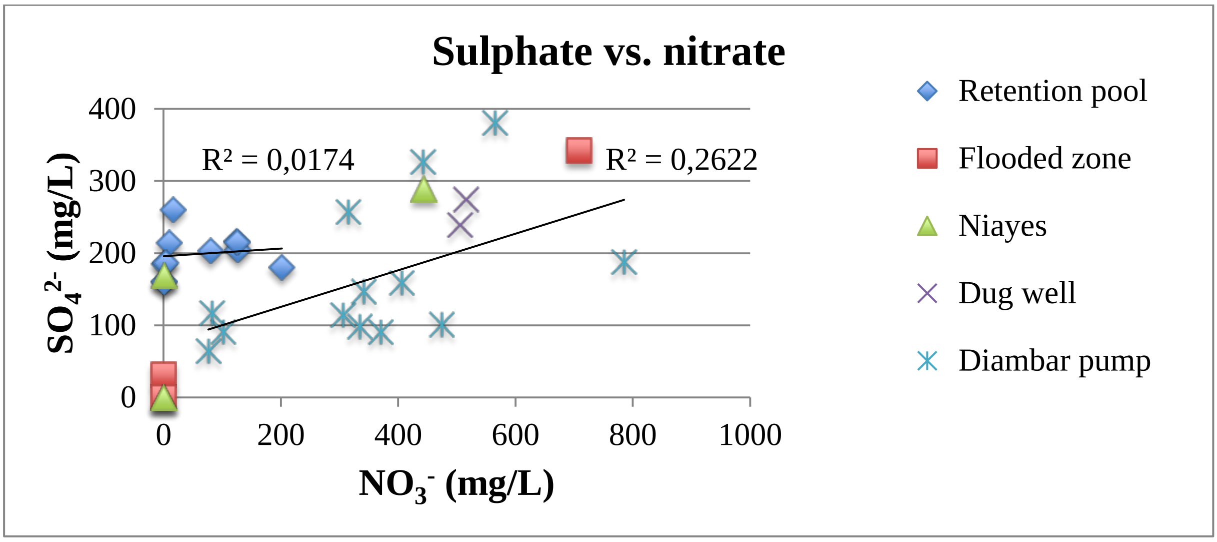

Figure 13.12: The lack of a negative correlation between sulphate and nitrate suggest that denitrification is not taking place.

13.6.4 Remineralisation/ammonification

The high algal activity results in high growth and decay rates in the surface waters. The algae assimilate originally enriched nitrate. The catabolic reactions of amino acids in organisms produce volatile ammonia of the lighter molecules, while heavy molecules accumulate in the organic matter. During remineralisation of this organic nitrogen, the produced ammonium, and the further derived nitrate, is even more enriched than before the first uptake. If this cycle is repeated, the enrichment in both the nitrate and in the algae may be significant. Also, as seen in Chapter 9.4.2, ammonification may fractionate the nitrogen in the algae resulting in decay products depleted in ^{15}N relative to the residual organic matter, which becomes enriched in ^{15}N. Unusually high $\delta^{15}N_{Algae}$-values of up to +25 ‰ measured in the algae could therefore indicate that the isotopic composition of the nitrate in the surface waters is related to this remineralisation of the algae. The enrichment due to remineralisation is normally not as significant as observed in this study (ε_{N2-NO3} around -14 to -18 ‰), but if the analysed values of $\delta^{15}N$ in both the algae and the nitrate in water are overrepresented, or the cycle repeated, it can be a plausible explanation.

13.6.5 Volatilisation

Due to the acidic pH in most samples, the loss of N by ammonia volatilisation is assumed to be very small. Only when the pH approaches 9 and there is presence of ammonium, may volatilisation be a contributing factor to the sinks of nitrogen and create an isotopic fractionation with enrichment of ^{15}N in the residual ammonium.

13.7 Evaporation

The relationship between $\delta^{2}H$ and $\delta^{18}O$ is linear and regression lines for both the ground- and surface waters show a very good correlation (R^2-values close to 0.99). The slope of the regression lines indicates that there has been isotopic fractionation due to evaporation: a slope smaller than 8 suggests the occurrence of evaporation. The slopes for the samples from the Diambar pumps, the retention pools and the flooded zones are practically equal; being 5.38, 5.76, and 5.41 respectively (Figure 13.14). These values indicate that there has been evaporation from both the ground- and surface waters. It was expected that the surface waters would be evaporated. What is interesting is that the groundwater taken from the Diambar pumps, at depths between 2 to 15 m, also seems to be largely affected by evaporation. A tendency of enriched $\delta^{18}O$ (Figure 13.13a) and increased evaporation (Figure 13.13b) with decreasing depth to the Diambar pumps is observed. The depths of the pumps were obtained during the interview with the owners (Appendix VIII) and are appriximatifs.

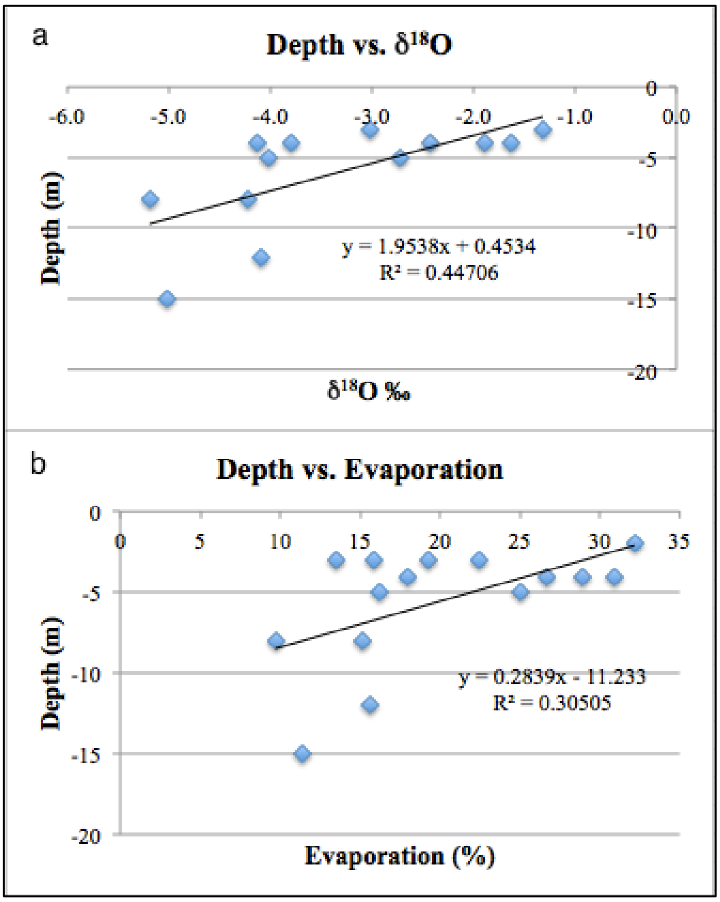

Figure 13.13: Correlation between δ^{18}O and amount of evaporation as a function of depth. The fraction of evaporation increases with decreasing depth to the Diambar pump.

Two samples, F3 and N2, are far more enriched in heavy isotopes than any of the other samples. This enrichment corresponds to the high conductivity measured at these to sites in the field and indicates extensive evaporation. The point where the evaporation line and the LMWL intercept is the average isotopic composition of the precipitation that may recharge the aquifer. By interpolating the regression line of the Diambar pumps in Figure 13.14, the intercept is found at $\delta^{2}H_{R}$ = -41.5 ‰ and $\delta^{18}O_{R}$ = -6.5 ‰ (the *R* notation signifies recharge). All the samples seem to originate from the same water, or mixture of waters, and they follow the same evaporation trend, only with different extent of evaporation, which indicates good circulation between the ground- and surface waters.

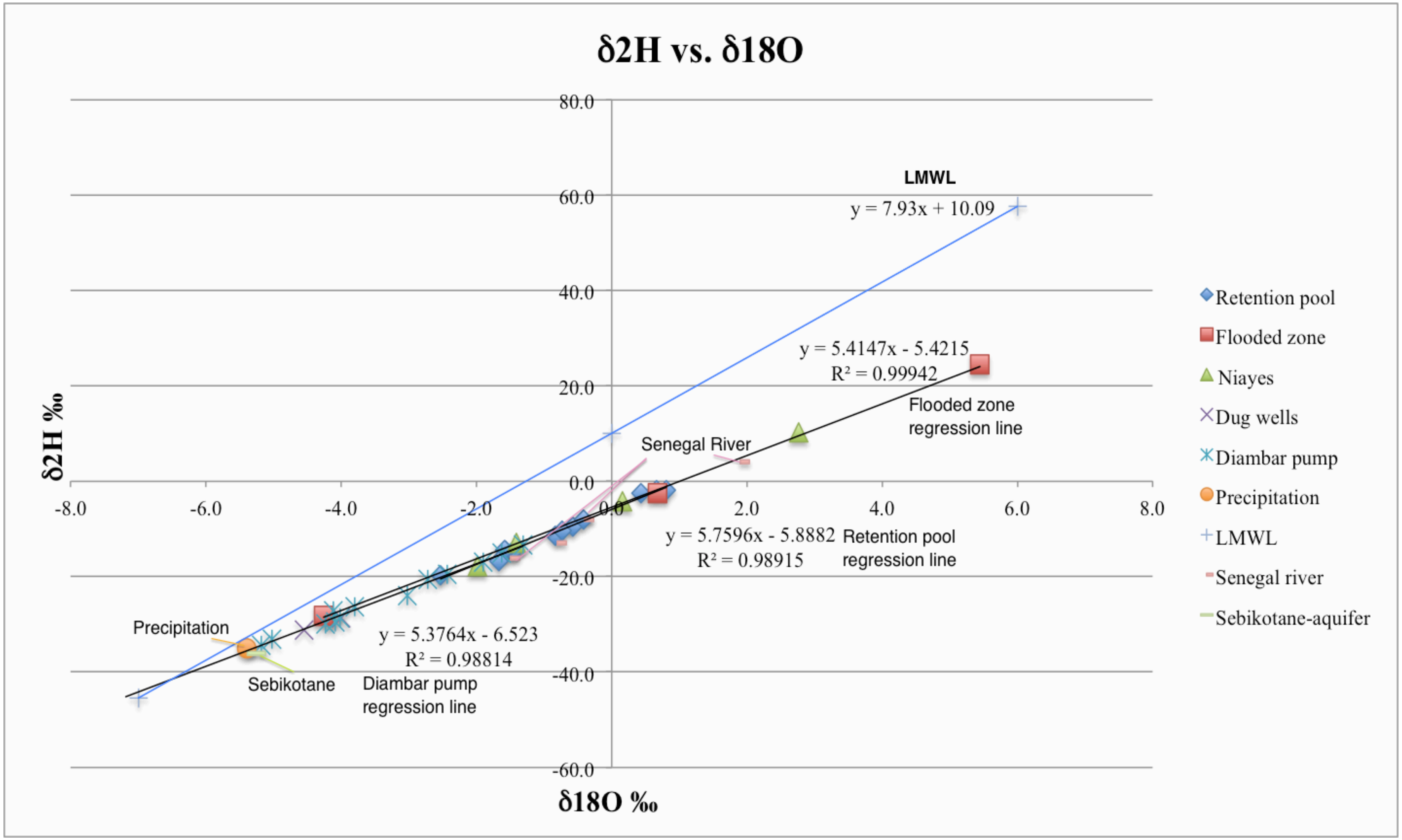

Figure 13.14: Isotopic composition water samples. Regression lines represent the evaporation lines. LMWL = Local Meteoric Water Wine for Dakar after Travi et al., (1987). Values for the precipitation are taken from Diouf et al. (2012) and for the Sebikotane aquifer from Madioune (2009).

Quantification of evaporation

The amount of evaporation can be calculated with the use of the equations presented in Chapter 9. First, the equilibrium fractionation factor between water (notation *l*) and vapour, $\alpha'^{2}H_{l\text{-}v}$, is calculated with eq. 9.20 based on the average temperature (in Kelvin) of the groundwater. The corresponding equilibrium enrichment factor, $\varepsilon'_{l\text{-}v}$, can then be derived from eq. 9.13. For the groundwater samples with an average temperature of 28.01 °C, the values are:

$$\alpha'^{2}H_{l\text{-}v} = 1.07627$$
$$\varepsilon'^{2}H_{l\text{-}v} = 76.27\ ‰$$

In Dakar, the humidity is around 65 % during the winter months, when the samples were taken, but because evaporation happens throughout the year, the average annual humidity of around 73 % might be more representative when calculating the effect of kinetic fractionation (eq. 9.17 and 9.18):

$$\Delta\varepsilon^{18}O_{l\text{-}v} = 14.2(1-0.73) = 3.83$$
$$\Delta\varepsilon^{2}H_{l\text{-}v} = 12.5(1-0.73) = 3.38$$

The total enrichment of the water body during evaporation, with regard to hydrogen isotopes, is thus (eq. 9.19):

$$\varepsilon^{2}H_{l\text{-}v} = \varepsilon'^{2}H_{l\text{-}v} + \Delta\varepsilon^{2}H_{l\text{-}v} = (76.27 + 3.38)\ ‰ = 79.65\ ‰$$

This can then be transformed back to the total fractionation factor, $\alpha_{l\text{-}v}$, for the combined equilibrium and kinetic effect:

$$\alpha^{2}H_{l\text{-}v} = \varepsilon^{2}H_{l\text{-}v}/1000 + 1 = 1.0797$$

The Rayleigh equation for evaporation must include the fractionation factor from vapour to water (the inverse of the factor from water to vapour), $\alpha^{*}_{v\text{-}l} = 1/\alpha_{l\text{-}v}$ (eq. 9.12):

$$\alpha^{*2}H_{v\text{-}l} = 1/\alpha^{2}H_{l\text{-}v} = 0.9262$$

The Rayleigh equation for evaporation at humidities < 100 % can then be approximated to (eq. 9.9):

$$f\hat{}(\alpha^{*} - 1) = \delta^{2}H_{x} + 1000) / (\delta^{2}H_{R} + 1000)$$

where the f is the fraction of remaining water, $\delta^{2}H_{x}$ the isotopic composition of the sample and $\delta^{2}H_{R}$ the estimated composition of the recharged water.

