ACC DAR Adapting to Climate Change in Coastal Dar es Salaam

ANALYSIS OF THE SENSITIVITY TO SEAWATER INTRUSION OF DAR ES SALAAM'S COASTAL AQUIFER WITH REGARD TO CLIMATE CHANGE

WORKING PAPER April 2013

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1 Introduction, Scope, and Motivation

1.1 Background

The ACC Dar Project aims to improve the effectiveness of municipal initiatives for supporting coastal peri-urban populations in their efforts to adapt to Climate Change (CC) impacts, thus contributing to the implementation of the National Adaptation Programme of Action (NAPA) of the United Republic of Tanzania.

More specifically, project activities will enhance the capacities of Dar's municipalities by increasing their understanding of adaptation practices, and by developing methodologies for integrating adaptation activities into strategies and plans for Urban Development and Environment Management (UDEM) in unplanned and underserviced coastal settlements.

In order to provide a series of enhanced methodologies for improving municipal activities related to CC issues in the water management sector, the specific environmental phenomenon of seawater intrusion was investigated. This phenomenon is already contributing - and will increasingly contribute as CC progresses - to the degradation of those natural resources on which a large part of Dar es Salaam's peri-urban livelihoods depend.

In the framework of Activity 2.2, "Develop methodologies for exploring CC vulnerability scenarios", 5 survey campaigns, based on a network of 80 monitoring wells, were conducted in order to quantitatively and qualitatively analyze the groundwater.

Through the implementation of various analytical methods, tailored to the available set of climatic and hydrogeological data (both historical and current data), the climatic and anthropogenic drivers and the temporal evolution of the phenomenon were studied.

This report, revised according to the contents of Prof. D. Fidelibus evaluation report, presents the results of the analysis of the current state of seawater intrusion into Dar es Salaam's coastal aquifer, and introduces some considerations regarding its potential future evolution, thus supporting local institutions in defining successful long-term climate adaptation strategies with respect to water resource management.

1.2 Goals and scope

The overall objective of this study is to explore the current degree of seawater intrusion into Dar es Salaam's coastal aquifer, and its relationships with climatic conditions and urbanization processes, in order to identify the areas of the city with the highest priority for adaptation action implementation.

More specifically, the study aims to assess the local hydrogeological and geochemical dynamics determining the phenomenon, as well as the anthropogenic and climatic factors that have influenced its present condition.

Identification of the relationships with environmental parameters, related to climate variability, and anthropogenic factors, related to changes in land cover and the population's water demand, is expected to provide the knowledge base with which to develop future scenarios of the aquifer's Sensitivity to the phenomenon, in terms of the future evolution of both seawater intrusion and groundwater availability for municipal water supply.

In order to increase the capacity of local institutions to cope with seawater intrusion, the study also aims to develop enhanced methodologies for analyzing groundwater salinization processes, as well as groundwater monitoring procedures and environmental data

management, which are tailored respectively to the set of available data, and to the capacity and resources of Dar es Salaam’s municipal services.
It is hoped that enhanced knowledge on the evolution of seawater intrusion, as well as the development of methodologies, analytical methods, and monitoring procedures will contribute to the definition of adaptation actions aimed at reducing the impacts of and people’s vulnerability to groundwater salinization.
Moreover, by enhancing knowledge and methodologies, the study lays the groundwork for future scientific research oriented towards a deeper understanding of the cause-effect relationships between CC and groundwater on a local scale (especially as regards seawater intrusion), which is currently the subject of fervent scientific interest.

1.3 Motivation

Groundwater is the largest reserve of freshwater available worldwide, and thus plays a crucial role in the adaptability of the world population to the effects of climate change on rainfall, soil moisture content, and surface water (Margat, 2006).
Recent IPCC assessment reports have concluded that very little is known about the relationship between groundwater and CC (IPCC, 2001; IPCC, 2007; IPCC, 2008); however it is recognized that CC usually acts as an effects multiplier in already altered hydrogeological systems, with obvious consequences for dependant ecosystems and communities (Appleton, 2003).
In fact, the impacts of CC can generally lead to a decrease in groundwater quantity and quality, as in the case of seawater intrusion in coastal aquifers (Kundwewiks et al., 2008), which represents one of the major factors of saline contamination of coastal groundwater, as it can cause salt content in groundwater to reach levels exceeding the acceptable standards for drinking and irrigation (Custodio and Bruggeman, 1987; FAO, 1997; Bear et al.,1999).
Seawater intrusion in a costal aquifer occurs spontaneously as a function of the natural variations in aquifer recharge (alternating periods of supply and discharge) and the periodic fluctuations in sea level (tidal effect) (Ataie-Ashtiani et al., 1999). However, phenomena such as freshwater supply loss due to a decrease in direct groundwater recharge (connected with local climate and land use changes), coastal erosion due to mean sea level rise, and increase in groundwater withdrawals as an alternative solution for water supply where surface waters are already in crisis, can alter the saltwater/freshwater equilibrium, seriously affecting water resources and related activities for decades (Bobba et al., 2000; Ranjan et al., 2006; Sherif et al.,1999).
As a consequence, groundwater salinization can become a determinative problem for socio-economic development, especially in large Southern coastal cities, where the rapid urbanization processes that typically occur can encourage the overexploitation of groundwater and the increase in sources of pollution (Mato, 2002; Steyl and Dennis, 2010), thus producing deterioration in aquifer quality and increases in seawater intrusion.
These dynamics are evident in the case of Dar es Salaam. Over the past 20 years, the population of Dar es Salaam has increased considerably (from 1.8 to over 3.2 million inhabitants in 2009 with an expected growth trend of around 5% according to the projections of the World Population Prospects 2011), leading to unplanned development of the urban fabric (extended peri-urban areas), the proliferation of informal settlements, and the deterioration of basic public services, together with a significant increase in the water demands of inhabitants (UN-HABITAT, 2009).

Currently, the municipal piped water system is based on the exploitation of surface water in the Ruvu River, located north-west of the city. It serves about 37% (including leakage and illegal tapping) of the total water demand, especially in planned areas, while the sewerage system serves only 10% of the population, with the remainder of inhabitants using on-site sanitation facilities (septic tanks and pit latrines), whose effluents are potential sources of pollution for the aquifer (AA.VV., 2004; UN-HABITAT, 2009; Dodi Moss et al., 2012).

The inadequacy of the municipal water system has led in recent years to massive groundwater exploitation in order to meet the growing water demand for anthropogenic activities (Kjellen, 2006; AA.VV., 2011). Over the past 15 years, the number of wells has increased significantly, up from a few dozen to more than 2200 official private wells and an unknown number of informal boreholes (Mjemah et al., 2009; JICA, 2012). And these numbers continue to increase (Mtoni et al., 2012).

Moreover, the changes in climatic conditions, which show significant trends of rainfall decrease (from about 1200mm/year in the 1960s to about 1000mm/year in 2009) and mean temperature rise (the highest temperature values have been recorded in the last decade) (Tanzania Meteorological Authority, 2011), have contributed to the impoverishment of local freshwater resources and an additional demand of groundwater.

The growing exploitation of groundwater raises many issues of great scientific interest as regards the present and future quantity and quality of water resources, which are increasingly affected by salinization processes caused by anthropogenic pollution (Mato, 2002; Mjemah, 2007), a rise in saline fossil water (Mjemah, 2007), and increasing seawater intrusion (Mtoni et al., 2012).

Surveys conducted under the ACC Dar project show that groundwater salinization is already a major concern for households living in peri-urban neighbourhoods within the coastal plain. In fact, most of them depend heavily on boreholes for access to water for domestic and productive (mostly agriculture-related) purposes.

Notwithstanding the social importance of groundwater availability, the studies on seawater intrusion in the coastal aquifer are still scarce. It is therefore extremely important to enhance the knowledge on and develop methodologies for studying the evolution of seawater intrusion and its causes and possible consequences, in order to support local institutions in the identification of adaptation activities to be mainstreamed into water management plans and strategies. How future climatic and anthropogenic factors could affect the aquifer's sensitivity to the phenomenon must also be assessed, notwithstanding uncertainty regarding the future of socio-economic, environmental, and climatic systems.

Underestimating the processes that are currently occurring in the coastal aquifer, or the role of groundwater in water resource management, could lead to inappropriate strategies with important consequences for the population and environment.

Assessment of the present condition and the future potential of the phenomenon provides information that will contribute to the definition of societal adaptation objectives (through backcasting scenario analysis) and community visions for future development as regards access to safe water for Dar es Salaam's population, which will be part of the project's subsequent activities.

2 Approach and Methods

2.1 Overall Approach

This report refers to a scientific study carried out in the framework of the broader methodological approach chosen as the structure for the overall ACC Dar project.

The conceptual framework adopted in this case is widely used in the CC and impact research community (Füssel, 2007; IPCC, 2007) and aims to define adaptation actions through an assessment of people's vulnerability to a specific phenomenon, which can be amplified by the effects of CC (Figure 1).

According to this approach, vulnerability is defined as *"the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity"* (IPCC, 2007).

Vulnerability = f (Exposure, Sensitivity, Adaptive Capacity)[1]

In this regard, the purpose of a vulnerability assessment is to develop a qualitative understanding of the environmental, social, and economic processes that can turn the consequences of climate change into possible risk factors for communities (Downing and Patwardhan, 2003; Füssel and Klein, 2006; Heltberg et al., 2009). Vulnerability assessments can identify the regions and social groups that are most susceptible to the consequences of a particular disturbance, consequences that could be increased and aggravated by the effects of climate change, and can provide a knowledge base for the implementation of adaptation strategies for specific socio-economic contexts (Downing and Patwardhan, 2003; IPCC, 2007).

This study incorporates the vulnerability assessment framework, which refers to sensitivity in terms of its natural and social components. The former is understood as the possibility that an environmental system be damaged by the *"duress of changing climate conditions and hazardous events as well as the dependency of societies and specific economic activities on environmental structures"* (ESPON, 2009: 2). The social component refers to the *"sensitivity of different social groups to climate change effects, in relation to the demographic, ethnic, cultural or physical composition of the groups and to the levels of marginality and social segregation or other weaknesses and restrictions in the access to social, economic or health-related assets"* (ESPON, 2009: 2).

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[1] According to Füssel and Klein (2006) and IPCC (2007), in this study we will refer to the following definitions of the components of vulnerability:

Exposure: the nature and degree to which a system is exposed to significant climatic variations.

Sensitivity: the degree to which a system is affected, either adversely or beneficially, by climaterelated stimuli. The effect may be direct or indirect.

Adaptive capacity (in relation to CC impacts): the ability of a natural or human system to adjust to climatechange (including climate variability and extremes) to moderate potential damages, to takeadvantage of opportunities, or to cope with the consequences.

Drawing on these methodological premises, this study focuses first on analyzing the current sensitivity of the Dar es Salaam's coastal aquifer to seawater intrusion, and subsequently on drafting future sensitivity scenarios (Figure 2).

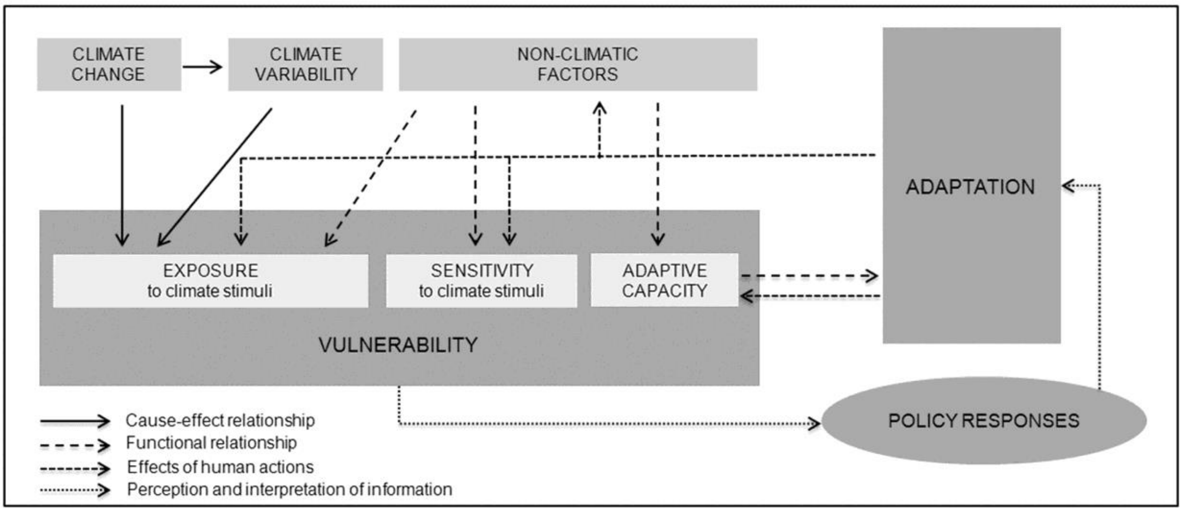


Figure 1 - Conceptual framework for vulnerability assessment (Mod. from Füssel and Klein, 2006)

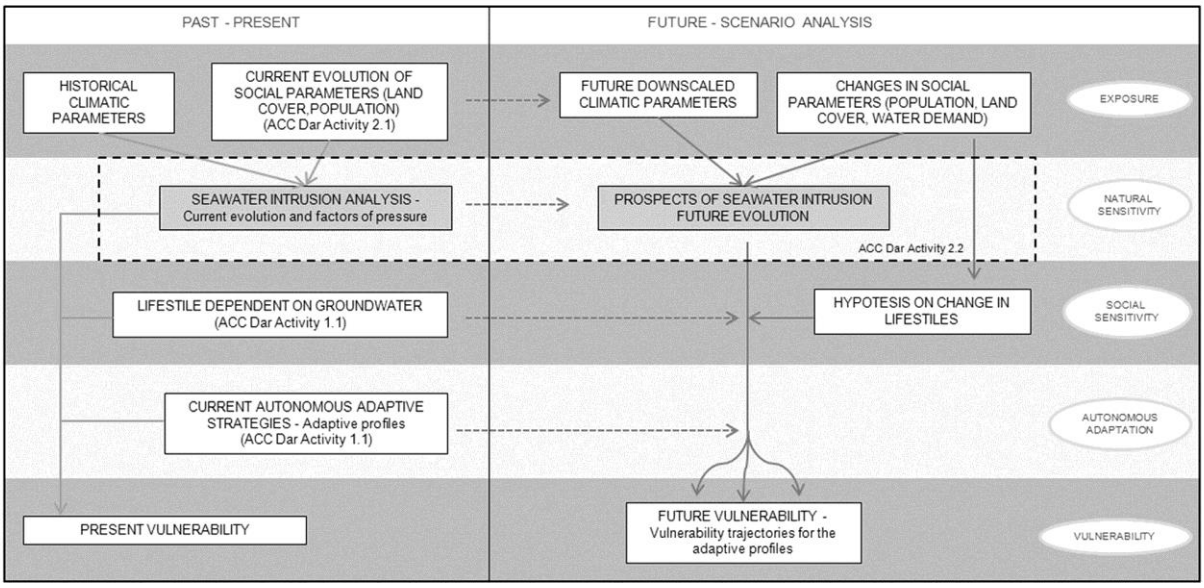


Figure 2 - Placement of this study (ACC Dar Activity 2.2) in the vulnerability assessment framework

The methodology for assessing the aquifer's sensitivity to seawater intrusion consists of the following analytical steps:

- Bibliographic data collection and analysis to assess the geological and hydrogeological sketch of the Dar es Salaam coastal plain;
- Seawater intrusion assessment by hydro chemical methods, through physical and chemical testing of a monitored network of representative boreholes from 2001 to 2012;
- Analysis of climatic and anthropogenic influences on hydrogeological dynamics through investigations on piezometric surface and Active Groundwater Recharge temporal evolutions;

- Development of qualitative hypothesis for seawater intrusion trends related to the possible evolution of climatic and non-climatic factors.

The analytical methods developed in each phase are consistent with the type and availability of data, as well as the capacity and resources of municipal services.
The results of this study, together with the identification of social sensitivity and different adaptive profiles (subject to other ACCDar WP project activities), will provide the knowledge necessary for defining successful adaptation strategies on the basis of different priority criteria and in accordance with the factors that make a community socially vulnerable.
The different phases of the activity are shown in Figure 3.

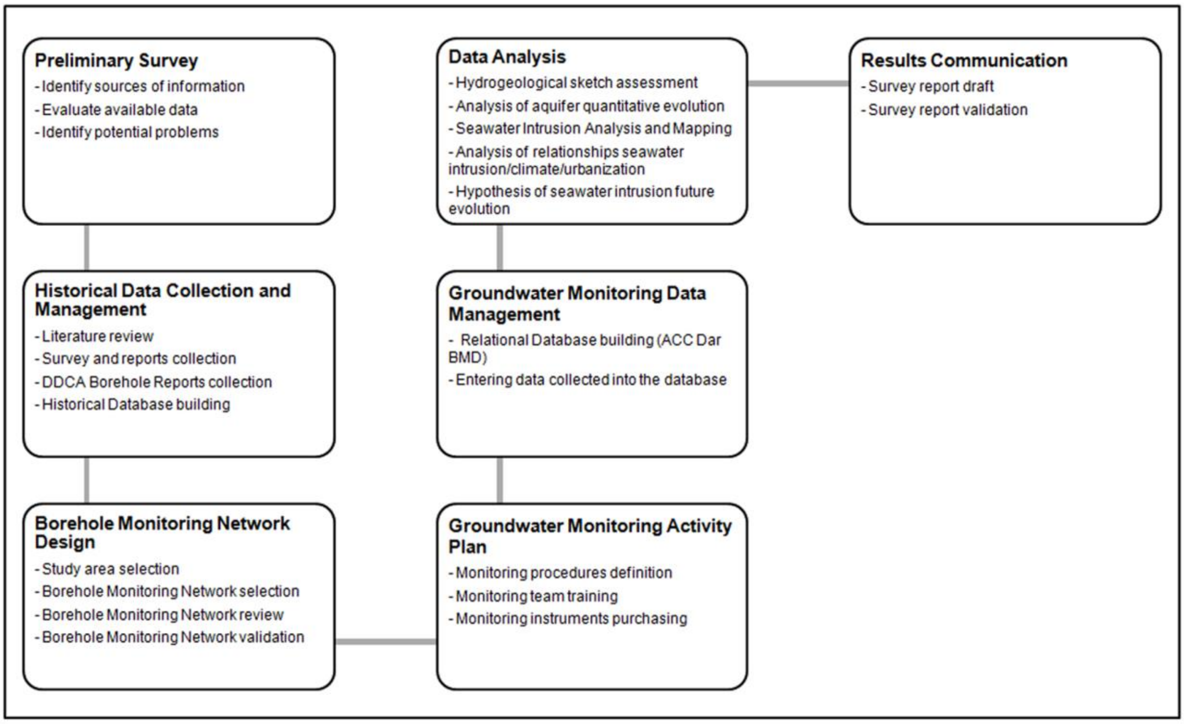


Figure 3 - Activity Workflow

2.2 *Data Collection and Analysis Methods*

2.2.1 **Data Collection and Management**

A preliminary survey was carried out in order to get familiarized with the study area, identify potential sources of information, and to evaluate the type and quality of available data and tools, as well as the potential problems that could arise during data collection activities.
On the basis of the information gathered during this preliminary phase, a data collection methodology was defined. That methodology consisted of two main activities: collection of historical data from a variety of existing sources, and the execution of groundwater monitoring campaigns (June 2012 - January 2013), in order to compile a set of historical and current data that will be useful when evaluating the evolution of seawater intrusion.