For the groundwater samples, with an average of $\delta^{2}H = -25.2$ ‰, the fraction of the water remaining in the bulk becomes:

$$\ln(f) = \frac{974.8/958.5}{0.9262-1} = -0.2286$$
$$f = e^{-0.2286} = 0.7956 \approx 80\ \%$$

The fraction of the water that is evaporated from the groundwater, since it was recharged, is then 20 % in average.

Following the same calculations for the surface waters, of which the average temperature is 24.4 °C and mean $\delta^{2}H$ is -8.2 ‰, the fraction of evaporation becomes 35 %. The calculated evaporation fraction for all the samples can be found in Appendix VII.

The results of these calculations coincide with what was expected; that the surface waters are more evaporated than the groundwater. However, the difference is not only due to more intensive evaporation. The groundwater is constantly being recharged by infiltration of domestic water throughout the year. This is less evaporated and the groundwater becomes diluted by lighter water. The actual evaporation from the groundwater may actually be higher than estimated here. In the meantime, at the surface water sites with plants, like the Niayes and flooded zones, water is transpired, which means that the total evapotranspiration is higher at these sites also. The Aïnoman (F2) site gives evidence of this. As can be seen in Figure 7.1, there are a lot of plants and algae at this site, covering the surface of the water almost completely. The water in Aïnoman is very depleted in heavy isotopes, plotting amongst the groundwater samples (Figures 12.10 and 13.14), and because transpiration does not cause any isotopic fractionation, it can be concluded that the rate of transpiration is high, while less evaporation occurs.

The quantification of evaporation shows that the retention pool Nietty Mbar (RP6-RP10), with an average 37 % evaporation, is more evaporated than the retention pool Bagdad, with 30 % (Figure 10.2, Appendix VII). The retention pools are shallow and probably of the same depth of 3-4 m. The effect of sun radiation and thus the amount of evaporation should be similar. The difference in estimated evaporation can therefore be an indicator of the hydrological connectivity with the groundwater. Surface waters with relatively less apparent evaporation might suggest a good circulation between the enriched surface waters and the relatively depleted groundwater. Surface waters with higher fractions of evaporation have then poorer hydrologic connectivity with the groundwater and are more stagnant waters.

13.8 Mixing

Seawater has the isotopic composition of $\delta^2H = 0$ ‰ and $\delta^{18}O = 0$ ‰ (close to Dakar the values are $\delta^2H = +4.2$ ‰ and $\delta^{18}O = +0.75$ ‰ (measured in the fall 2012 by Benoît Zen-Rufinen, student at UNIL, Switzerland) due to evaporation of water from the equatorial surface ocean water). Because all samples plot along a typical freshwater evaporation line, there is no evidence of mixing with seawater. However, the groundwater samples are taken at shallow depths, and one can therefore not conclude that no saltwater intrusion occurs in deeper parts of the Thiaroye aquifer, as proposed by Re et al. (2011).

The sampling was done during the dry period and the last rainfall happened approximately three months earlier. Nevertheless, all the types of water samples show the same tendency and lie on the same evaporation line. The hypothesis that the retention pools are in direct contact with the aquifer is thus strengthened. The aquifer is partly recharged throughout the year by drinking water transported from Lake Guiers, which in turn is filled up by water from the Senegal River, and from the Sebikotane aquifer in the Ndiass horst. Values of the isotopic composition of four samples from the Senegal River are plotted in Figure 13.14. The values, which were found in Diaw et al. (2010), are heavier than the local precipitation probably because of evaporation both during precipitation within the catchment of the Senegal River and during the surface flow of the river towards the Atlantic Ocean. The isotopic composition of the local precipitation, $\delta D = -35$ ‰ and $\delta^{18}O = -5.4$ ‰ (orange point in Figure 13.14) is taken from Diouf et al.,

(2012) and was measured at a meteorological station in Guédiawaye. The water from the confined Sebikotane aquifer resembles the local precipitation, with an average isotopic composition of $\delta^{2}H$ = -36 ‰ and $\delta^{18}O$ = -5.3 ‰ (green short line in Figure 13.14). The local precipitation and the water from both the Senegal River and from the Sebikotane aquifer plot on the same evaporation line as the surface and groundwater samples in Pikine and Guédiawaye. It can thus be concluded that a mixture of precipitation and drinking water recharge both the groundwater, the retention pools and other surface waters. It is likely that the flow goes from the groundwater towards the retention pools and other surface waters during the dry season, while during the rainy season, when surface runoff collects in the pools, the flow direction turn and the groundwater gets recharged by the surface waters.

Conclusion

The work on this master thesis has resulted in a thorough study of the water quality, both of the shallow parts of the groundwater and of the surface waters in the suburban araes of the Dakar Region. Together with the studies of the Niayes (e.g. Gueye-Girardet, 2010; Ndiaye, 2009; Niang et al, 2012 (Mbeubeuss study)) and Lake Retba (e.g. Zen-Rufinen, 2013), the water quality of the region is now well mapped.

The average concentration of nitrate in the groundwater, 375 mg-NO_3/L, largely exceeds WHO regulatory limit of 50 mg/L for drinking water. The source of pollution is mainly leaching and infiltration of human wastes from pit latrines and permeable septic tanks. Water from the Diambar pumps was found to have an average isotopic composition of $\delta^{15}N_{NO3}$ = +12.2 ‰ and $\delta^{18}O_{NO3}$ = +7.8 ‰, indicating an origin of manure or human wastes. Land use further links human wastes to the densely habited suburban areas if Pikine and Guédiawaye, while at the Niayes sites, organic fertilisers may be a contributing source of pollution.

The urea in the urine gets degraded to ammonia, which is rapidly nitrified into nitrate under the pH and Eh conditions measured in the groundwater. At the sites where the amount of dissolved oxygen is low and pH is more acidic than 6, the rate of nitrification is reduced, which is reflected in the presence of ammonium at these sites.

In the flooded zone F1, the nitrate in the water is very enriched in ^{15}N ($\delta^{15}N_{NO3}$ = + 28.3 ‰), while the $\delta^{15}N_{Algae}$ at the three flooded sites, F1-F3, are 10.5 ‰, 4.3 ‰, and 1.1 ‰, respectively. This difference is peculiar, and may indicate errors in the measurements. It might also be a result of several fractionation processes happening at the same time, and that the nitrate in F1 originate from both human wastes and from the ammonification of organic matter.

Surface waters have a mean concentration of 97 mg-NO_3/L, while the retention pools contain in average 57 mg-NO_3/L. The sink in the nitrate concentrations in the surface waters compared to the groundwater is probably a result of several processes; the most important being the uptake of nitrate by aquatic plants and algae. This is first indicated by the trophic state of the surface waters, all being eutrophic. Further, extensive uptake by plants and algae is supported by the inverse relationship of both the nitrate concentration vs. the amount of dissolved organic matter, and nitrate concentration vs. bicarbonate. Finally, the high values of $\delta^{15}N$ of the algae in the retention pools, correspond to the assimilation of nitrate the originates from human wastes.

The nitrate in the surface waters is more enriched in both ^{15}N and ^{18}O than the groundwater and than any typical source of pollution. It is evident that a certain fractionation occurs as the NO_3^--rich groundwater mixes with the surface waters. The isotopic composition of the nitrate in the surface waters, $\delta^{15}N_{NO3}$ up to +30.8 ‰ and $\delta^{18}O_{NO3}$ up to +34.2 ‰, and the slope of the $\delta^{18}O/\delta^{15}N$-relationship give strong indications of denitrification. On the other hand, the criterias for denitrification regarding redox conditions, amount of dissolved oxygen and pH are not always fulfilled in the surface waters. Due to somewhat unclear and opposing results obtained in this part of the study, it can neither be concluded nor excluded that denitrification is taking place in the surface waters.

Other possible explanations for the isotopic enrichment of the nitrate and/or the low NO_3-concentrations in the surface waters include the process of remineralisation of organic N and, at sites where the pH approaches 9, ammonia volatilisation.

Dilution with surface runoff is not an important factor in the lowering of nitrate concentrations in the surface waters.

Measurements of the isotopic composition of water have given new insight to the hydrological connectivity between the ground- and surface waters. Regression lines on a δ^2H vs. $\delta^{18}O$-plot for the different types of water (Diambar pumps, dug wells, retention pools, Niayes and flooded zones) coincide and make up the same evaporation line, with a slope between 5.38-5.76. The isotopic composition for the different recharge sources (precipitation and water from Lake Guiers and the Sebikotane aquifer) plot on the same evaporation line as the samples analysed in this study. The positive correlation in isotopic composition between the different types of samples and with the isotopic composition of the different sources of recharged water, indicate that the hydrological connectivity at the ground-/surface water interface is good and that the groundwater mix with the surface waters.

The hypothesis that the flow direction during the dry season is from the groundwater towards the surface waters is strengthened.

Quantifications of evaporation for the different sites show that the surface waters, with 37 % evaporation on average, are more evaporated that the groundwater, which was expected for the dry season. However, the extent of evaporation from the groundwater is surprisingly high, ranging from 10-32%, with a tendency of increased evaporation at shallower depths. The total amount of evapotranspiration is probably even higher than estimated here, due to dilution by continuously infiltration of domestic water, and due to transpiration by plants in the surface waters.

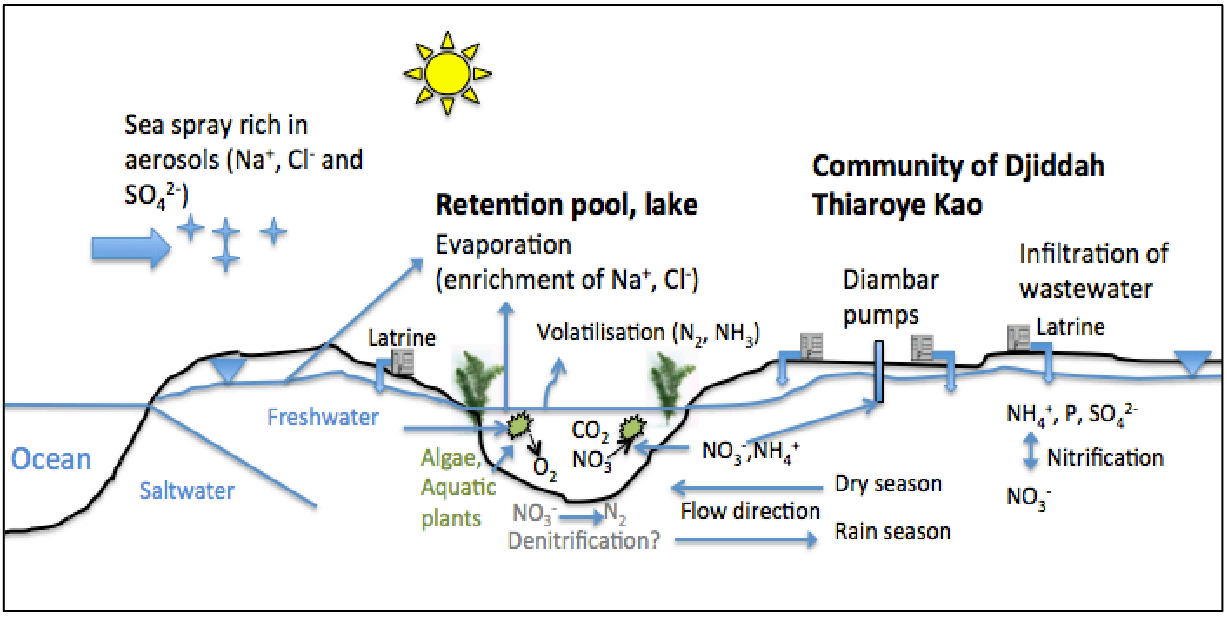

Figure 13.15: Schematic figure of the processes happening at the ground-/surface water interface in the suburban parts of the Dakar Region (author)

Future Research

The current study has focused on surface waters and the uppermost part of the groundwater of the Thiaroye aquifer. The retention pools are fairly shallow, probably around 3 to 4 m deep, and the water column is considered well mixed. However, it could be interesting to verify if there is any stratification in the retention pools and if the content of nitrate is higher at depth where there is less algal activity. The old drilled wells in Thiaroye, of which one is currently in use, and in Beer-Thialane, extract water from 25 to 40 m depth. Gueye-Girardet (2010) reported that the nitrate concentration in the water extracted from the Thiaroye wells increased from 175 mg/L in 1988 to 530 mg/L in 2003. No recent sampling from these wells during the last decade is available, but the constant increase of in habitants in the region might result in even higher concentrations today. Contrary to this study, which has mapped the water quality on a horizontal plan, a study of the vertical distribution of nitrate would increase the understanding of how the pollution spreads throughout the aquifer. Samples from different depths throughout the aquifer would be necessary. If the groundwater is to be used for agriculture in the future, it is the deep Thiaroye and Beer-Thialane wells that will be exploited. It is therefore necessary to know the water quality of the groundwater at depth, to decide on treatment measures.