<u>Historical Data Collection</u>
The study started with the review of relevant documents and literature on the geological and hydrogeological characteristics of the Dar es Salaam Region, surveys on the physical and

chemical characteristics of the groundwater carried by various academics, public authorities, and international cooperation agencies, and reports on environmental conditions and changes in Dar es Salaam.
A fundamental part of this process was developed in collaboration with the DDCA (Drilling & Dam Construction Agency, URT Ministry of Water). Their Borehole Report (in hardcopy) was a precious source of technical data regarding the boreholes throughout the Dar es Salaam Region.
The output of these activities is a set of historical data that includes climatic parameters (precipitation and temperature data for 3 gauges with reference to the last 50 years), hydrogeological characteristics of the coastal aquifer, and the physical and chemical parameters of the groundwater for nearly 400 boreholes located in the Dar es Salaam Region.
All data relating to the 400 geo-referenced boreholes were digitized, standardized, and organized in a database.

Groundwater monitoring activity

Given the morphological and geological characteristics of the Dar es Salaam Region, the first step was the assessment of the study area in order to design a borehole monitoring network. That network includes the coastal sandy plain[2], progressing from the Indian Ocean towards inland, and including the entire metropolitan area as well as some peri-urban areas (not located in the plateau) within the Kinondoni, Ilala and Temeke districts.
The study area has a surface of approximately 260 km2, which extends along a 40 km stretch of coastline to the north of the City centre and is bordered to the east by the Indian Ocean. The western boundary is the Dar es Salaam Plateau, which rises west of the Ocean along the entire study area up to the Pugu Hills. The hydrogeological boundaries are the Mzinga River to the South and the Nyakasangwe River to the North.
A subset of boreholes located in the study area was chosen for the monitoring network from the database of 400 georeferenced boreholes, with consideration for uniformity of spatial distribution: the network consists of 79 boreholes, uniformly distributed with a frequency of about 1 borehole per 3 km2.
The study area and the borehole monitoring network are shown in Figure 4.
The monitoring procedures consisted in a variety of survey activities depending on temporal scale (long-term and monthly surveys) and the type of data to be collected (in situ and laboratory measures).
The monitoring campaigns were performed following the scheme in the Table 1.
In order to manage the large quantity of data collected during the monitoring campaigns and to assure its consistency and maintenance over time, a specific relational database for the ACC-Dar Borehole Monitoring Network Storage was built in MS Access (ACC-Dar BMD).
Table 2, below, contains a summary of the number and kind of investigation and analysis results by year.

[2] Coastal Plain spans the central area of Dar es Salaam from the coast towards the west, rising from 0 m to 60 m above sea level with a gradient varying from 0% to 5% and it includes three geological features: alluvial and river terraces, white-buff sands and gravels and raised coral reef limestone (Mjemah, 2007). As it will be shown later, the analysis will focus on the coastal aquifer located in Quaternary sand deposits.

Monitoring campaigns	Frequency	Data collected
Long-term monitoring activity involving the entire borehole network (79 boreholes)	Twice in 6 months: -June 2012 (after the "long rainy season") -November 2012 (before the "short rainy season")	SWL measure (using contact meters) Physical parameters in situ measure (using multiparametric probes): T, pH, EC, TDS Chemical parameters lab measure (laboratory analysis of collected water sample): Ca++, Mg++, Na+, K+, HCO3-, SO4--, Cl-, NO3--, F-, NH4+
Monthly monitoring activity involving a sub-group of the borehole network (33 boreholes, mainly located in the area close to the coastline)	Monthly: -September 2012 -October 2012	SWL measure (using contact meters) Physical parameters in situ measure (using multiparametric probes): T, pH, EC, TDS

Table 1 - Scheme of the monitoring campaigns

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	June 2012	Nov 2012
G (mas)	32	6	52	15	8	6	5	4	1	54	0
depth	32	6	51	15	8	6	5	4	1	33	0
SW m	32	6	51	15	8	6	5	4	1	79	0
T C°	0	0	0	0	0	0	2	1	0	79	0
pH	32	6	52	15	8	6	5	4	1	79	0
EC uS/cm	32	6	52	15	8	6	5	4	1	79	0
Total Fitrate Residue mg/l	1	0	12	6	7	4	4	0	0	0	0
TDS mg/l	0	0	0	0	0	0	2	2	1	0	0
Carbonate Hardness mg CaCO3/l	7	6	12	6	7	4	3	2	1	0	0
Non Carbonate Hardness mg CaCO3/l	30	5	39	10	4	5	3	3	1	0	0
Ca mg/l	32	6	52	15	8	6	5	4	1	79	71
Mg mg/l	32	6	52	15	8	6	5	4	1	79	70
Na mg/l	32	6	52	15	8	6	5	4	1	79	70
K mg/l	32	6	52	15	8	6	5	4	1	79	70
Fe mg/l	26	5	47	15	8	4	5	3	1	0	0
Mn mg/l	25	5	21	10	7	2	4	2	0	0	0
NO3 mg/l	26	4	45	12	8	6	5	4	1	79	71
Cl mg/l	32	6	52	15	8	6	5	4	1	79	71
SO4 mg/l	32	6	52	15	8	6	5	4	1	79	71
PO4 mg/l	30	4	30	15	8	3	5	0	0	0	0
F	0	0	20	0	0	2	2	2	0	0	0
HCO3 mg/l	0	0	0	0	0	0	0	0	0	79	71
CO3 (mg/l)	0	0	0	0	0	0	0	0	0	0	23
P	0	0	0	0	0	0	0	0	0	0	71
ZN	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0
NH4	0	0	0	0	0	0	0	0	0	0	71
MN	0	0	0	0	0	0	0	0	0	0	0

Table 2 - Numbers and kinds of investigation and analysis results

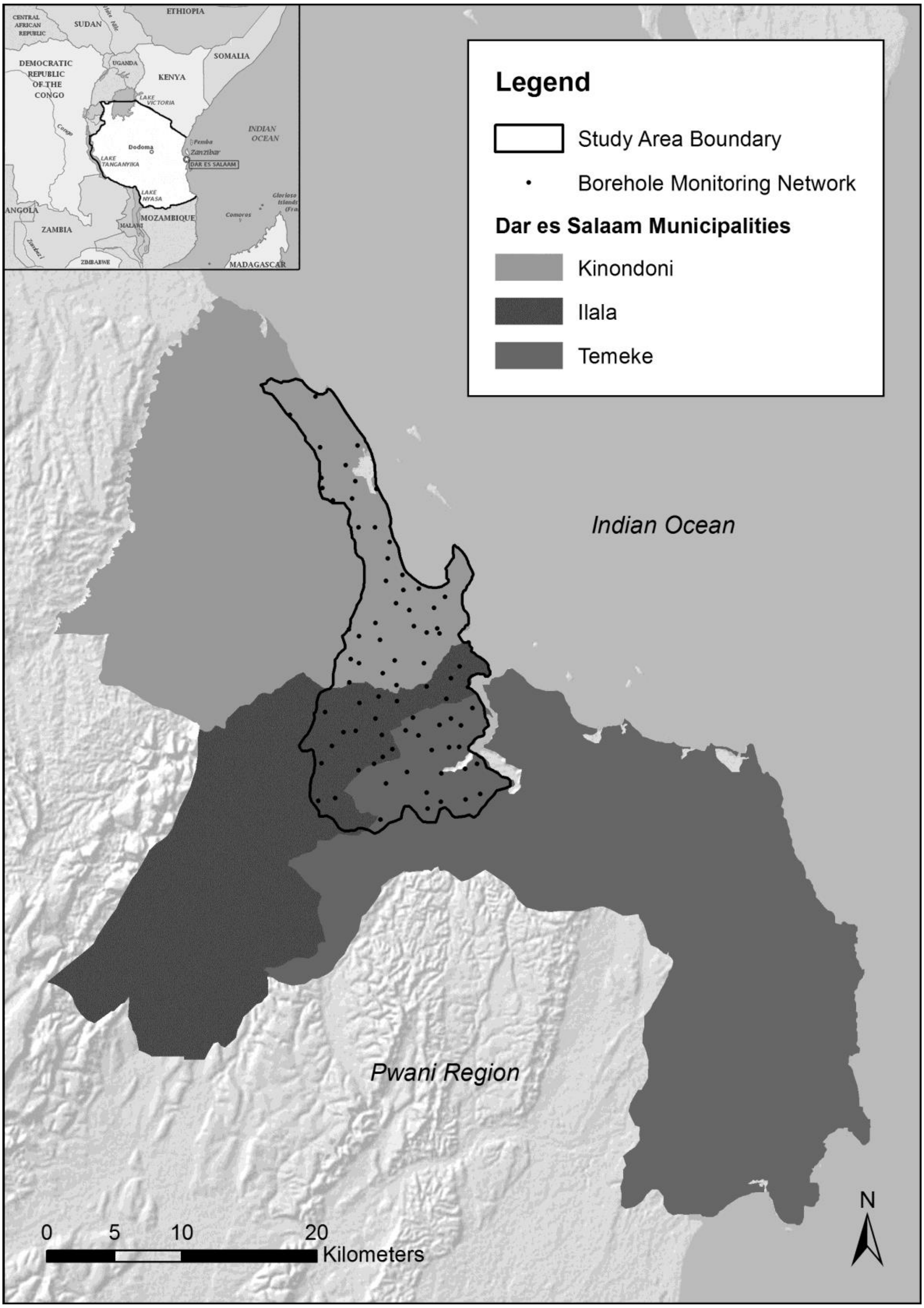


Figure 4 - The Study Area and the designed Borehole Monitoring Network

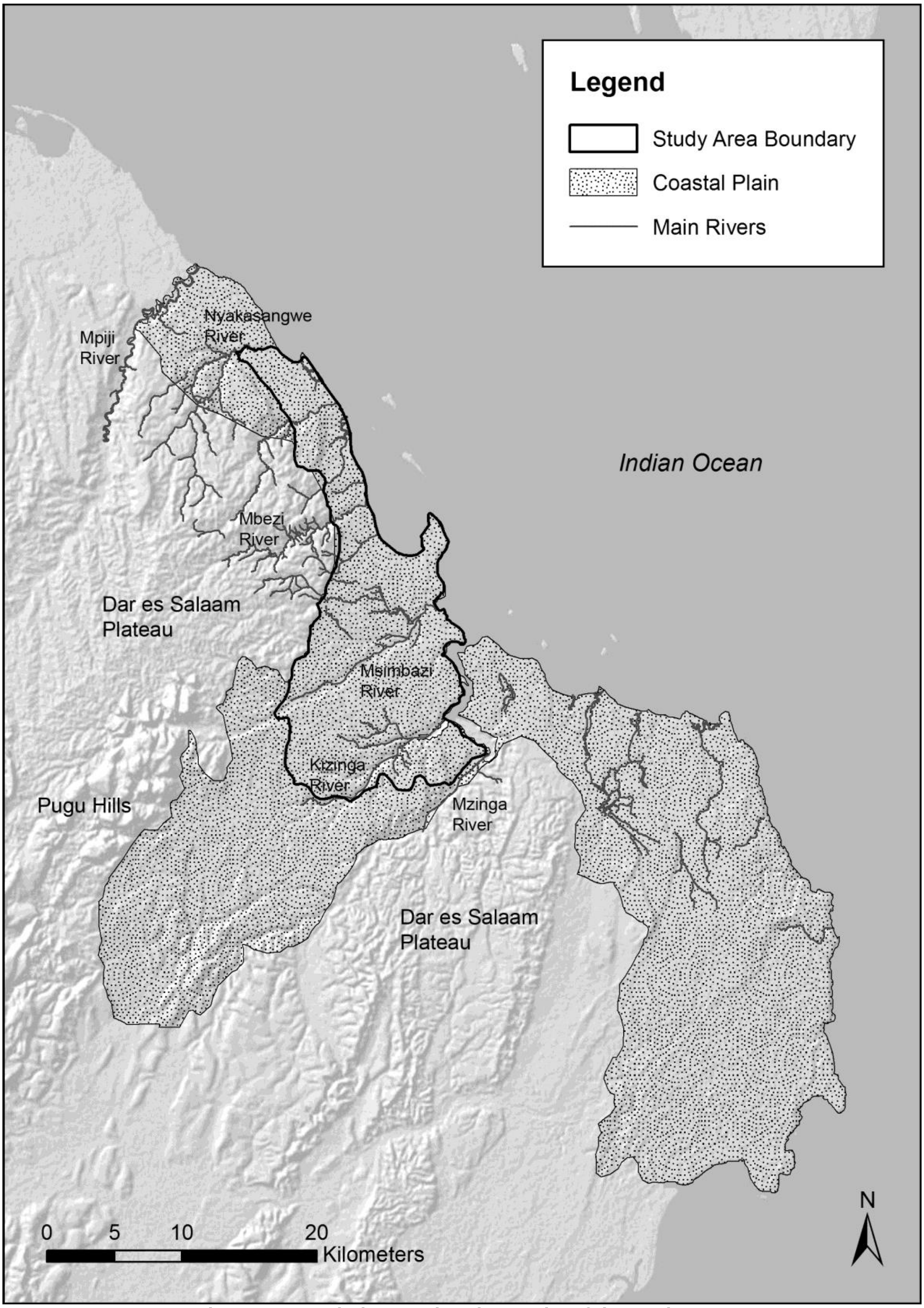


Figure 5 - Morphology and Hydrography of the study area

ACC-Dar Borehole Monitoring Database

The ACC-Dar BMD is a relational database built in the framework of Activity 2.2 in order to store and manage all the hydrogeological data gathered concerning seawater intrusion into the Dar es Salaam coastal aquifer (Figure 6).

The monitoring network is currently made up of 79 boreholes, the details of which are stored in the BMD.

Through the BMD, technical (depth, year of construction, coordinates, etc.) and historical chemical-physical data on the boreholes can be accessed and updated according to the information gathered during present and future survey activities.

Considering its notoriety and user-friendly accessibility, Microsoft Access was deemed the most appropriate relational DBMS to develop the ACC-Dar BMD.

As with all relational databases, data in the ACC-Dar BMD are arranged in tables, related to each other through a system of primary keys (in this case, the borehole ID, made by the first three Characters of the district of location and a number).

The ACC-Dar BMD structure is presented in Figure 7.

Specific queries have been built to quickly recover the most interesting data (stratigraphies, static water levels, chemical analysis, etc.).

The ACC-Dar BMD is intended as the basic tool for future seawater intrusion survey activities, whose purpose is to serve as a reference point for similar projects in the future.

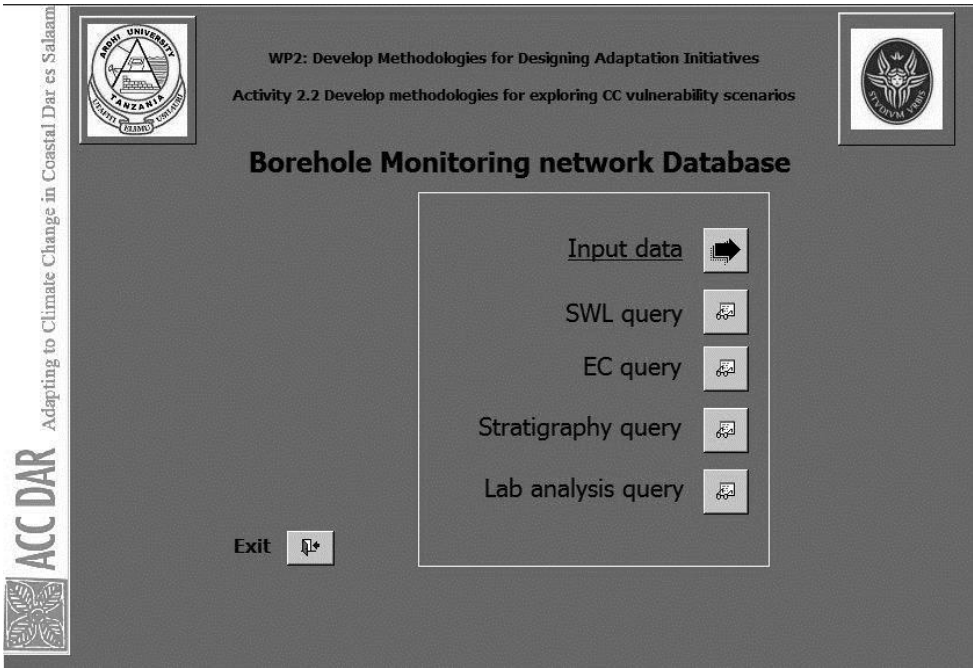


Figure 6 - ACC-Dar BMD main-page

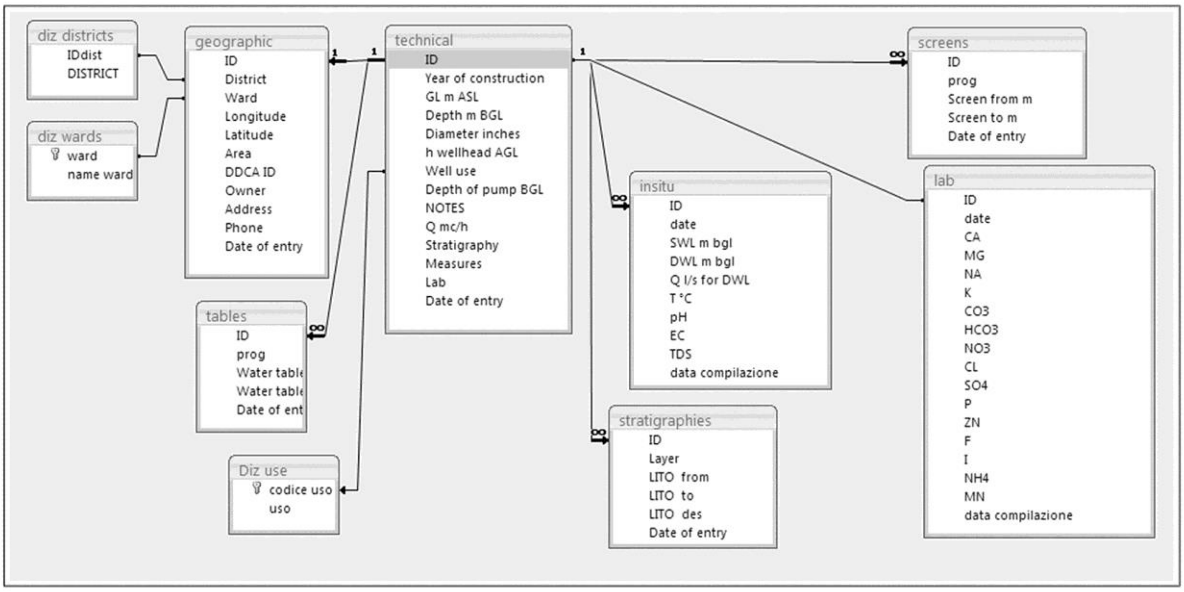


Figure 7 - The structure of the ACC-Dar BMD

2.2.2 Data Analysis Methods

The present section summarizes the data analysis methods adopted in the elaboration and interpretation of the data sets mentioned above.

The analysis of piezometric evolution in the area under study began with the measurements of static water levels from 2001 to 2012. In order to determine the piezometric surface for a given year, an IDW (Inversed Distance Weight) method was applied, supported by GIS software. Since the measurements taken in wells were of very different depths, output results were then corrected, taking into account the hydrogeological assessment of the area and the surface stream network.

Active Groundwater Recharge was evaluated using the Hydrogeological Inversed Budget Method (Civita and De Maio , 2001) as modified by Sappa, Trotta, and Vitale (2013). That method involves a spread parameters approach, based on the discretization of the study area in 25,000 m2 cells, and on the estimation of a given input parameter, such as precipitation or land cover, referred to each cell. The final evaluation of active groundwater recharge refers to the whole study area and comes from the addition of the results coming from each cell.

In the aim of evaluating seawater intrusion and its evolution over the last ten years, the study proceeded according to the following steps:

In the aim of evaluating the seawater intrusion and its evolution in the last ten years, the study has proceeded according to the following steps:

- Elaboration of distribution maps for various parameters (TDS, Cl, SO4, and EC);
- Graphical representation in the form of a Piper diagram, in order to distinguish water types and identify the most significant groups;
- Data analysis using Cl—Y diagrams (cross plots) related to the theoretical freshwater-seawater dilution line;
- Hydrochemical facies analysis by Stuyfzand (1986, 1993) classification.