Nitrate that originates from human and animal wastes can often be an indicator of pollution of microorganisms when bacteriological studies are lacking. A bacteriological study of the same sites will be a good complement to the current study. It would be useful to know the correlation between nitrate and microorganisms, so that in the future, if sanitary systems are developed, the water quality can be monitored more easily. It would also be valuable to detect any potential hazard of today’s use of the groundwater from the Diambar pumps (cf. epidemiological study of Ndiaye (2009, chapter 5)).

Before estimating a nitrogen balance, the type and amount of plants, algae and fungi that are found in the surface waters must be identified. This would help the quantification of nitrogen uptake and indicate the possibility of and rate of denitrification.

Investigations of the sediments at the base of the retention pools would give insight to whether precipitation of calcite occurs or not.

The processes resulting in the sink of nitrate concentrations in the surface waters are still not fully understood. Further isotope studies, on larger set of samples, also from the rainy season, are recommended. It would be useful to analyse both the algae and the nitrate, but also other nitrogen compounds, like nitrite or ammonium, if present.

More data on $^{2}H/^{1}H$ and $^{18}O/^{16}O$ of precipitation during the rainy season, of the drinking water and of the water from the deep Thiaroye wells would be helpful to improve the understanding of the local hydrological cycle.

As regards the problems flooding, a study of the infiltration capacity of the soil would be helpful in the mitigation of surface runoff and reduction of flooding during the rainy season.

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http://www.webelements.com

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http://web.sahra.arizona.edu/programs/isotopes/oxygen.html

Appendix

Appendix I – Geological profiles of the Cap-Vert Peninsula

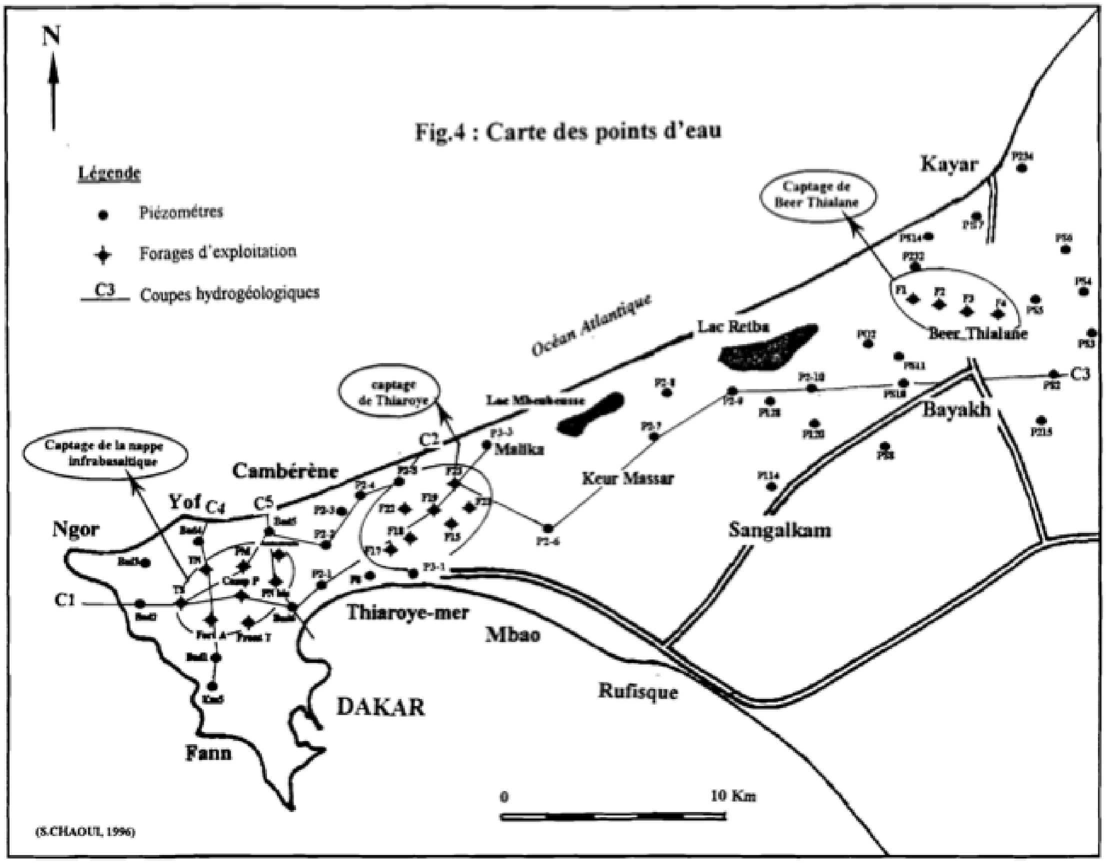


Figure I.1: Overview of the profiles (Chaoui, 1996)

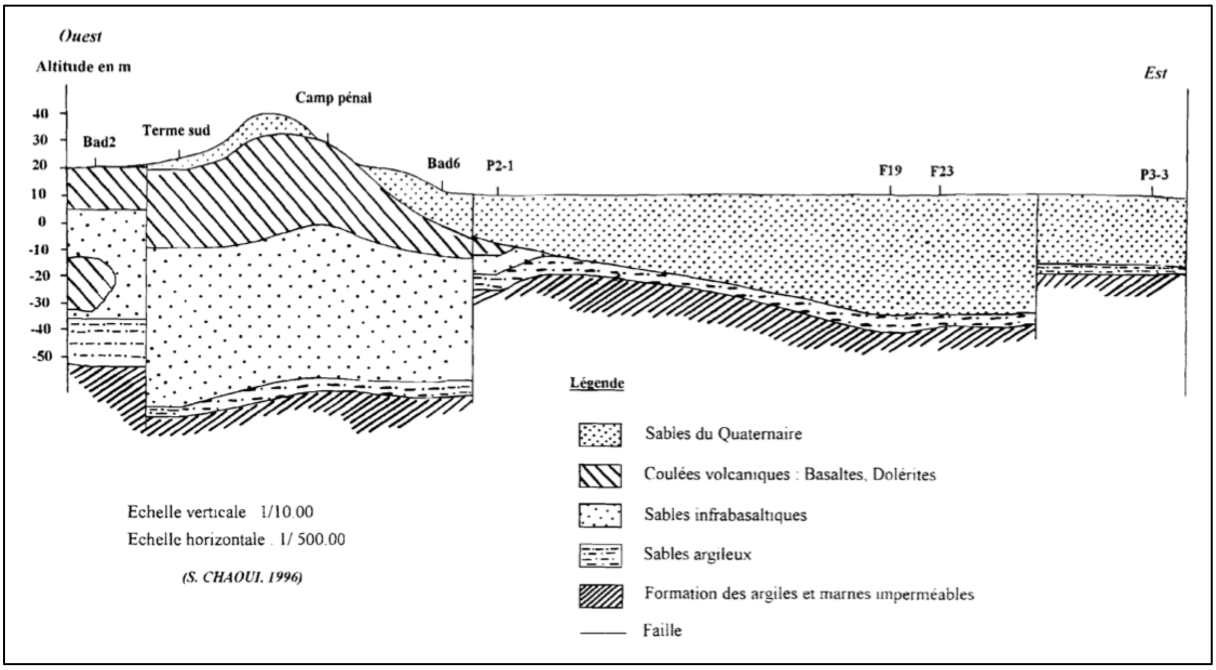


Figure I.2: Profile C1 (Chaoui, 1996)

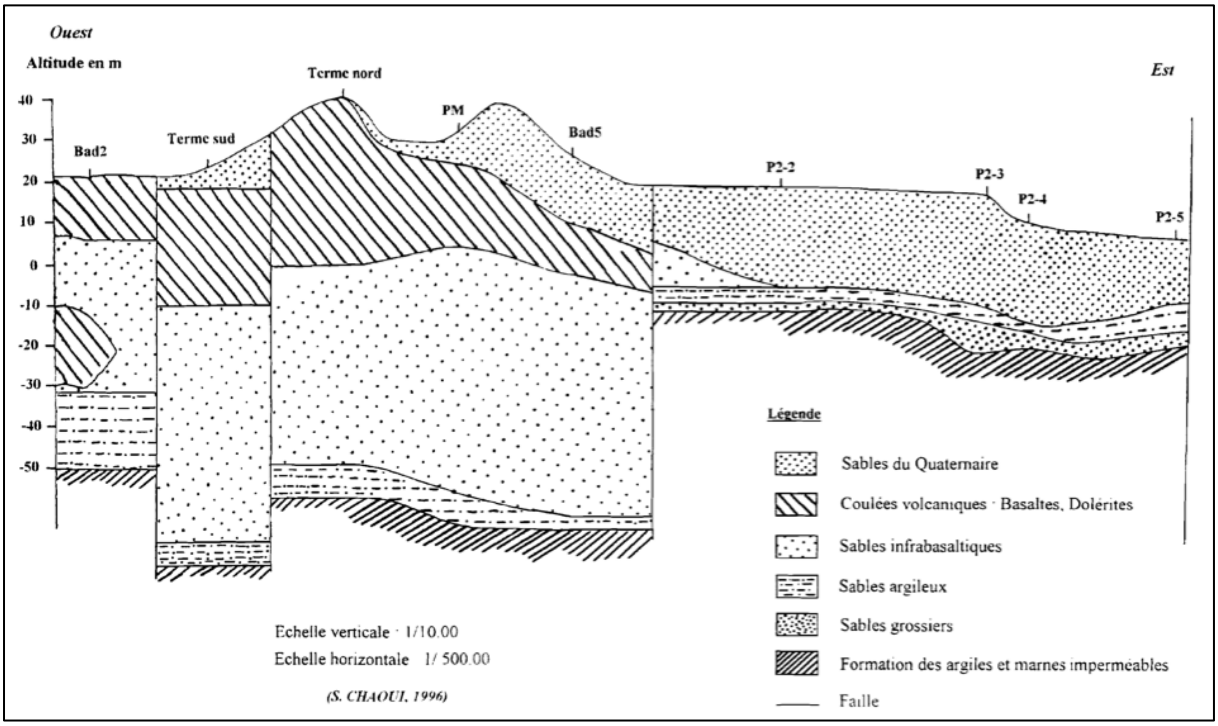


Figure I.3: Profile C2 (Chaoui, 1996)

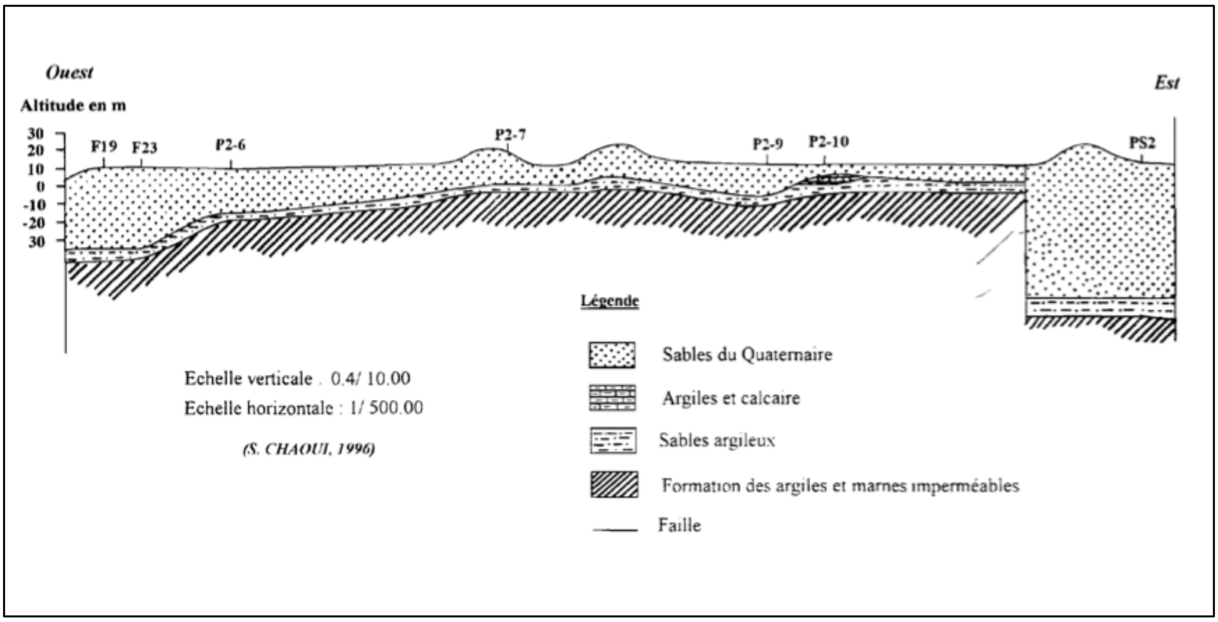


Figure I.4: Profile C3 (Chaoui, 1996)