The joint use of these methods allows for the comparison of water samples according to two end members (a freshwater and a salt one), involved in the mixing represented by a line.
The ∆ionics , which overlap simple mixing between fresh water and salt water and recognise the presence of other salt sources, were calculated in order to qualitatively and quantitatively study the processes.
Once the chemical composition of the two presumptive end-members of mix are defined, the cross plots of each constituent vs. chloride will allow comparison of the data with the theoretical mixing line.

Defining

C^i_{samp} = concentration of the ith ion in the sample
C^i_S = concentration of the ith ion in seawater end-member
C^i_F = concentration of the ith ion in fresh water end-member
C^{Cl}_{samp} = chloride concentration in the sample
C^{Cl}_F = chloride concentration in fresh water end-member
C^{Cl}_S = chloride concentration in seawater end-member
C^i_{mix} = concentration of the ith ion corresponding to the C^{Cl}_{samp}, calculated according to the non-reactive mixing

$$f_s = \left(C^{Cl}_{samp} - C^{Cl}_F\right) \Big/ \left(C^{Cl}_S - C^{Cl}_F\right)$$

will give the fraction of seawater in the mixed water.
So,

$$C^i_{mix} = f_s \cdot C^i_S + (1 - f_s) \cdot C^i_f$$

This way, each sample of chloride concentration C^{Cl}_{samp} will correspond to a theoretical concentration of the ith ion, C^i_{mix}, which will be compared to C^i_{samp} measured as such:

$$\Delta C^i = C^i_{samp} - C^i_{mix}$$

These values will be defined in the following as ∆ion (deficits, if the value of ∆ is negative, or excesses, if the value of ∆ is positive). These ∆ values for major constituents are a guide in interpreting the involvement of various processes that can be responsible for the deviation of ion concentrations from values determined by conservative mixing. In any case, the ∆s allow for the formulation of hypotheses about processes that differ from classical seawater intrusion, which could be accountable for salinization (Fidelibus, 2001).

3 Findings

3.1 Bibliographic data collection and analysis

3.1.1 The Dar es Salaam area and its geomorphology

The study area is located in the coastal plain of Dar es Salaam, United Republic of Tanzania, in Sub-Saharan Africa.

The coastal plain of Tanzania is a narrow coastal belt protected by a coral reef, and the mainland is covered by a large central plateau and highlands. The interior plateau extends from southern Kenya, increasing in width from 17 km at the Kenyan border to 150 km in the Dar es Salaam Region (Kapilima, 1984; Kent, 1971). Kilimanjaro, the highest mountain in Africa, lies in north-eastern Tanzania, at an altitude of 5895 m. The Great Rift Valley extends to the centre of the country, and contains Lake Victoria at the northern border, and Lake Tanganyika to the west.

Dar es Salaam city, located in the eastern part of the Tanzanian mainland, between latitudes 6°36' and 7°0' South and longitudes 39°0 and 33°33' East, covers about 0.19 per cent of the total land area of the Tanzanian mainland.

The total surface area of Dar es Salaam City is about 1800 km2, including 1393 km2 of landmass comprised by eight offshore islands. The city consists of three municipalities: Temeke, the largest by surface area at 652 km2, followed by Kinondoni with 531 km2 and Ilala with 210 km2 (AA.VV., 2011).

The geomorphology of Dar es Salaam is characterized by a variety of geological, hydrogeological, hydrographic, and topographic features, all of which affect landform evolution.

The general topography reflects the geological history of Tanzania, consisting of a plain along the coast, a plateau in the central area with gently sloping plains, and a plateau scattered with hills and wetlands.

A coastal plain runs along the coastline, and is 10 k wide to the west and north-west of Dar es Salaam. It narrows to a width of 2 k in the north, before widening again at the Mpiji River. In the southwest of the city, the plain merges inland into the more elevated headwaters of the Mzinga River.

As regards morphological conditions, the coastal plain is fairly uniform, with less than 3% slopes, except along the margins of the Mzinga and Msimbazi valley systems (Temple, 1970), and it is dissected by several river valleys.

A unique feature of the lower coastal plain is the swamp depressions. Within the costal terraces the creeks are U-shaped.

To the south-west of Dar es Salaam, the coastal plain becomes more irregular, rising to greater heights inland of Ras Kimbiji, where there are outcrops of the lower Miocene clay-bound sands, which give rise to a marked trellis drainage. Faulted and probably karstified raised reef limestone can be found along the coast.

A zone of uniform relief surrounded by general flat hills extends inland of the coastal plain. This declines in elevation northward, while to the south it rises to several hundreds of meters in height in the Pugu Hills.

The Pugu Hills form a separate morphological unit within the coastal plain, extending to the west from Dar es Salaam and the Indian Ocean. Most of the hills trend NNE-SSW. The main

structural features are NNE-SSW trending faults associated with the East African Rift Valley system (Schwaighofer and Muller, 1987).
The uplift along these fault-lines has led to erosion and a series of steep U-shaped valleys.
The Pugu sandstone formations belong to the East Africa coastal sediments, which extend from Kenya to Mozambique. In this landform, trellis drainage is determined by the Msimbazi and Kimani rivers, which both discharge into the Indian Ocean.
Soils are influenced by the geological and geomorphological history of Tanzania. The soil coverage in the Dar Es Salaam Region includes mainly Ferralic Arenosols.
The dominant soils found in the city are sandy clays and clayey sands, but in the main river valley systems that run across the Coastal Plain (Msimbazi, Mzinga, Kizinga) mixed alluvial deposits can be found (Temple, 1970).

3.1.2 Geological and hydrogeological framework

The geological structure of Tanzania reflects the geological history of the whole African Continent. It is the result of a series of events that began with the evolution of the Archean shield, followed by its modification through metamorphism.
Generally, the African continent preserves evidence of crust-forming events, like cycles of continental break-up and growth.
The Tanzanian craton covers the central part of the territory up to the southern and eastern parts of Lake Victoria. Faulting and sea level heavily impact the shoreline. The faulting events mark the main boundaries between the metamorphic crystalline rocks of the inland and the sedimentary rocks of the coastal basin.
Following the break represented by metamorphism, the East African Coast was affected by tectonic movement during the Permo-Triassic period (Kent, 1972).

With the development of the Indian Ocean, the important tectonic events that occurred along the East African coast were as follows (Kapilima, 2002):

- karro rifting, which affected the Tanzanian coast during the Permian (Kent, 1972);
- the breakup of the Gondwana continent, which started with rifting in the Triassic and the opening of the Somali basin in the Middle Jurassic;
- the Cenozoic rifting along the East coast Africa.

The geology of Tanzania consists of two different environments: the Precambrian sediments and the Karoo sequence (Figure 8).