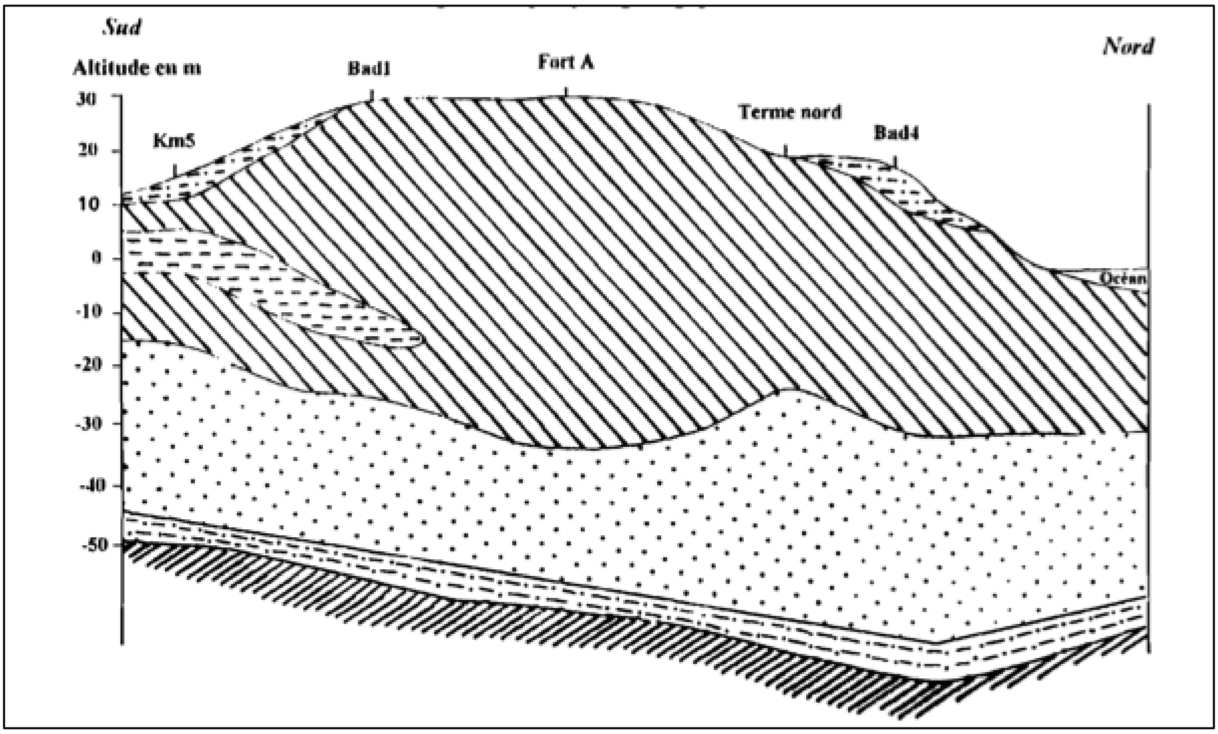


Figure I.5: Profile C4 (Chaoui, 1996)

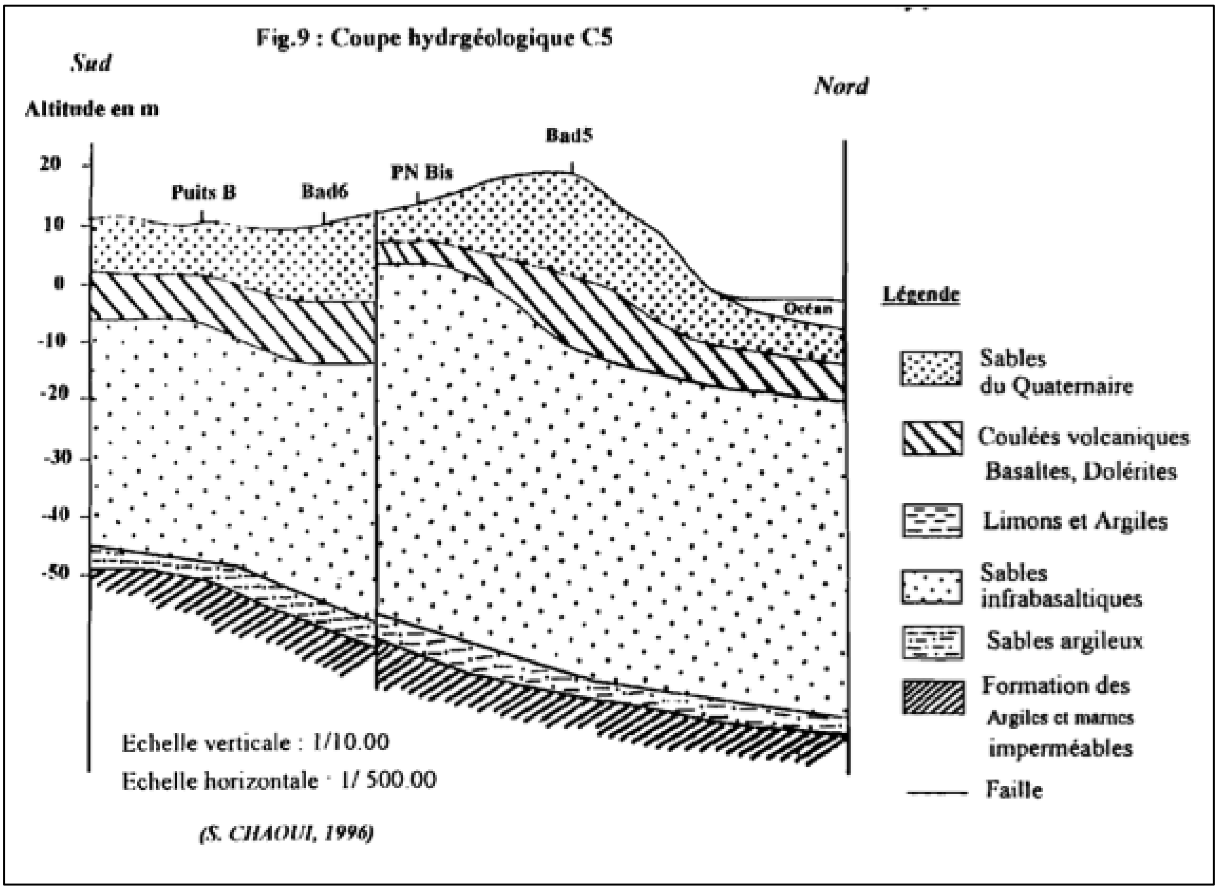
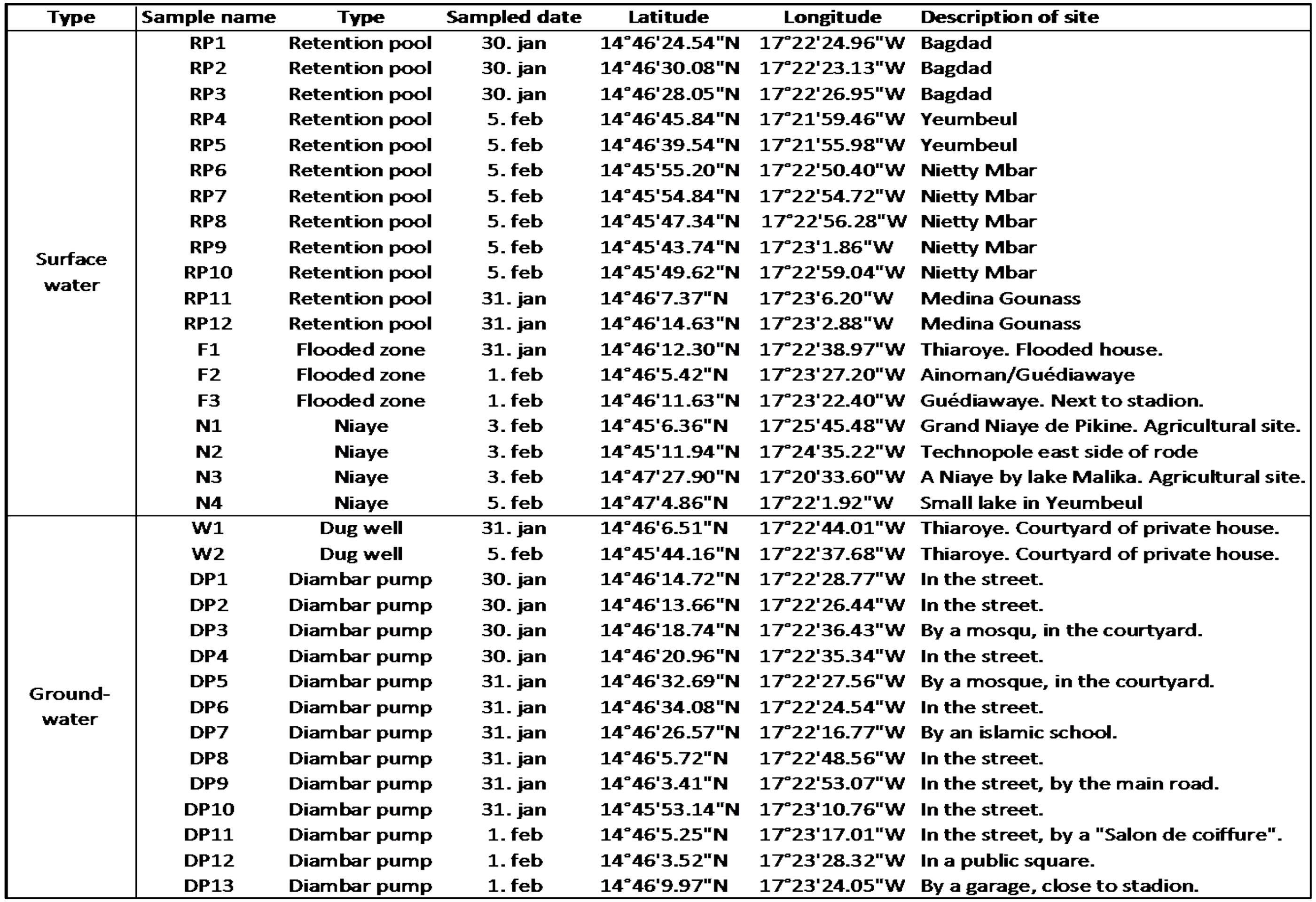


Figure I.6: Profile C5 (Chaoui, 1996)

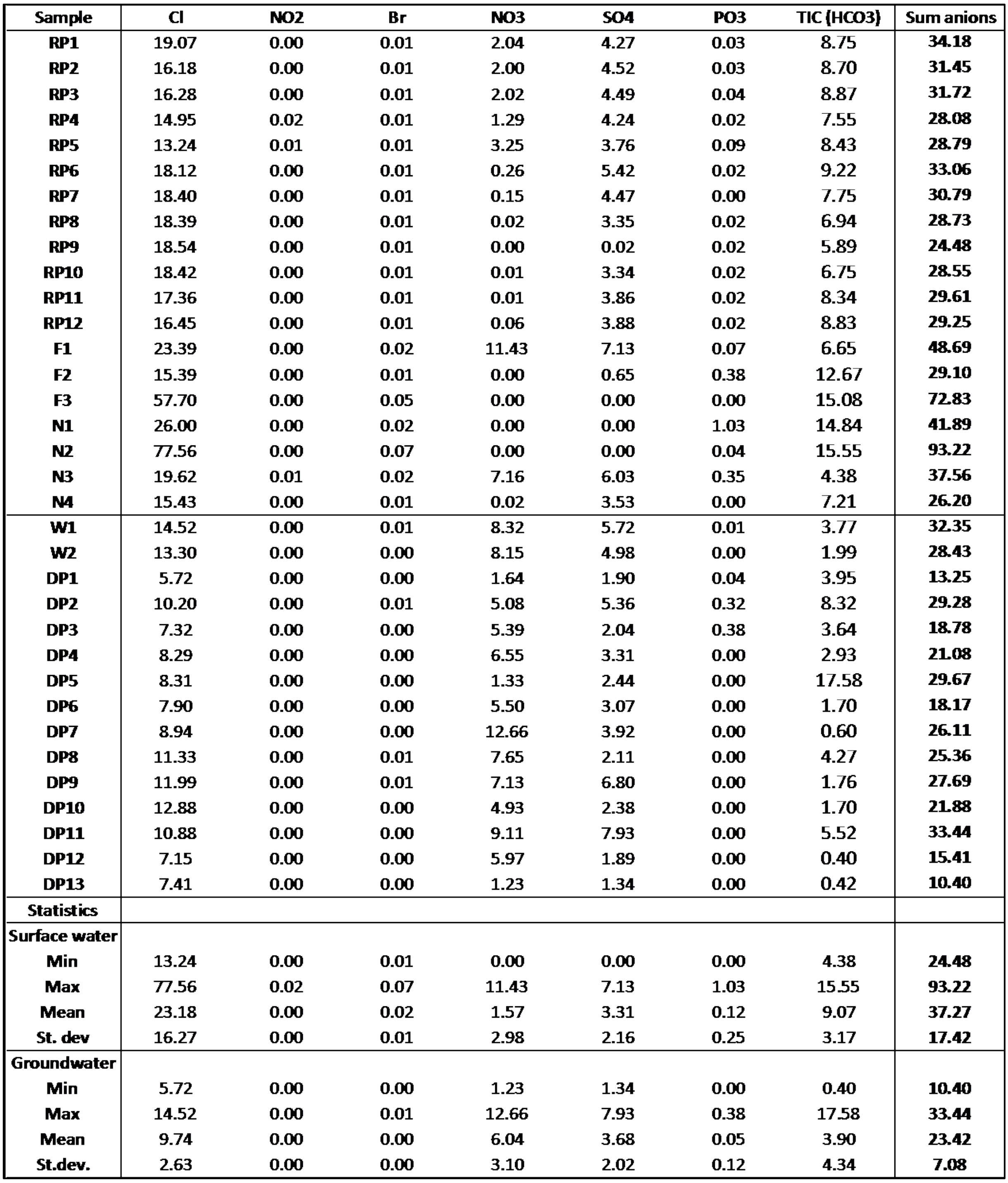
Appendix II – List of the samples with GPS coordinates and descriptions



Type	Sample name	Type	Sampled date	Latitude	Longitude	Description of site
Surface water	RP1	Retention pool	30. jan	14°46'24.54"N	17°22'24.96"W	Bagdad
	RP2	Retention pool	30. jan	14°46'30.08"N	17°22'23.13"W	Bagdad
	RP3	Retention pool	30. jan	14°46'28.05"N	17°22'26.95"W	Bagdad
	RP4	Retention pool	5. feb	14°46'45.84"N	17°21'59.46"W	Yeumbeul
	RP5	Retention pool	5. feb	14°46'39.54"N	17°21'55.98"W	Yeumbeul
	RP6	Retention pool	5. feb	14°45'55.20"N	17°22'50.40"W	Nietty Mbar
	RP7	Retention pool	5. feb	14°45'54.84"N	17°22'54.72"W	Nietty Mbar
	RP8	Retention pool	5. feb	14°45'47.34"N	17°22'56.28"W	Nietty Mbar
	RP9	Retention pool	5. feb	14°45'43.74"N	17°23'1.86"W	Nietty Mbar
	RP10	Retention pool	5. feb	14°45'49.62"N	17°22'59.04"W	Nietty Mbar
	RP11	Retention pool	31. jan	14°46'7.37"N	17°23'6.20"W	Medina Gounass
	RP12	Retention pool	31. jan	14°46'14.63"N	17°23'2.88"W	Medina Gounass
	F1	Flooded zone	31. jan	14°46'12.30"N	17°22'38.97"W	Thiaroye. Flooded house.
	F2	Flooded zone	1. feb	14°46'5.42"N	17°23'27.20"W	Ainoman/Guédiawaye
	F3	Flooded zone	1. feb	14°46'11.63"N	17°23'22.40"W	Guédiawaye. Next to stadion.
	N1	Niaye	3. feb	14°45'6.36"N	17°25'45.48"W	Grand Niaye de Pikine. Agricultural site.
	N2	Niaye	3. feb	14°45'11.94"N	17°24'35.22"W	Technopole east side of rode
	N3	Niaye	3. feb	14°47'27.90"N	17°20'33.60"W	A Niaye by lake Malika. Agricultural site.
	N4	Niaye	5. feb	14°47'4.86"N	17°22'1.92"W	Small lake in Yeumbeul
Ground-water	W1	Dug well	31. jan	14°46'6.51"N	17°22'44.01"W	Thiaroye. Courtyard of private house.
	W2	Dug well	5. feb	14°45'44.16"N	17°22'37.68"W	Thiaroye. Courtyard of private house.
	DP1	Diambar pump	30. jan	14°46'14.72"N	17°22'28.77"W	In the street.
	DP2	Diambar pump	30. jan	14°46'13.66"N	17°22'26.44"W	In the street.
	DP3	Diambar pump	30. jan	14°46'18.74"N	17°22'36.43"W	By a mosqu, in the courtyard.
	DP4	Diambar pump	30. jan	14°46'20.96"N	17°22'35.34"W	In the street.
	DP5	Diambar pump	31. jan	14°46'32.69"N	17°22'27.56"W	By a mosque, in the courtyard.
	DP6	Diambar pump	31. jan	14°46'34.08"N	17°22'24.54"W	In the street.
	DP7	Diambar pump	31. jan	14°46'26.57"N	17°22'16.77"W	By an islamic school.
	DP8	Diambar pump	31. jan	14°46'5.72"N	17°22'48.56"W	In the street.
	DP9	Diambar pump	31. jan	14°46'3.41"N	17°22'53.07"W	In the street, by the main road.
	DP10	Diambar pump	31. jan	14°45'53.14"N	17°23'10.76"W	In the street.
	DP11	Diambar pump	1. feb	14°46'5.25"N	17°23'17.01"W	In the street, by a "Salon de coiffure".
	DP12	Diambar pump	1. feb	14°46'3.52"N	17°23'28.32"W	In a public square.
	DP13	Diambar pump	1. feb	14°46'9.97"N	17°23'24.05"W	By a garage, close to stadion.

Appendix III – Ion balance with the results from the IC analyses

Table III.1a: Anions of the ion balance. All values in meq/L.



Sample	Cl	NO2	Br	NO3	SO4	PO3	TIC (HCO3)	Sum anions
RP1	19.07	0.00	0.01	2.04	4.27	0.03	8.75	**34.18**
RP2	16.18	0.00	0.01	2.00	4.52	0.03	8.70	**31.45**
RP3	16.28	0.00	0.01	2.02	4.49	0.04	8.87	**31.72**
RP4	14.95	0.02	0.01	1.29	4.24	0.02	7.55	**28.08**
RP5	13.24	0.01	0.01	3.25	3.76	0.09	8.43	**28.79**
RP6	18.12	0.00	0.01	0.26	5.42	0.02	9.22	**33.06**
RP7	18.40	0.00	0.01	0.15	4.47	0.00	7.75	**30.79**
RP8	18.39	0.00	0.01	0.02	3.35	0.02	6.94	**28.73**
RP9	18.54	0.00	0.01	0.00	0.02	0.02	5.89	**24.48**
RP10	18.42	0.00	0.01	0.01	3.34	0.02	6.75	**28.55**
RP11	17.36	0.00	0.01	0.01	3.86	0.02	8.34	**29.61**
RP12	16.45	0.00	0.01	0.06	3.88	0.02	8.83	**29.25**
F1	23.39	0.00	0.02	11.43	7.13	0.07	6.65	**48.69**
F2	15.39	0.00	0.01	0.00	0.65	0.38	12.67	**29.10**
F3	57.70	0.00	0.05	0.00	0.00	0.00	15.08	**72.83**
N1	26.00	0.00	0.02	0.00	0.00	1.03	14.84	**41.89**
N2	77.56	0.00	0.07	0.00	0.00	0.04	15.55	**93.22**
N3	19.62	0.01	0.02	7.16	6.03	0.35	4.38	**37.56**
N4	15.43	0.00	0.01	0.02	3.53	0.00	7.21	**26.20**
W1	14.52	0.00	0.01	8.32	5.72	0.01	3.77	**32.35**
W2	13.30	0.00	0.00	8.15	4.98	0.00	1.99	**28.43**
DP1	5.72	0.00	0.00	1.64	1.90	0.04	3.95	**13.25**
DP2	10.20	0.00	0.01	5.08	5.36	0.32	8.32	**29.28**
DP3	7.32	0.00	0.00	5.39	2.04	0.38	3.64	**18.78**
DP4	8.29	0.00	0.00	6.55	3.31	0.00	2.93	**21.08**
DP5	8.31	0.00	0.00	1.33	2.44	0.00	17.58	**29.67**
DP6	7.90	0.00	0.00	5.50	3.07	0.00	1.70	**18.17**
DP7	8.94	0.00	0.00	12.66	3.92	0.00	0.60	**26.11**
DP8	11.33	0.00	0.01	7.65	2.11	0.00	4.27	**25.36**
DP9	11.99	0.00	0.01	7.13	6.80	0.00	1.76	**27.69**
DP10	12.88	0.00	0.00	4.93	2.38	0.00	1.70	**21.88**
DP11	10.88	0.00	0.00	9.11	7.93	0.00	5.52	**33.44**
DP12	7.15	0.00	0.00	5.97	1.89	0.00	0.40	**15.41**
DP13	7.41	0.00	0.00	1.23	1.34	0.00	0.42	**10.40**
Statistics								
Surface water								
Min	13.24	0.00	0.01	0.00	0.00	0.00	4.38	**24.48**
Max	77.56	0.02	0.07	11.43	7.13	1.03	15.55	**93.22**
Mean	23.18	0.00	0.02	1.57	3.31	0.12	9.07	**37.27**
St. dev	16.27	0.00	0.01	2.98	2.16	0.25	3.17	**17.42**
Groundwater								
Min	5.72	0.00	0.00	1.23	1.34	0.00	0.40	**10.40**
Max	14.52	0.00	0.01	12.66	7.93	0.38	17.58	**33.44**
Mean	9.74	0.00	0.00	6.04	3.68	0.05	3.90	**23.42**
St.dev.	2.63	0.00	0.00	3.10	2.02	0.12	4.34	**7.08**

Table III.1b: Ion balance calculated with the results from the IC analyses for both anions and cations. Red numbers in the "Error" column represent the samples with an error > |5|. All values are in meq/L.

Sample	Na	NH4	K	Mg	Ca	Sum cations	Error %
RP1	16.15	0.00	1.64	4.32	8.62	**30.73**	**-5.30**
RP2	16.48	0.00	1.75	4.44	8.81	**31.47**	**0.05**
RP3	16.64	0.00	1.72	4.44	8.79	**31.60**	**-0.18**
RP4	15.24	0.05	1.48	5.06	6.39	**28.22**	**0.24**
RP5	13.44	0.05	1.11	4.71	9.62	**28.93**	**0.25**
RP6	18.55	0.01	1.71	4.49	8.24	**32.99**	**-0.11**
RP7	19.34	0.07	1.92	4.50	5.71	**31.55**	**1.22**
RP8	19.12	0.09	2.06	4.27	3.86	**29.41**	**1.16**
RP9	19.47	0.10	2.09	4.36	3.56	**29.57**	**9.43**
RP10	18.69	0.11	2.01	4.19	3.64	**28.64**	**0.14**
RP11	17.81	0.10	1.84	4.21	6.93	**30.88**	**2.11**
RP12	17.12	0.10	1.72	4.17	8.02	**31.13**	**3.10**
F1	23.43	0.15	2.72	6.25	12.36	**44.91**	**-4.04**
F2	15.76	0.57	1.43	3.80	6.14	**27.70**	**-2.48**
F3	58.48	0.38	1.97	9.16	1.96	**71.95**	**-0.61**
N1	23.68	0.01	1.87	6.76	6.35	**38.67**	**-4.01**
N2	66.30	0.00	3.98	16.18	4.66	**91.12**	**-1.14**
N3	17.94	0.00	1.33	4.55	9.67	**33.50**	**-5.72**
N4	14.43	0.02	1.18	4.12	3.64	**23.38**	**-5.70**
W1	14.94	1.19	1.39	3.84	8.51	**29.88**	**-3.97**
W2	12.99	0.14	1.47	2.85	9.53	**26.98**	**-2.62**
DP1	5.63	0.08	0.53	1.21	4.30	**11.75**	**-5.98**
DP2	12.32	0.91	1.64	2.33	7.32	**24.51**	**-8.87**
DP3	7.47	0.05	1.09	1.48	5.74	**15.82**	**-8.57**
DP4	9.51	0.00	2.07	1.60	6.08	**19.26**	**-4.50**
DP5	8.44	4.89	1.87	1.95	5.08	**22.22**	**-14.35**
DP6	7.83	0.03	0.90	1.41	5.47	**15.64**	**-7.47**
DP7	11.17	0.95	1.93	1.69	7.52	**23.27**	**-5.76**
DP8	11.29	0.24	1.40	1.66	7.72	**22.31**	**-6.40**
DP9	15.39	0.27	2.29	2.52	6.33	**26.79**	**-1.65**
DP10	10.66	0.54	1.04	1.74	4.39	**18.38**	**-8.69**
DP11	19.86	0.95	1.90	2.74	9.35	**34.79**	**1.99**
DP12	7.02	0.09	0.74	1.59	4.16	**13.59**	**-6.28**
DP13	5.68	0.01	0.27	1.52	1.59	**9.07**	**-6.86**
Statistics							
Surface water							
Min	13.44	0.00	1.11	3.80	1.96	**23.38**	**-5.72**
Max	66.30	0.57	3.98	16.18	12.36	**91.12**	**9.43**
Mean	22.53	0.09	1.87	5.47	6.68	**36.65**	**-0.61**
St. dev	14.34	0.15	0.63	2.88	2.70	**16.73**	**3.59**
Groundwater							
Min	5.63	0.00	0.27	1.21	1.59	**9.07**	**-14.35**
Max	19.86	4.89	2.29	3.84	9.53	**34.79**	**1.99**
Mean	10.68	0.69	1.37	2.01	6.21	**20.95**	**-6.00**
St.dev.	3.98	1.23	0.60	0.71	2.17	**7.11**	**3.74**

Appendix IV – Cation results and ion balance from the ICP-MS analyses

Table IV.1a: Results from the ICP-MS analyses at NTNU. DP7 was not analysed. All values are in mg/L.