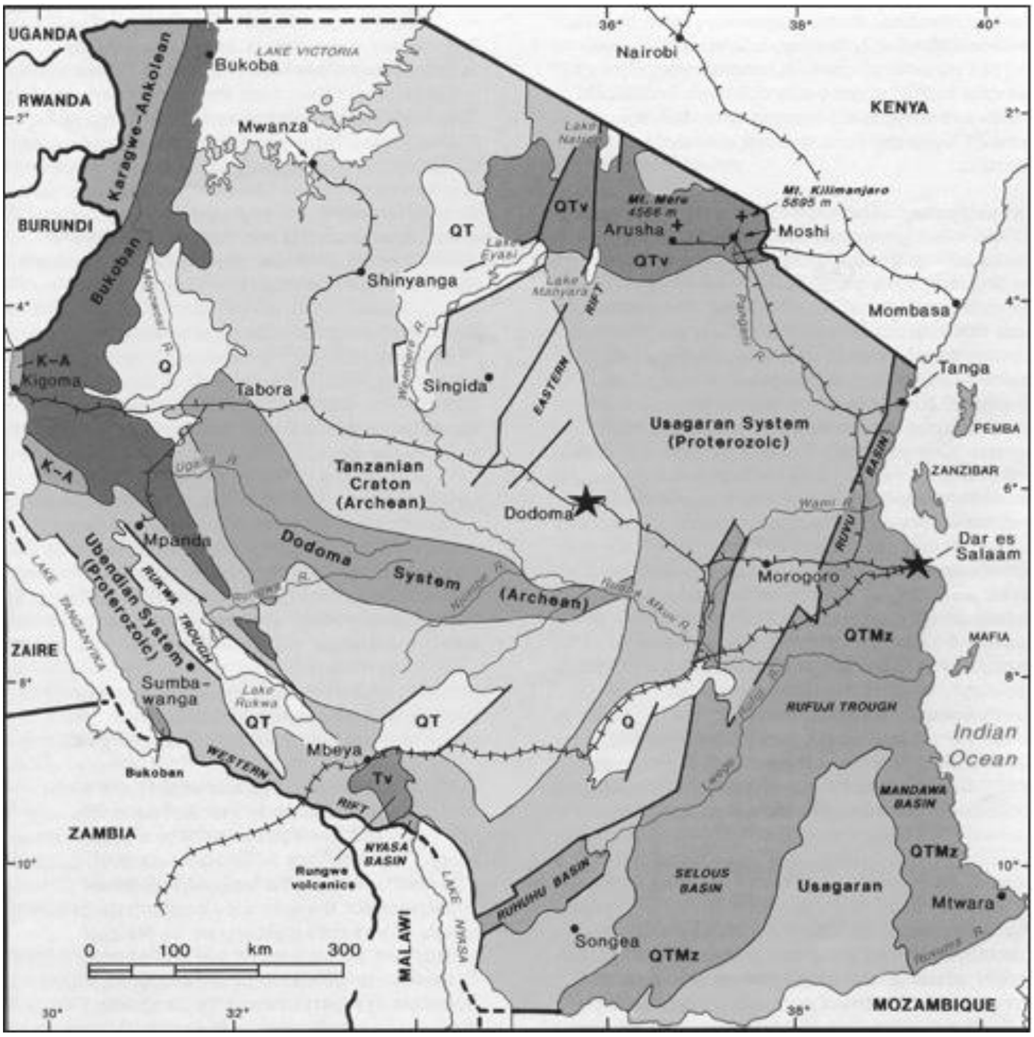


Figure 8 - Geological map of Tanzania

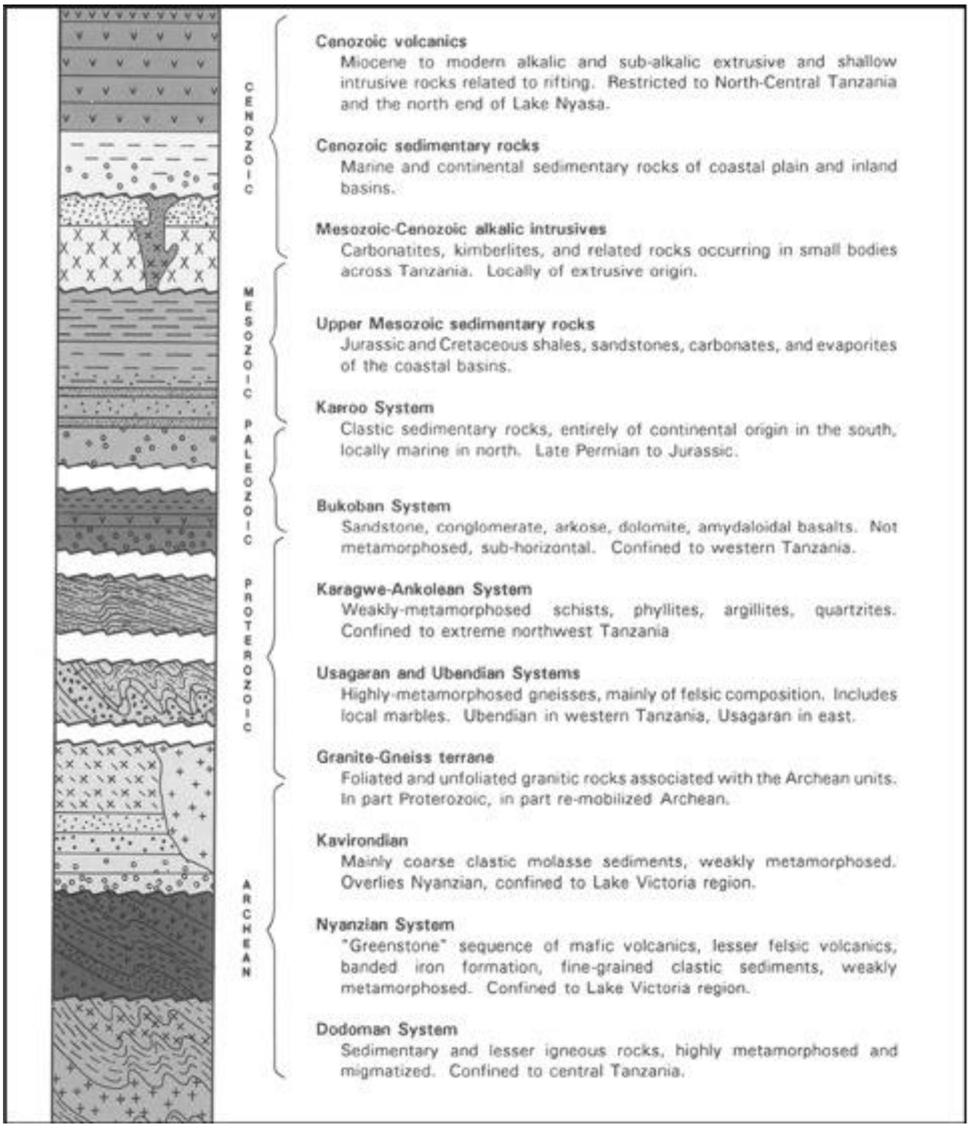


Figure 9 - Geological section of Tanzania (Semkiwa et al, 2005)

The Precambrian basement rock in coastal Tanzania includes the oldest sediments of the Archean age. It consists of the crystalline and high grade metamorphic rocks of the Mozambique Orogenic Belt. The Precambrian rocks are predominantly sediments of the Archean age, which cover most part of the area on the western side of the Tanga fault (Mpanda, 1997).

The continental Karoo sequence forms the basal part of the sedimentary sequence in the coastal basin of Tanzania. This sequence unconformably overlies the Precambrian basement of metamorphic rocks of the Tanganyika shield. It includes lithofacies from various ages, ranging from the Upper Palaeozoic to the Early Jurassic (Mjemah, 2007), as the result of different rates of subsidence and the varied sedimentary environments.

In Tanzania, Karoo sediments were deposited mainly in the East, in low relief areas adjacent to the Mozambique belt (Kent et al., 1971). They include mainly sandstones and siltstones on top of basal conglomerates (Mpanda, 1997).

When the first marine transgression overlapped the continental Karoo, the coastal basin of Tanzania became a continental shelf. The Middle Jurassic sediments are spread along almost the entire coastal belt. The marine transgression continued in the Upper Jurassic and in the Dar es Salaam Region the sediments are mainly marlstones, calcareous sandstones.

A marine regression characterized the early Cretaceous period. Sediments deposited in this regression are continental and deltaic sedimentary rocks. Most of these deposits are found in southern Tanzania. Alternating periods of regression and transgression characterized the Tertiary.

During the Palaeogene, deposits formed a narrow strip in the southern coastal zone of Tanzania. In regression periods, clays, silty layers, and silty limestone dominated. In transgression periods, sediments mainly consisted of calcareous, sandy, and shelly limestone.

The Neogene period in this region was characterized by important tectonic activities, which defined the present topographic features. Neogene sediments can be found everywhere in the coastal basin of Tanzania. The deposited sediments are arenaceous facies with minor limestone beds interbedded with clay materials.

The most important outcrop of the Miocene is the kaolinitic sandstone in the Pugu Hills. The Pugu Hills form a separate physiographic hilly block in the south-west of Dar, within the coastal pain. The Precambrian metamorphic rocks of the Uluguru mountains are a probable source od the kaolinitic sediments in the Pugu Hill Formation, as there may be a relationship between the mineral constituents of the products of weathering from the crystalline rocks of the Uluguru Mountains and the Pugu Hill clay deposits (Schwaighofer and Muller, 1987). Clay-bound sands overlie the Pugu sandstones.

During the Quaternary period, deposition and erosion processes occurred in relation to tectonics, sea level, and climate change. In the Dar es Salaam Region, the quaternary deposits can be divided into three geological layers: alluvial, coastal plain, and coral reef limestone deposits. Alluvial deposits fill the valleys of the Mzinga, Kizinga, and Msimbazi rivers. They consist of an alternation of fine and coarse-grained sands, clay, and sometimes gravel and pebbles. The coastal plain consists of unconsolidated sediments, predominantly sandy, with evidence of several marine intercalations. The presence of coralline limestone is found along the coastal strip. Carbonate rocks are present as fringing reefs and raised reefs. The northern part of the region has few fringing reefs, while raised reefs dominate the western margins of the upland (Msindai, 2002).

The geological setting of the Tanzanian coastal area can be divided into different regions, depending on their distinctive tectonic development (Kent, 1971).

The northern Mainland is a narrow strip in which Mesozoic formations dominate. The central Mainland area, bounded by the Ruvu and Rufiji river valleys and the Ocean Indian, includes the Dar es Salaam embayment. It is characterized by lithological units of the Cretaceous and Neogene. The southern mainland includes the Karoo salt basin, Cretaceous deposits, and marine tertiary beds.

In the area of concern, two main geological units are recognized: Quaternary and Neogene. The geology of the Dar es Salaam City area is characterized by quaternary sediments, which mainly underlie the coastal plain of Dar es Salaam. The quaternary terrace sandstones are more widespread in the central and southern parts of the Dar es Salaam Region. The quaternary deposits also include coral reef limestone, nearer the coast.

Neogene sandstone formations, interbedded with siltstones and mudstones, occupy the upland zone south and west of the city centre. Within the Neogene formations, several distinct varieties are recognizable. Sandstones occupy over three quarters of the region and comprise a variety of main types. The massive terrace sandstone is the bedrock that limits the extent of terraces (Msindai, 2002). The Pugu sandstones comprise massive, kaolinitic, and cross-bedded sandstones. Calcareous sandstones also occur on back reef areas of the uplands.

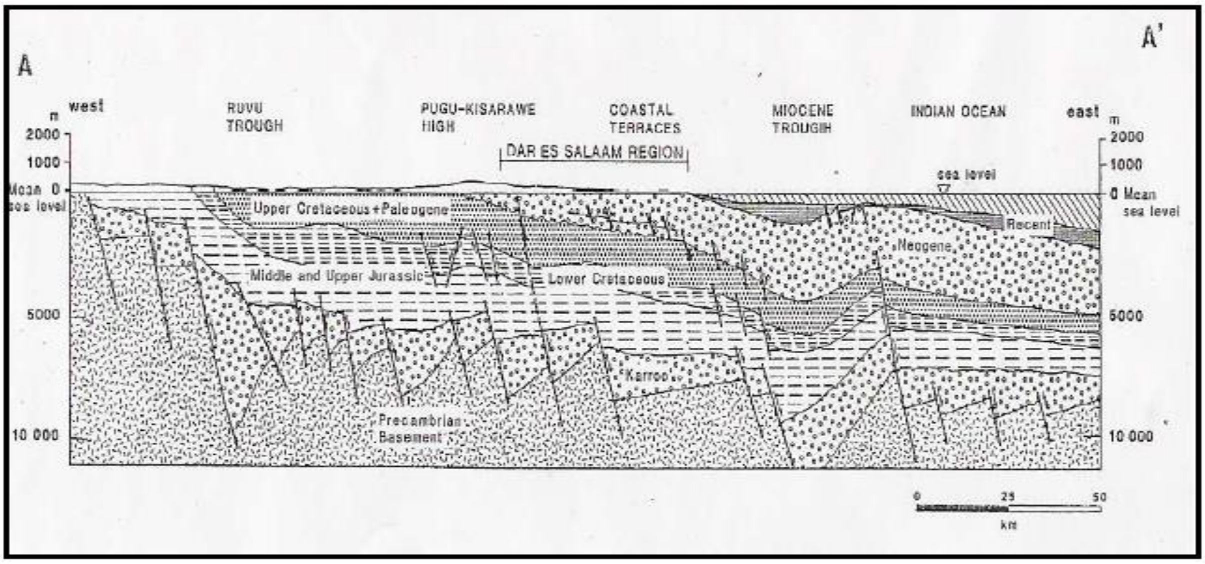


Figure 10 - A geological cross section through the study area (Msindai, 1988)

The occurrence of groundwater is largely influenced by geological conditions, such as lithology, type, and texture of formations and structures. The groundwater reservoir is located within the coastal plain in the quaternary sediments, as the quaternary deposits have higher hydraulic conductivity than the underlying and surrounding Miocene sequence, which includes clay intercalations.

The aquifer system in the study area includes two main aquifers, both from Quaternary: an upper unconfined sand aquifer and a lower semi-confined sand aquifer, separated by a clay aquitard. The sediment type for both aquifers is almost the same, and consists of quaternary deposits from Pleistocene to the recent age.

The different hydrogeological formations characterizing the groundwater system in the area of concern are described in Table 3 below (Mjemah, 2007).

AQUIFER	PERIOD	EPOCH	LITHOLOGY
Unconfined	Quaternary	Pleistocene to recent	Fine sand to medium sand with silts and clay, coral reef limestone and calcareous, alluvial clay, silts and gravels
Aquitard	Quaternary	Pleistocene to recent	Clay, sandy clay (clay)
Semiconfined Aquifer	Quaternary	Pleistocene to recent	Medium to Coarse sand and gravels with clay
Aquitard	Neogene	Mio-pliocene	Clay-bound sands

Table 3 - Hydrogeological scheme

The unconfined aquifer consists of fine to medium sand, with varying percentages of silt and clay. For the high percentage of sand, it is defined a sand aquifer, which is considered the most important aquifer for water supply.

The semi-confined aquifer consists of medium to coarse sands.

The lower aquifer overlies the substratum formed by Mio-Pliocene clay-bound sand and gravel (Mjemah, 2007) and kaolinitic Pugu sandstones.

The clay aquitard consists mainly of clay-bound sands.

Near to the coastline, there is a limestone aquifer comprised of reef limestone from the Pleistocene to the recent age, which is often in contact with the sandy aquifer underlying it.
Assessment of the hydraulic parameters of the different aquifers, estimated through pumping test data analysis, produced the following values: for the upper aquifer average hydraulic conductivity is around 1.6 m/d, and for the lower aquifer it is around 2.1 m/d (Van Camp M. et al., 2012).
The major source of renewable groundwater in the Pleistocene aquifer is rainfall during the rainy seasons. The groundwater flow generally follows the topography: the topography rises from east to west, and groundwater levels rise and groundwater depth increases in the west, discharging in the Indian Ocean.
The area of study has four main rivers, Mzinga, Kizinga, Msimbazi, and Mbezi, and several seasonal streams. The first three are perennial, while the Mbezi River is seasonal.
The lithology of the drainage basin could play an important role in river flow: the Mbezi River, in the clay-bound sand deposits, favors runoff and reduced groundwater recharge; the Kizinga River, located within the coastal plain where sandy sediments favor infiltration, feeds river flow during the dry seasons; the Mzinga River, on the border of the coastal plain and the clay-bound sand area, is affected by both influences (Mjemah, 2007).

3.2 Seawater intrusion assessment

3.2.1 Hydrochemical Framework

<u>Present assessment</u>
Seawater intrusion implies two main hydrochemical processes:

- Mixing between fresh water and sea water;
- Modifyng phenomena due the water-rock interaction.

The first process supposes changes in the composition of water (meaning an increase in mineralization); the second involves the mixing water of two different chemical phases, which originates water that is initially in disequilibrium with the rock. This water approaches a new stage of equilibrium with the groundwater, producing water-rock interactions determined primarily according to lithology. This behavior implies the existence of overlapping processes.
First of all, to identify the facies of Dar es Salaam's coastal groundwater, all samples related to the June 2013 campaign have been plotted in a Piper diagram (Figure 11).
In general, all the waters are located in the areas corresponding to chlorinate or sulphated facies.

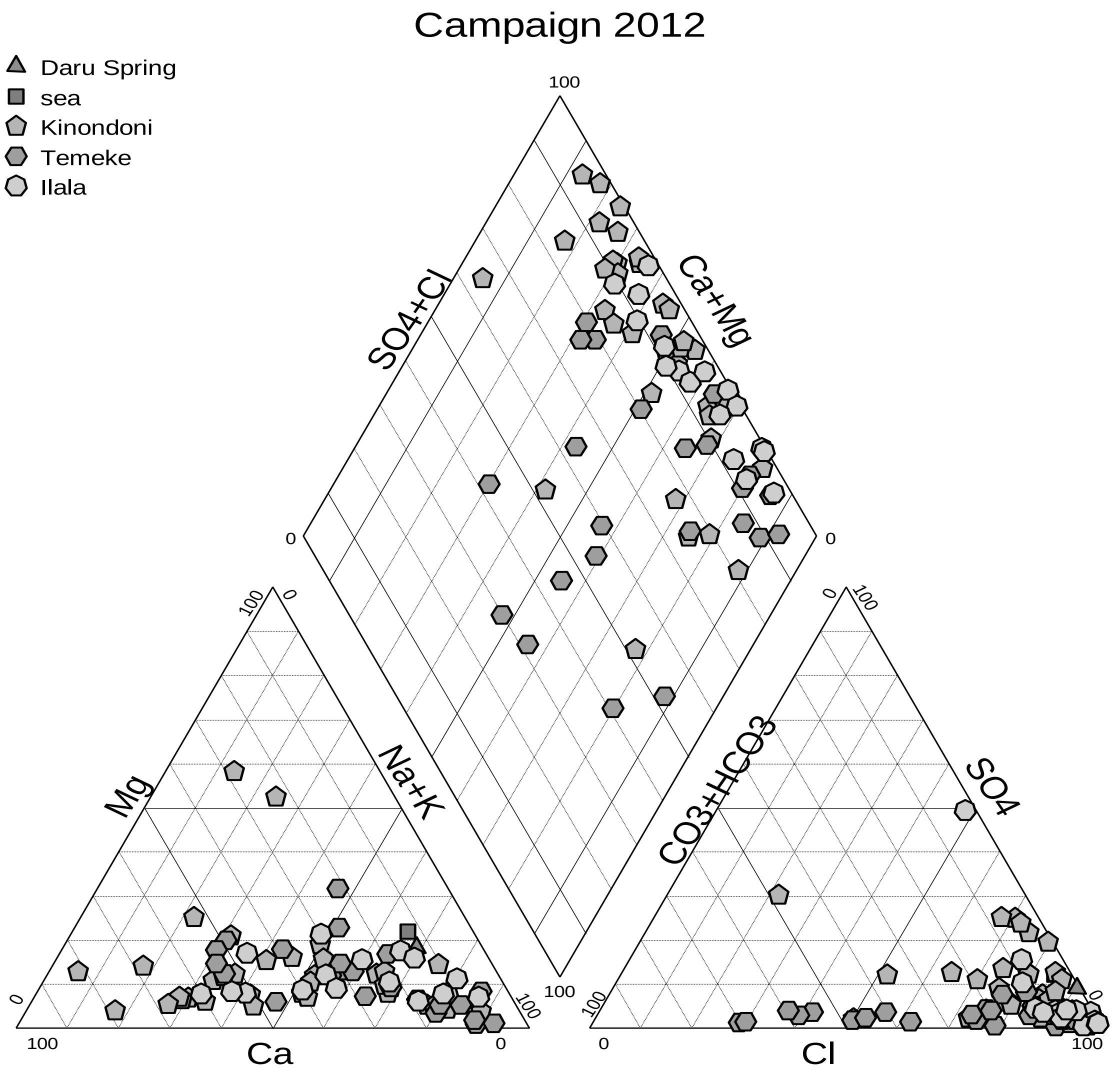


Figure 11 - Piper Diagram of groundwater samples referred to the study area

The distribution of the representative points of the samples on the anionic triangle, facilitated differentiation of three groups, corresponding almost exactly to the three districts in the study area: Kinondoni, Ilala, and Temeke.

Samples coming from Kinondoni seem to be more a calcium chloride-sulphate type and less a sodium-chloride one. On the other hand, most of NaCl types were found in Ilala and Temeke, where the Daru Spring sample was also taken. This water type is particularly influenced by saline water ascending through faults, probably from deep marine Miocene Spatangid Shales (Mjemah, 2007).

A third group characterized by calcium –bicarbonate type is present in the southern district.

Although the analysis, based on this classification, suffers from the lack of information regarding whether each sample came from the lower aquifer or the upper one, it is evident that the water types found in the study area are influenced by the recharge mechanism of the coastal plain, as further surveys confirm.

To understand the relative importance of chlorinated and sulphated facies on overall salt content, the respective relationships between these parameters are shown below. In Figure 12, TDS is compared with the sum of chlorides and sulphates, revealing a strong linearity among the samples represented. It therefore appears that the salinity of a majority of the samples depends mainly on Cl and SO4 ions.

Despite the possibility that aquifer waters reflect a mixing process between three water types, the present hydrochemical study assumed that the principal process occurring in the aquifer is the mixing of intruding seawater and freshwater (albeit characterized by high salinity) that feeds laterally. The main process that takes places in detrital aquifers is the ionic exchange, which implicates mostly the major cations Ca, Mg, Na, and K.