Sample	Li	B	Na	Mg	Al	Si	K	Ca	Ti	V	Cr	Mn	Fe
RP1	0.012	0.238	452.000	39.900	0.005	0.302	93.300	162.000	0.251	0.025	0.004	0.023	0.693
RP2	0.013	0.258	465.000	43.900	0.039	0.293	98.900	177.000	0.247	0.025	0.003	0.026	0.791
RP3	0.010	0.207	483.000	35.200	0.004	0.224	102.000	141.000	0.246	0.026	0.003	0.023	0.620
RP4	0.008	0.187	437.000	47.900	0.006	1.920	88.300	123.000	0.200	0.028	0.002	0.024	0.525
RP5	0.009	0.153	355.000	42.200	0.002	9.010	61.700	175.000	0.273	0.022	0.002	0.099	0.710
RP6	0.017	0.309	523.000	38.600	0.032	0.707	95.800	143.000	0.249	0.009	0.003	0.031	0.663
RP7	0.015	0.369	536.000	40.000	0.010	0.400	106.000	104.000	0.177	0.010	0.002	0.015	0.489
RP8	0.012	0.404	527.000	41.200	0.029	0.606	112.000	76.300	0.120	0.012	0.002	0.010	0.387
RP9	0.012	0.373	545.000	36.600	0.014	0.427	116.000	62.000	0.109	0.012	0.002	0.005	0.319
RP10	0.013	0.400	547.000	39.800	0.058	0.515	116.000	72.200	0.118	0.012	0.001	0.032	0.416
RP11	0.012	0.366	514.000	41.300	0.008	0.067	105.000	139.000	0.200	0.010	0.002	0.011	0.677
RP12	0.009	0.324	503.000	36.600	0.009	0.075	101.000	143.000	0.227	0.012	0.001	0.013	0.655
F1	0.032	0.251	656.000	59.800	0.009	13.100	150.000	242.000	0.297	0.056	0.002	0.005	0.980
F2	0.013	0.317	436.000	35.900	0.026	16.200	77.100	123.000	0.156	0.007	0.004	1.050	0.775
F3	0.031	0.871	1660.000	92.100	0.023	2.840	115.000	47.500	0.049	0.017	0.009	0.012	0.318
N1	0.008	0.260	631.000	67.400	0.007	16.900	94.200	142.000	0.210	0.005	0.003	0.120	0.572
N2	0.018	0.613	1880.000	163.000	0.009	3.440	214.000	105.000	0.087	0.016	0.004	0.093	0.452
N3	0.003	0.280	489.000	47.500	0.006	0.921	68.800	219.000	0.311	0.057	0.002	0.015	0.923
N4	0.023	0.219	410.000	42.700	0.014	1.360	64.000	82.100	0.134	0.006	0.001	0.353	0.365
W1	0.004	0.123	410.000	34.700	0.013	4.800	74.700	158.000	0.220	0.012	0.002	0.369	0.670
W2	0.002	0.257	351.000	27.400	0.019	3.970	78.300	186.000	0.232	0.008	0.002	0.165	0.777
DP1	0.001	0.277	129.000	11.000	0.012	5.670	23.400	88.900	0.158	0.007	0.002	0.014	0.313
DP2	0.001	0.423	295.000	19.300	0.002	9.160	73.900	133.000	0.281	0.021	0.001	0.105	0.414
DP3	0.002	0.247	169.000	13.100	0.010	10.000	47.200	110.000	0.205	0.017	0.001	0.070	0.347
DP4	0.001	0.468	233.000	16.200	0.019	3.690	97.400	128.000	0.228	0.003	0.001	0.069	0.466
DP5	0.001	0.189	224.000	20.300	0.003	7.260	85.800	111.000	0.183	0.007	0.001	0.141	0.367
DP6	0.002	0.276	193.000	13.500	0.051	3.540	42.700	113.000	0.199	0.041	0.000	0.015	0.471
DP8	0.001	0.412	289.000	16.900	0.010	9.100	68.400	166.000	0.288	0.004	0.001	0.058	0.595
DP9	0.004	0.390	400.000	25.500	0.031	3.720	114.000	139.000	0.256	0.002	0.000	1.450	2.100
DP10	0.003	0.310	282.000	16.800	0.069	3.780	52.800	91.400	0.164	0.005	0.000	0.229	0.420
DP11	0.001	0.563	515.000	27.300	0.003	6.920	93.100	201.000	0.337	0.034	0.001	0.063	0.784
DP12	0.007	0.141	174.000	15.900	0.458	5.240	35.500	90.200	0.141	0.004	0.000	0.582	0.894
DP13	0.015	0.048	142.000	14.400	0.066	6.690	13.100	33.700	0.027	0.002	0.000	2.780	0.996

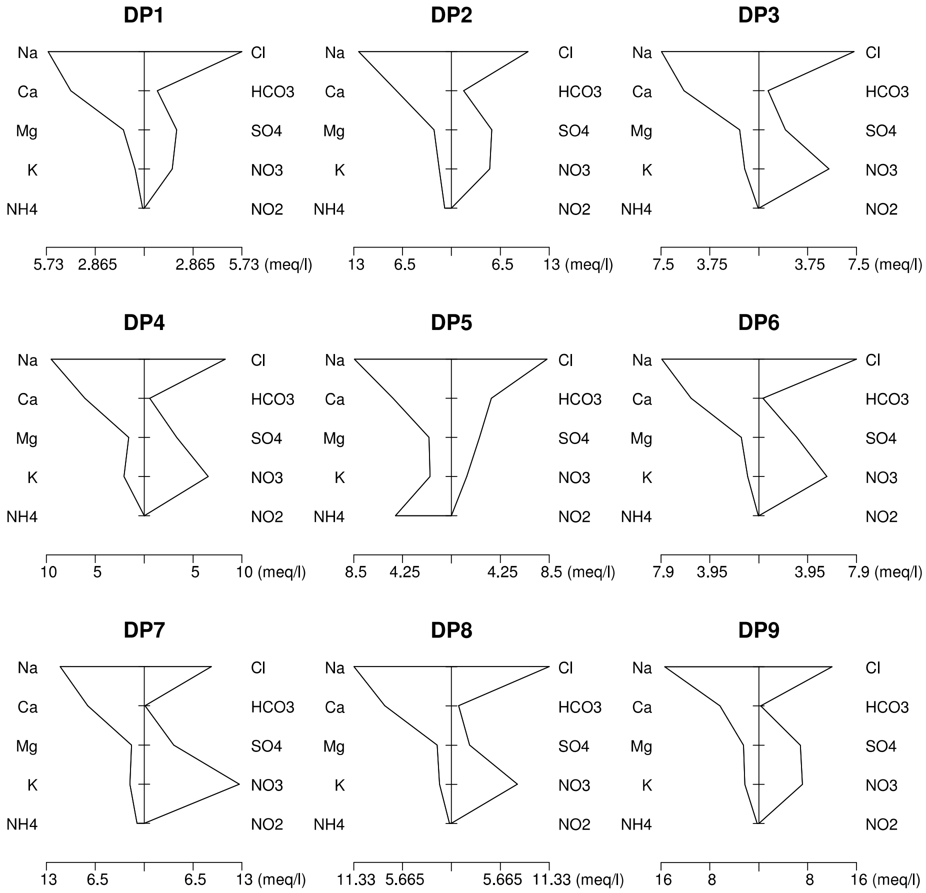
Table IV.1b: Results from the ICP-MS analyses at NTNU. DP7 was not analysed. All values are in mg/L.

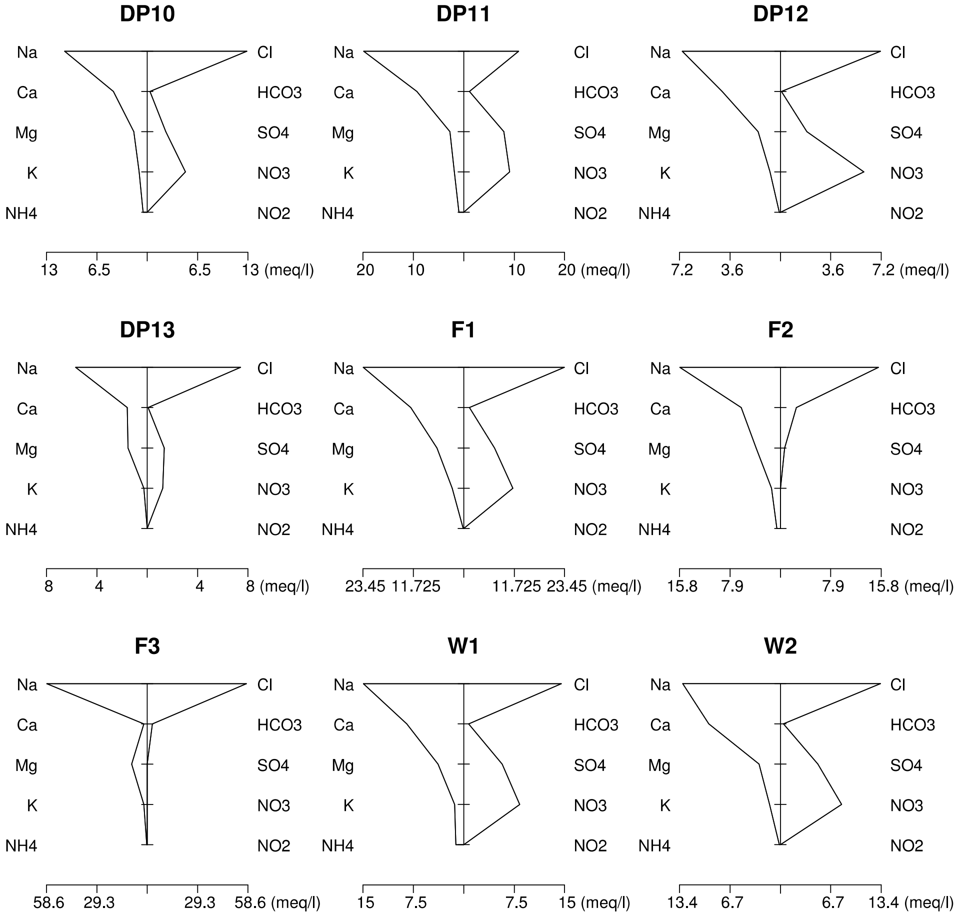
Sample	Ni	Co	Cu	Zn	Ga	As	Rb	Sr	Mo	Cs	Ba	U
RP1	0.007	0.003	0.011	0.079	0.001	0.005	0.137	1.360	0.003	0.001	0.078	0.002
RP2	0.008	0.003	0.012	0.031	0.001	0.005	0.138	1.500	0.003	0.001	0.075	0.002
RP3	0.006	0.002	0.010	0.022	0.001	0.004	0.143	1.190	0.003	0.001	0.090	0.002
RP4	0.003	0.001	0.007	0.015	0.001	0.004	0.122	1.230	0.006	0.001	0.062	0.003
RP5	0.003	0.001	0.007	0.016	0.001	0.003	0.111	1.320	0.003	0.001	0.078	0.002
RP6	0.005	0.001	0.005	0.015	0.001	0.006	0.138	1.470	0.004	0.000	0.074	0.002
RP7	0.004	0.001	0.006	0.051	0.001	0.006	0.144	1.270	0.003	0.000	0.086	0.002
RP8	0.003	0.001	0.006	0.024	0.001	0.008	0.148	1.050	0.002	0.000	0.040	0.001
RP9	0.002	0.001	0.005	0.012	0.001	0.007	0.150	0.890	0.002	0.000	0.048	0.001
RP10	0.002	0.001	0.006	0.021	0.001	0.007	0.148	0.998	0.002	0.000	0.080	0.001
RP11	0.003	0.001	0.005	0.018	0.001	0.007	0.139	1.410	0.004	0.000	0.066	0.001
RP12	0.004	0.001	0.005	0.023	0.001	0.005	0.131	1.290	0.003	0.000	0.079	0.002
F1	0.005	0.001	0.010	0.033	0.001	0.007	0.166	2.610	0.006	0.001	0.072	0.004
F2	0.005	0.003	0.005	0.063	0.004	0.002	0.101	0.886	0.000	0.000	0.238	0.000
F3	0.005	0.001	0.012	0.028	0.001	0.011	0.096	0.742	0.001	0.000	0.079	0.002
N1	0.003	0.001	0.006	0.012	0.002	0.005	0.109	0.994	0.002	0.000	0.130	0.000
N2	0.003	0.001	0.011	0.020	0.002	0.011	0.221	1.190	0.002	0.000	0.100	0.004
N3	0.018	0.004	0.016	0.039	0.002	0.005	0.059	1.360	0.011	0.000	0.142	0.007
N4	0.004	0.002	0.005	0.020	0.002	0.004	0.100	0.854	0.001	0.000	0.126	0.001
W1	0.015	0.014	0.014	0.057	0.001	0.002	0.099	1.010	0.002	0.002	0.056	0.005
W2	0.007	0.004	0.008	0.036	0.001	0.002	0.061	1.210	0.003	0.001	0.048	0.001
DP1	0.001	0.001	0.007	0.050	0.001	0.001	0.026	0.388	0.002	0.000	0.074	0.001
DP2	0.004	0.001	0.007	0.023	0.001	0.004	0.117	0.848	0.008	0.001	0.046	0.001
DP3	0.004	0.002	0.007	0.018	0.001	0.004	0.058	0.495	0.003	0.000	0.056	0.000
DP4	0.003	0.001	0.010	0.040	0.001	0.001	0.087	0.628	0.004	0.001	0.057	0.000
DP5	0.010	0.004	0.078	0.062	0.001	0.016	0.119	0.352	0.008	0.002	0.033	0.004
DP6	0.003	0.001	0.007	0.022	0.001	0.004	0.039	0.689	0.004	0.000	0.054	0.000
DP8	0.004	0.001	0.014	0.045	0.001	0.002	0.091	0.816	0.004	0.001	0.063	0.001
DP9	0.017	0.054	0.012	0.070	0.001	0.002	0.114	0.787	0.002	0.001	0.055	0.001
DP10	0.005	0.003	0.007	0.035	0.001	0.001	0.063	0.584	0.001	0.002	0.079	0.000
DP11	0.010	0.002	0.022	0.040	0.001	0.004	0.097	1.010	0.011	0.001	0.050	0.002
DP12	0.008	0.013	0.009	0.123	0.002	0.001	0.037	0.541	0.000	0.001	0.105	0.000
DP13	0.024	0.052	0.006	0.061	0.004	0.001	0.020	0.277	0.000	0.000	0.208	0.000

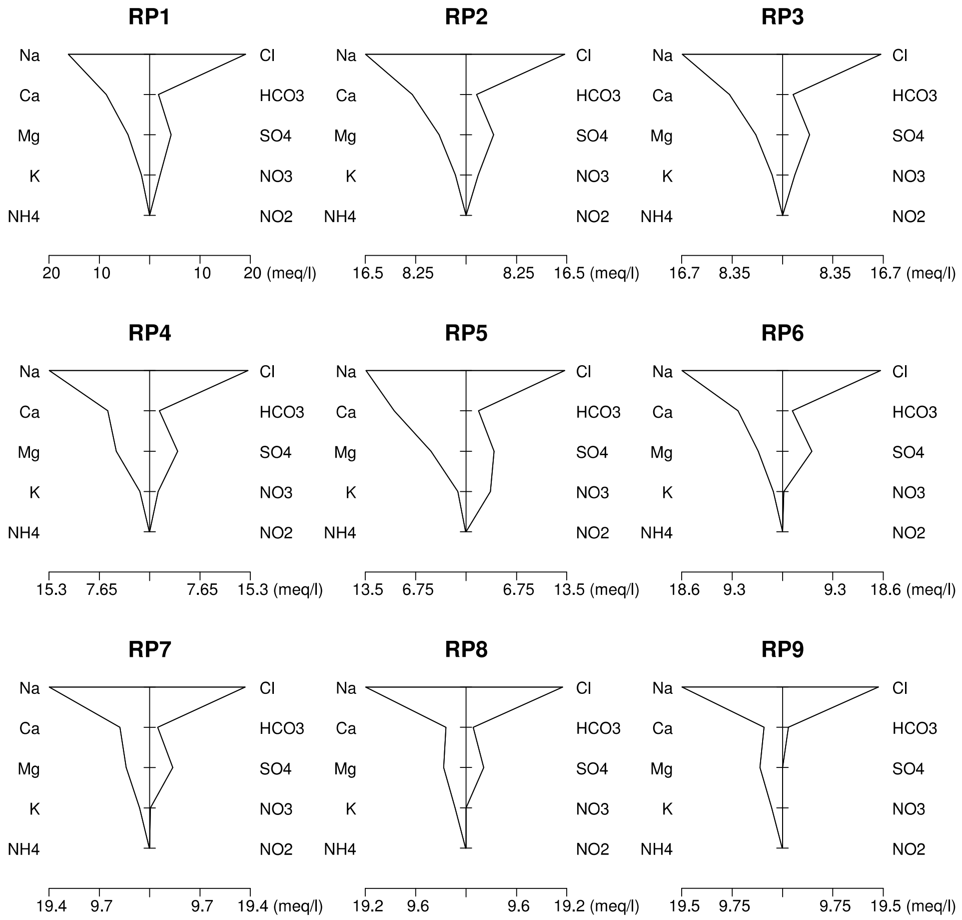
Table IV.2: Ion balance with the ICP-MS results for the cations and IC-results for the anions, DP7 and ammonium. Red numbers in the “Error” column represent the samples with an error > |5|. All values are in meq/L.

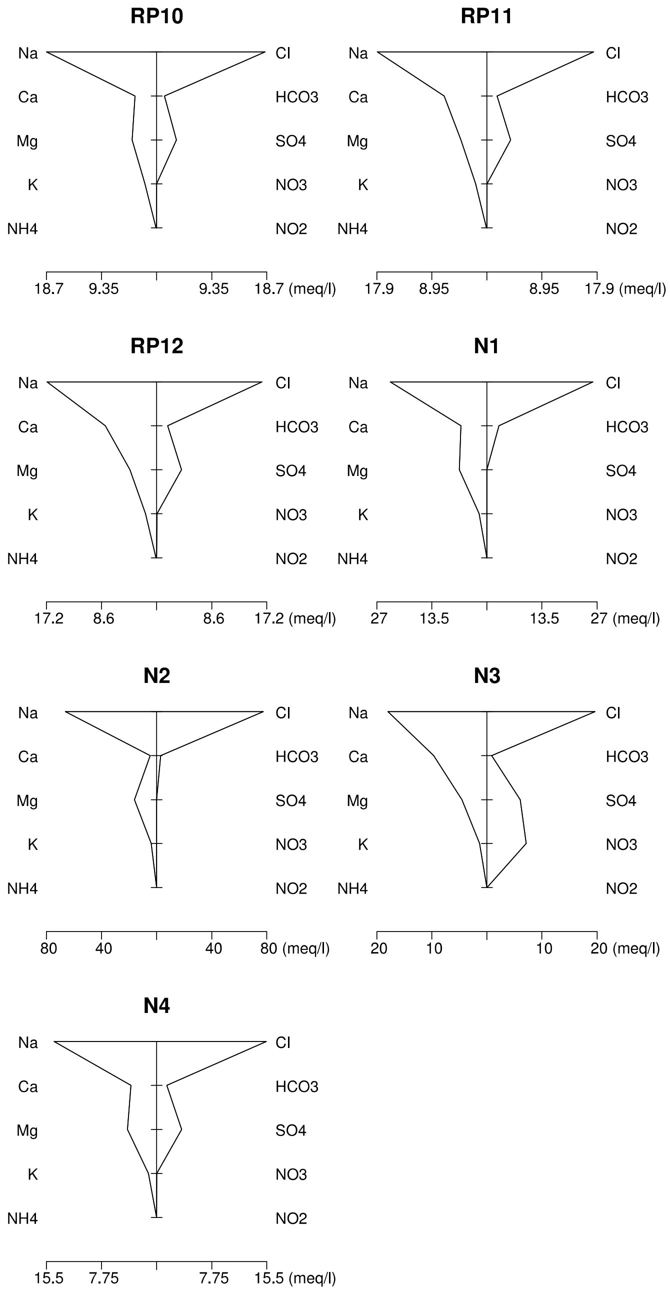
Sample	Na	NH4 (from IC)	K	Mg	Ca	Sum cations	Error %
RP1	19.65	0.00	2.39	3.28	8.08	**33.41**	**-1.14**
RP2	20.22	0.00	2.53	3.61	8.83	**35.19**	**5.62**
RP3	21.00	0.00	2.61	2.90	7.04	**33.54**	**2.79**
RP4	19.00	0.05	2.26	3.94	6.14	**31.38**	**5.56**
RP5	15.43	0.05	1.58	3.47	8.73	**29.27**	**0.82**
RP6	22.74	0.01	2.45	3.18	7.14	**35.51**	**3.57**
RP7	23.30	0.07	2.71	3.29	5.19	**34.57**	**5.79**
RP8	22.91	0.09	2.86	3.39	3.81	**33.06**	**7.02**
RP9	23.70	0.10	2.97	3.01	3.09	**32.87**	**14.63**
RP10	23.78	0.11	2.97	3.28	3.60	**33.73**	**8.31**
RP11	22.35	0.10	2.69	3.40	6.94	**35.47**	**9.00**
RP12	21.87	0.10	2.58	3.01	7.14	**34.70**	**8.52**
F1	28.52	0.15	3.84	4.92	12.08	**49.51**	**0.84**
F2	18.96	0.57	1.97	2.95	6.14	**30.59**	**2.48**
F3	72.17	0.38	2.94	7.58	2.37	**85.44**	**7.97**
N1	27.43	0.01	2.41	5.55	7.09	**42.49**	**0.70**
N2	81.74	0.00	5.47	13.41	5.24	**105.87**	**6.35**
N3	21.26	0.00	1.76	3.91	10.93	**37.86**	**0.40**
N4	17.83	0.02	1.64	3.51	4.10	**27.09**	**1.66**
W1	17.83	1.19	1.91	2.86	7.88	**31.67**	**-1.06**
W2	15.26	0.14	2.00	2.25	9.28	**28.94**	**0.89**
DP1	5.61	0.08	0.60	0.91	4.44	**11.63**	**-6.51**
DP2	12.83	0.91	1.89	1.59	6.64	**23.85**	**-10.23**
DP3	7.35	0.05	1.21	1.08	5.49	**15.17**	**-10.63**
DP4	10.13	0.00	2.49	1.33	6.39	**20.34**	**-1.77**
DP5	9.74	4.89	2.19	1.67	5.54	**24.03**	**-10.50**
DP6	8.39	0.03	1.09	1.11	5.64	**16.26**	**-5.53**
DP7 (from IC)	11.17	0.95	1.93	1.69	7.52	**23.27**	**-5.76**
DP8	12.57	0.24	1.75	1.39	8.28	**24.23**	**-2.29**
DP9	17.39	0.27	2.92	2.10	6.94	**29.61**	**3.36**
DP10	12.26	0.54	1.35	1.38	4.56	**20.10**	**-4.24**
DP11	22.39	0.95	2.38	2.25	10.03	**38.00**	**6.39**
DP12	7.57	0.09	0.91	1.31	4.50	**14.37**	**-3.51**
DP13	6.17	0.01	0.34	1.18	1.68	**9.38**	**-5.15**
Statistics							
Surface water							
Min	15.43	0.00	1.58	2.90	2.37	27.09	-1.14
Max	81.74	0.57	5.47	13.41	12.08	105.87	14.63
Mean	27.57	0.09	2.66	4.29	6.51	41.13	4.78
St. dev	17.74	0.15	0.87	2.48	2.57	20.10	3.97
Groundwater							
Min	5.61	0.00	0.34	0.91	1.68	9.38	-10.63
Max	22.39	4.89	2.92	2.86	10.03	38.00	6.39
Mean	11.78	0.69	1.66	1.61	6.32	22.06	-3.77
St.dev.	4.78	1.23	0.73	0.54	2.14	7.93	4.93

Appendix V – Stiff diagrams with IC results




DP10
DP11
DP12
DP13
F1
F2
F3
W1
W2
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
13 6.5 6.5 13 (meq/l)
20 10 10 20 (meq/l)
7.2 3.6 3.6 7.2 (meq/l)
8 4 4 8 (meq/l)
23.45 11.725 11.725 23.45 (meq/l)
15.8 7.9 7.9 15.8 (meq/l)
58.6 29.3 29.3 58.6 (meq/l)
15 7.5 7.5 15 (meq/l)
13.4 6.7 6.7 13.4 (meq/l)


RP1
RP2
RP3
RP4
RP5
RP6
RP7
RP8
RP9
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
20 10 10 20 (meq/l)
16.5 8.25 8.25 16.5 (meq/l)
16.7 8.35 8.35 16.7 (meq/l)
15.3 7.65 7.65 15.3 (meq/l)
13.5 6.75 6.75 13.5 (meq/l)
18.6 9.3 9.3 18.6 (meq/l)
19.4 9.7 9.7 19.4 (meq/l)
19.2 9.6 9.6 19.2 (meq/l)
19.5 9.75 9.75 19.5 (meq/l)


RP10
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
18.7
9.35
9.35
18.7 (meq/l)
RP11
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
17.9
8.95
8.95
17.9 (meq/l)
RP12
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
17.2
8.6
8.6
17.2 (meq/l)
N1
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
27
13.5
13.5
27 (meq/l)
N2
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
80
40
40
80 (meq/l)
N3
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
20
10
10
20 (meq/l)
N4
Na
Ca
Mg
K
NH4
Cl
HCO3
SO4
NO3
NO2
15.5
7.75
7.75
15.5 (meq/l)

Appendix VI – Quantification of evaporation

Constants		δ^2H_R	-41.5	‰	$\Delta\varepsilon^{18}O_{l-v}$	3.83	‰
Humidity	0.73	$\delta^{18}O_R$	-6.5	‰	$\Delta\varepsilon^2H_{l-v}$	3.38	‰

Sample	**Temp C**	**Temp K**	**$\ln(\alpha'^2H_{l-v})$**	**α'^2H_{l-v}**	**ε^2H_{l-v}**	**$\alpha^{*2}H_{v-l}$**	**δ^2H_x**	**$\ln[(\delta^2H_x + 1000) / (\delta^2H_R + 1000)]$**	**Fraction (f)**	**Evaporation %**
RP1	22.10	295.1	0.0795	1.0828	86.14	0.9207	-14.5	0.028	0.70	**30**
RP2	22.60	295.6	0.0790	1.0822	85.57	0.9212	-14.7	0.028	0.70	**30**
RP3	23.20	296.2	0.0784	1.0815	84.89	0.9218	-14.4	0.028	0.70	**30**
RP4	25.00	298.0	0.0765	1.0795	82.89	0.9235	-11.3	0.031	0.67	**33**
RP5	25.20	298.2	0.0763	1.0793	82.67	0.9236	-19.8	0.022	0.75	**25**
RP6	26.00	299.0	0.0755	1.0784	81.79	0.9244	-16.7	0.026	0.71	**29**
RP7	25.20	298.2	0.0763	1.0793	82.67	0.9236	-9.5	0.033	0.65	**35**
RP8	24.90	297.9	0.0766	1.0796	83.00	0.9234	-2.4	0.040	0.59	**41**
RP9	26.00	299.0	0.0755	1.0784	81.79	0.9244	-1.8	0.041	0.58	**42**
RP10	24.60	297.6	0.0769	1.0800	83.33	0.9231	-1.8	0.041	0.59	**41**
RP11	25.90	298.9	0.0756	1.0785	81.90	0.9243	-8.0	0.034	0.64	**36**
RP12	24.70	297.7	0.0768	1.0798	83.22	0.9232	-10.4	0.032	0.66	**34**
F1	19.90	292.9	0.0819	1.0853	88.70	0.9185	-2.5	0.040	0.61	**39**
F2	25.00	298.0	0.0765	1.0795	82.89	0.9235	-28.1	0.014	0.83	**17**
F3	28.70	301.7	0.0728	1.0755	78.92	0.9269	24.4	0.066	0.40	**60**
N1	22.40	295.4	0.0792	1.0824	85.80	0.9210	-4.3	0.038	0.62	**38**
N2	22.80	295.8	0.0788	1.0820	85.34	0.9214	10.3	0.053	0.51	**49**
N3	24.90	297.9	0.0766	1.0796	83.00	0.9234	-17.8	0.024	0.73	**27**
N4	25.10	298.1	0.0764	1.0794	82.78	0.9236	-12.9	0.029	0.68	**32**
W1	24.90	297.9	0.0766	1.0796	83.00	0.9234	-28.7	0.013	0.84	**16**
W2	27.20	300.2	0.0743	1.0771	80.50	0.9255	-31.1	0.011	0.87	**13**
DP1	28.20	301.2	0.0733	1.0761	79.44	0.9264	-15.0	0.027	0.69	**31**
DP2	26.90	299.9	0.0746	1.0774	80.82	0.9252	-28.7	0.013	0.84	**16**
DP3	28.00	301.0	0.0735	1.0763	79.65	0.9262	-17.0	0.025	0.71	**29**
DP4	26.90	299.9	0.0746	1.0774	80.82	0.9252	-27.2	0.015	0.82	**18**
DP5	27.00	300.0	0.0745	1.0773	80.72	0.9253	-13.3	0.029	0.68	**32**
DP6	27.10	300.1	0.0744	1.0772	80.61	0.9254	-20.7	0.021	0.75	**25**
DP7	28.90	301.9	0.0726	1.0753	78.71	0.9270	-26.4	0.016	0.81	**19**
DP8	28.80	301.8	0.0727	1.0754	78.81	0.9269	-19.5	0.023	0.73	**27**
DP9	29.60	302.6	0.0720	1.0746	77.98	0.9277	-29.6	0.012	0.84	**16**
DP10	28.60	301.6	0.0729	1.0756	79.02	0.9268	-29.9	0.012	0.85	**15**
DP11	30.70	303.7	0.0709	1.0735	76.86	0.9286	-23.9	0.018	0.77	**23**
DP12	28.70	301.7	0.0728	1.0755	78.92	0.9269	-33.0	0.009	0.89	**11**
DP13	28.60	301.6	0.0729	1.0756	79.02	0.9268	-34.3	0.007	0.90	**10**
Statistics										
Surface water										
Min	19.90	292.9	0.0728	1.0755	78.92	0.9185	-28.1	0.014	0.40	**17**
Max	28.70	301.7	0.0819	1.0853	88.70	0.9269	24.4	0.066	0.83	**60**
Mean	24.43	297.4	0.0771	1.0802	83.54	0.9229	-8.2	0.03	0.65	**35**
St. Dev.	1.91	1.9	0.0020	0.0021	2.13	0.0018	11.6	0.012	0.09	**9**
Groundwater										
Min	24.90	297.9	0.0709	1.0735	76.86	0.9234	-34.3	0.007	0.68	**10**
Max	30.70	303.7	0.0766	1.0796	83.00	0.9286	-13.3	0.029	0.90	**32**
Mean	28.01	301.0	0.0735	1.0763	79.66	0.9262	-25.2	0.02	0.80	**20**
St. Dev.	1.39	1.4	0.0014	0.0015	1.47	0.0013	6.6	0.007	0.07	**7**

Appendix VII – Isotopic composition of nitrate and algae

Isotopic composition of nitrate

Sample	Amount N (ug)	d15N measured	d15N corrected	Amount O (ug)	$d^{18}O$
RP3a	1541	29.681	*29.9*	1054	23.5
RP3b				1065	24.3
RP4	1029	30.575	*30.8*	450	34.2
RP5	1102	30.224	*30.4*	392	32.8
F1	226	28.087	*28.3*		
N3a	1643	24.859	25.1		
N3b	163	20.823	*21.0*		
W1	242	17.143	*17.3*	248	29.4
W2	488	14.285	*14.4*	201	19.7
DP1a	2423	12.410	12.5	1023	9.5
DP1b	3374	12.578	12.7	1040	11.1
DP1c	1484	12.730	12.9		
DP6a	2493	12.476	12.6	1090	8.0
DP6b	1497	12.483	12.6	979	9.4
DP6c				1036	7.5
DP8a	1419	11.327	11.5	1032	6.5
DP8b	1380	11.205	11.3	1010	6.9
DP8c				1027	6.9

Isotopic composition of algae

Sample	Amount N (ug)	d15N measured	d15N corrected
RP1	214	23.294	23.3
RP2	157	22.778	22.8
RP3	138	21.776	21.8
RP3b	50	21.84	21.9
RP4	213	24.915	24.9
RP4b	137	25.067	25.1
RP5	41	18.234	18.2
RP6	579	21.169	21.2
RP7	433	23.985	24.0
RP8	436	25.437	25.5
RP9	411	24.904	25.0
RP9b	275	24.847	24.9
RP10	337	23.716	23.8
RP10b	266	23.672	23.8
RP11	201	24.313	24.4
RP12	169	24.104	24.2
RP12b	170	24.185	24.3
F1	29	10.492	10.5
F2	50	4.271	4.3
F3	118	1.078	1.1
N1	111	17.112	17.1
N2	159	18.148	18.2
N3	217	21.054	21.1
N4	200	16.045	16.1

Appendix VIII – Questionnaire for the owners of the Diambar pumps and the dug wells

Number of the diambar pump: **DP1**	**Name of the interviewed person:** **Ndeye Diop**
Distance to the closest SDE conduct/tap? Year of installation.	
Are there any wells in the area? When were they abandoned?	During the period 1990-2000
The year of installation of the pump?	Around 2009
How did you obtain the pump? Bought, received (by whom)?	Bought by the father of the family for 100,000 CFA
Approx. depth of the pump?	Ap. 4 m
Daily exploitation.	100-200 L/d
How many families/persons use the pump?	Ap. 10 families
Continuity. Does it work the whole year?	Normally the whole year
Problems since installation (odour, colour, sand, periods with little water)?	Sand
Distance to septic tanks or latrines?	< 10 m
Are there any animals in the household? Which?	Yes (sheep, goats, ducks)
Uses of the water from the diambar pump?	Domestic use (washing, ect.)

Number of the diambar pump: **DP2**	**Name of the interviewed person:** **Ibrahima Diallo**
Distance to the closest SDE conduct/tap? Year of installation.	< 30 m
Are there any wells in the area? When were they abandoned?	No. Not since 1989.
The year of installation of the pump?	Around 2008
How did you obtain the pump? Bought, received (by whom)?	Received by an NGO
Approx. depth of the pump?	4-5 m
Daily exploitation.	100-200 L/d
How many families/persons use the pump?	10-20 families
Continuity. Does it work the whole year?	Normally the whole year, when there are no problems.
Problems since installation (odour, colour, sand, periods with little water)?	Sand
Distance to septic tanks or latrines?	< 100 m
Are there any animals in the household? Which?	Yes (wheep, goats)
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP3**	**Name of the interviewed person:** **Mame Sophie Nbaye**
Distance to the closest SDE conduct/tap? Year of installation.	< 50 m
Are there any wells in the area? When were they abandoned?	Long ago, not any more.
The year of installation of the pump?	One year ago (2011)
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	3-4 m
Daily exploitation.	200-250 L/d
How many families/persons use the pump?	Ap. 15 families
Continuity. Does it work the whole year?	Work continuously
Problems since installation (odour, colour, sand, periods with little water)?	Some sand
Distance to septic tanks or latrines?	< 100 m
Are there any animals in the household? Which?	Yes (sheep, goat, hens)
Uses of the water from the diambar pump?	Domestic use.

Number of the diambar pump: **DP4**	**Name of the interviewed person:** **Talla Guingue**
Distance to the closest SDE conduct/tap? Year of installation.	100 m
Are there any wells in the area? When were they abandoned?	Ap. 15 years ago.
The year of installation of the pump?	2003
How did you obtain the pump? Bought, received (by whom)?	Received by an NGO
Approx. depth of the pump?	3-4 m
Daily exploitation.	Ap. 60 L/d
How many families/persons use the pump?	Others only when there is water cut-of by SDE
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	Sand
Distance to septic tanks or latrines?	< 150 m
Are there any animals in the household? Which?	No (it is located inside the mosque’s courtyard)
Uses of the water from the diambar pump?	Only for “aboulition” washing before prayer.

Number of the diambar pump: **DP5**	**Name of the interviewed person:** **Yatama Fall**
Distance to the closest SDE conduct/tap? Year of installation.	< 50 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	2007
How did you obtain the pump? Bought, received (by whom)?	Received by goodwill
Approx. depth of the pump?	2 m
Daily exploitation.	< 100 L/week (only Fridays)
How many families/persons use the pump?	Only children of “daara”
Continuity. Does it work the whole year?	Work the whole year
Problems since installation (odour, colour, sand, periods with little water)?	Red/brown colour and sand
Distance to septic tanks or latrines?	< 30 m
Are there any animals in the household? Which?	No (it is located in the mosque’s courtyard)
Uses of the water from the diambar pump?	Only for “aboulition”

Number of the diambar pump: **DP6**	**Name of the interviewed person:** **Mariama Walhe**
Distance to the closest SDE conduct/tap? Year of installation.	10 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	1 year ago (2012)
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	?
Daily exploitation.	> 150 L/d
How many families/persons use the pump?	> 20 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	No (only one year since installation)
Distance to septic tanks or latrines?	< 20 m
Are there any animals in the household? Which?	Yes (sheep, goats)
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP7**	**Name of the interviewed person:** **Adama Diop**
Distance to the closest SDE conduct/tap? Year of installation.	< 30 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	Around 2010
How did you obtain the pump? Bought, received (by whom)?	Received by an NGO
Approx. depth of the pump?	2-3 m
Daily exploitation.	> 100 L/d
How many families/persons use the pump?	< 20 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	None
Distance to septic tanks or latrines?	< 100 m
Are there any animals in the household? Which?	Yes (sheep, goats)
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP8**	**Name of the interviewed person:** **Maimouna Sarr**
Distance to the closest SDE conduct/tap? Year of installation.	6 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	Around 2009
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	3-4 m
Daily exploitation.	< 150 L/d
How many families/persons use the pump?	< 10 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	Sand
Distance to septic tanks or latrines?	< 10 m
Are there any animals in the household? Which?	Yes (sheep)
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP9**	**Name of the interviewed person:** **Alioune Ba**
Distance to the closest SDE conduct/tap? Year of installation.	10 m
Are there any wells in the area? When were they abandoned?	Long time ago
The year of installation of the pump?	2012
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	12 m
Daily exploitation.	> 160 L/d
How many families/persons use the pump?	> 10 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	Sand in periods
Distance to septic tanks or latrines?	< 10 m
Are there any animals in the household? Which?	No
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP10**	**Name of the interviewed person:** **Alpha Mayoro Diop**
Distance to the closest SDE conduct/tap? Year of installation.	< 6 m
Are there any wells in the area? When were they abandoned?	Yes
The year of installation of the pump?	2009
How did you obtain the pump? Bought, received (by whom)?	Bought for 150,000 CFA
Approx. depth of the pump?	7-8 m
Daily exploitation.	> 200 L/d
How many families/persons use the pump?	> 10 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	None
Distance to septic tanks or latrines?	< 10 m
Are there any animals in the household? Which?	Yes (sheep)
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP11**	**Name of the interviewed person:** **Khady Ndiaye**
Distance to the closest SDE conduct/tap? Year of installation.	< 10 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	2011
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	2-3 m
Daily exploitation.	< 100 L/d
How many families/persons use the pump?	2 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	None
Distance to septic tanks or latrines?	< 50 m
Are there any animals in the household? Which?	No
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP12**	**Name of the interviewed person:** **Saidou M. Lam**
Distance to the closest SDE conduct/tap? Year of installation.	< 10 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	2000
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	15 m
Daily exploitation.	< 150 L/d
How many families/persons use the pump?	5-10 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	None
Distance to septic tanks or latrines?	< 5 m
Are there any animals in the household? Which?	No
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **DP13**	**Name of the interviewed person:** **Papa Ndiaye**
Distance to the closest SDE conduct/tap? Year of installation.	10 m
Are there any wells in the area? When were they abandoned?	No
The year of installation of the pump?	> 5
How did you obtain the pump? Bought, received (by whom)?	Bought
Approx. depth of the pump?	8 m
Daily exploitation.	< 100 L/d
How many families/persons use the pump?	The atelier and surrounding people
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	None
Distance to septic tanks or latrines?	< 20 m
Are there any animals in the household? Which?	Yes (sheep)
Uses of the water from the diambar pump?	To wash cars and for the atelier.

Number of the diambar pump: Well W1	**Name of the interviewed person: Amadou Ndiaye**
Distance to the closest SDE conduct/tap? Year of installation.	< 3 m
Are there any wells in the area? When were they abandoned?	This one!
The year of installation of the pump?	Around 1972
How did you obtain the pump? Bought, received (by whom)?	Paid to dug the well
Approx. depth of the pump?	Ap. 8 m (water table at ap. 2m depth)
Daily exploitation.	> 80 L/d
How many families/persons use the pump?	> 10 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	None
Distance to septic tanks or latrines?	< 10 m
Are there any animals in the household? Which?	No
Uses of the water from the diambar pump?	Domestic use

Number of the diambar pump: **W2**	**Name of the interviewed person:** **Maty Samb**
Distance to the closest SDE conduct/tap? Year of installation.	20 m
Are there any wells in the area? When were they abandoned?	This one!
The year of installation of the pump?	Around 1993
How did you obtain the pump? Bought, received (by whom)?	Dug
Approx. depth of the pump?	6 m (WT at around 2m below ground)
Daily exploitation.	100-150 L/d
How many families/persons use the pump?	10 families
Continuity. Does it work the whole year?	Continuously
Problems since installation (odour, colour, sand, periods with little water)?	Sometimes sand.
Distance to septic tanks or latrines?	6 m
Are there any animals in the household? Which?	Yes (sheep)
Uses of the water from the diambar pump?	Domestic use and cooking. (Use also as drinking water when SDE is not working. They then ad “sterilizing” tablets first)