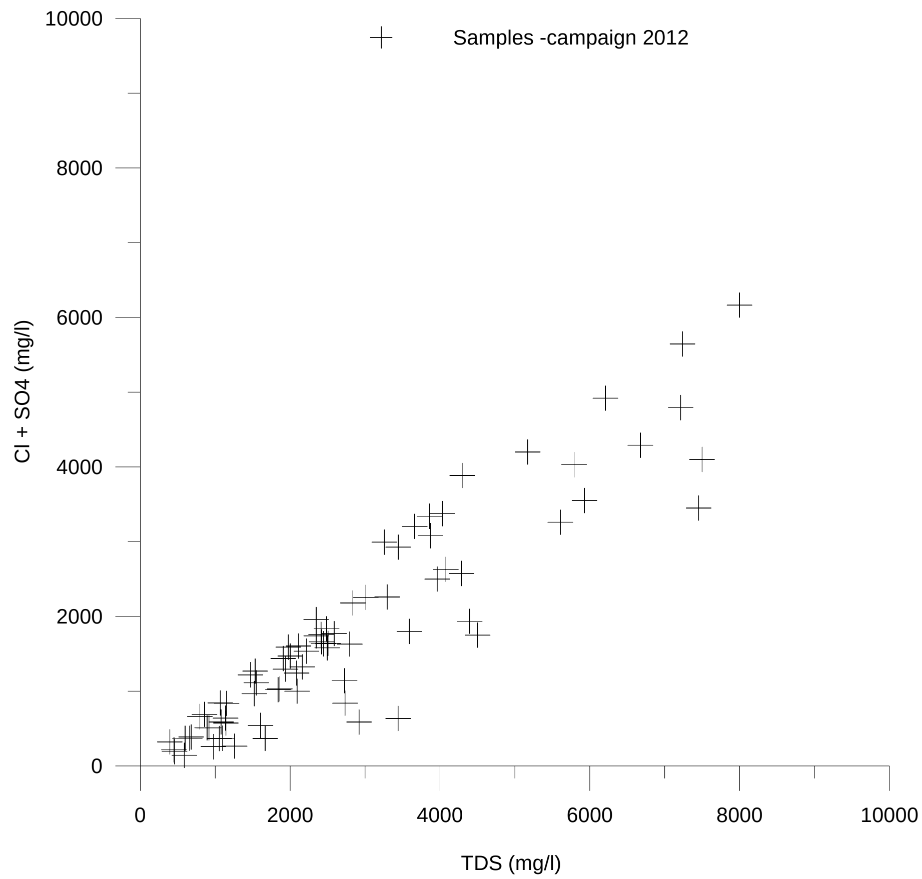


Figure 12 - TDS vs Cl+SO4 in samples collected in 2012

When salt water intrudes into an aquifer containing fresh water, there is generally a reverse-type exchange, which involves a decrease in the concentration of Na and a parallel increase of Ca in the water. On the other hand, when fresh water displaces salt water there is a direct exchange. Potassium commonly follows sodium in the process, like magnesium does with calcium, usually when fresh water has a calcium-magnesium bicarbonate character. However, is important to note that the seawater is an important source of Mg, which implies, at the beginning of the process, an exchange of Mg with the Na cation. In any case, the behavior of Mg depends on many factors (chemical composition of the water, nature and structure of the clay, redox potential). As a result of ion exchange, the concentration of Na (K, Mg) increases or decreases in the water according to the loss or enrichment of Ca (Mg). Obviously, these changes in Mg and Ca content in the water interferes with the above process when the same type of ion is present, so that if the change causes an increase in Ca the precipitation of calcium carbonate can be facilitated, while a decrease may cause the reverse reaction. All these aspects are particularly evident in the processes that occur in the study area. Considering chloride to be representative of the proportion of seawater intruding into the aquifer, the study of graphic correspondences between it and the other major ions, and the correlation of the samples relative to the conservative mixing line (built through the two end members: seawater and fresh water), is useful in identifying processes annexed to the mixing phenomenon. The following plots (Figure 13 and Figure 14) show the concentration of major cations of the samples taken during the 2012 campaign, distinguished by district. For each district were chosen as fresh end member, water of deepest borehole between those most fresh available and as salty end member the Indian ocean water sample.

The analysis of the distribution of the samples shows that a small group of them follows the conservative mixing line, instead, an important group, taken mainly in the Kinondoni district, highlights an enrichment of calcium ions and a depletion of Na, K, and Mg, typical of an inverse cation exchange. By plotting the same ratio for single districts, specific sectors of the study area can be identified. The Kinondoni group (Appendix A) reflects behavior attributable to inverse ionic exchange for the following boreholes: KIN01, KIN02, KIN09, KIN010, KIN011, in the NE sector; KIN033, KIN037, KIN038, and KIN039 for the SW sector, and KIN023 in the SE sector. Sectors affected by seawater intrusion appear to be fewer in Ilala and Temeke: samples from ILA002, ILA004, ILA017, ILA009, and ILA011 for the former and TEM06, TEM008, TEM009, TEM011 and TEM025 for the latter. For these two groups, it is interesting to observe that the first follows the phenomenon observed in Kinondoni, while Temeke shows intrusion only along the coast.

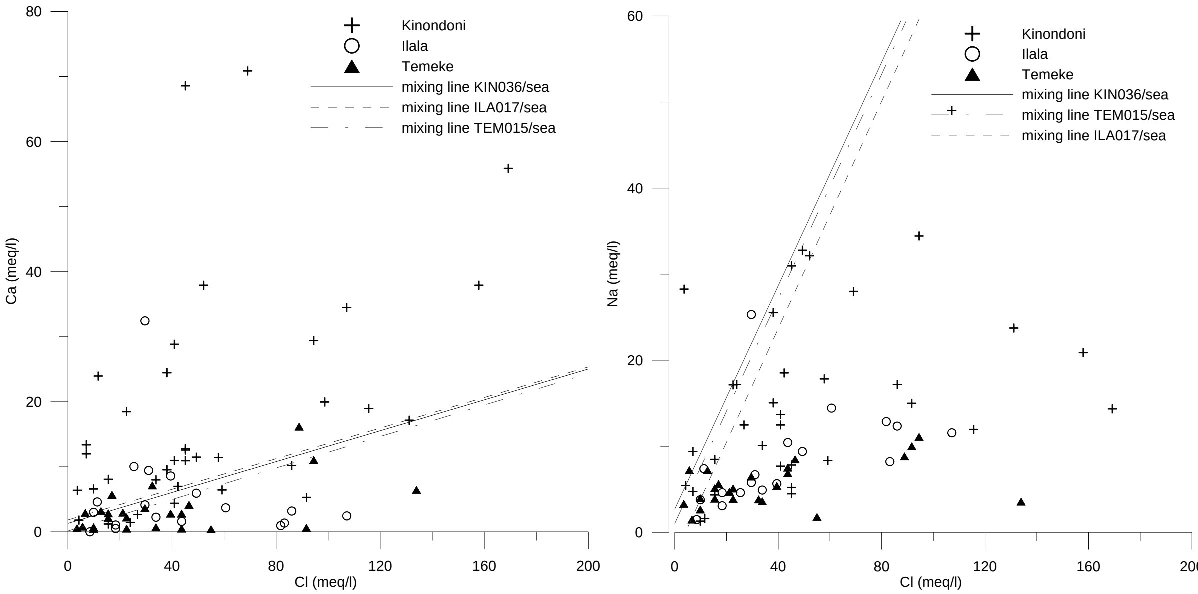


Figure 13 - Ca and Na vs Cl concentration of the 2012 campaign data, distinguished by districts

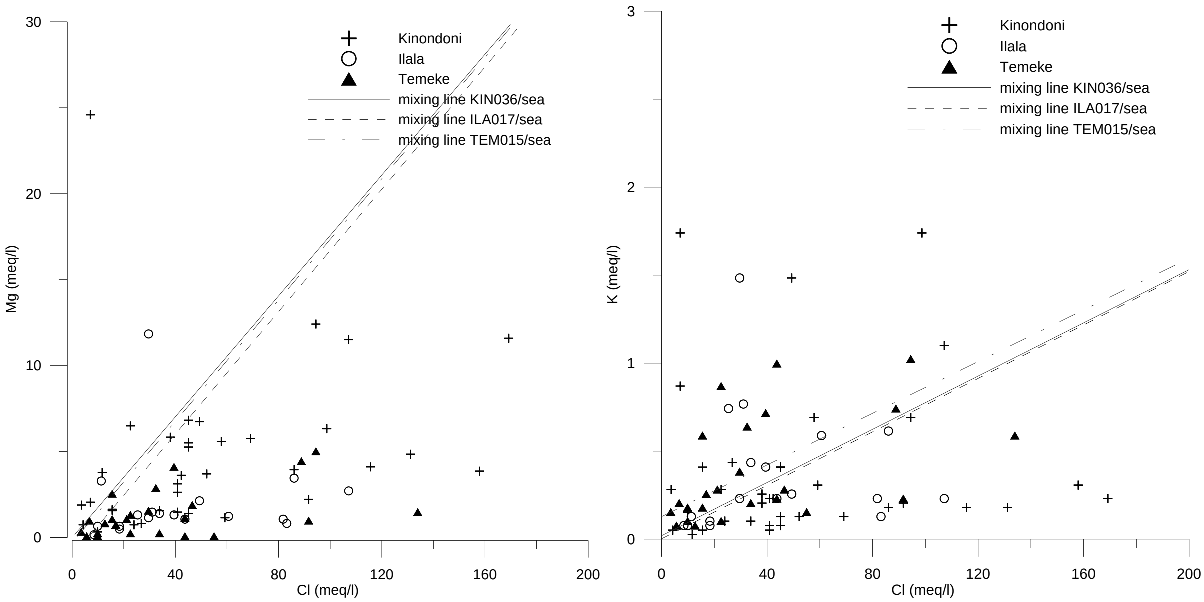


Figure 14 - Mg and K vs Cl concentration of the 2012 campaign data, distinguished by districts

All sectors affected by seawater intrusion are highlighted in the map shown in Figure 15.

Figure 15 - Sectors affected by seawater intrusion

In order to summarize the results of the analysis described so far, the following example from the Kinondoni district plots ionic delta versus chloride increase (Figure 16):

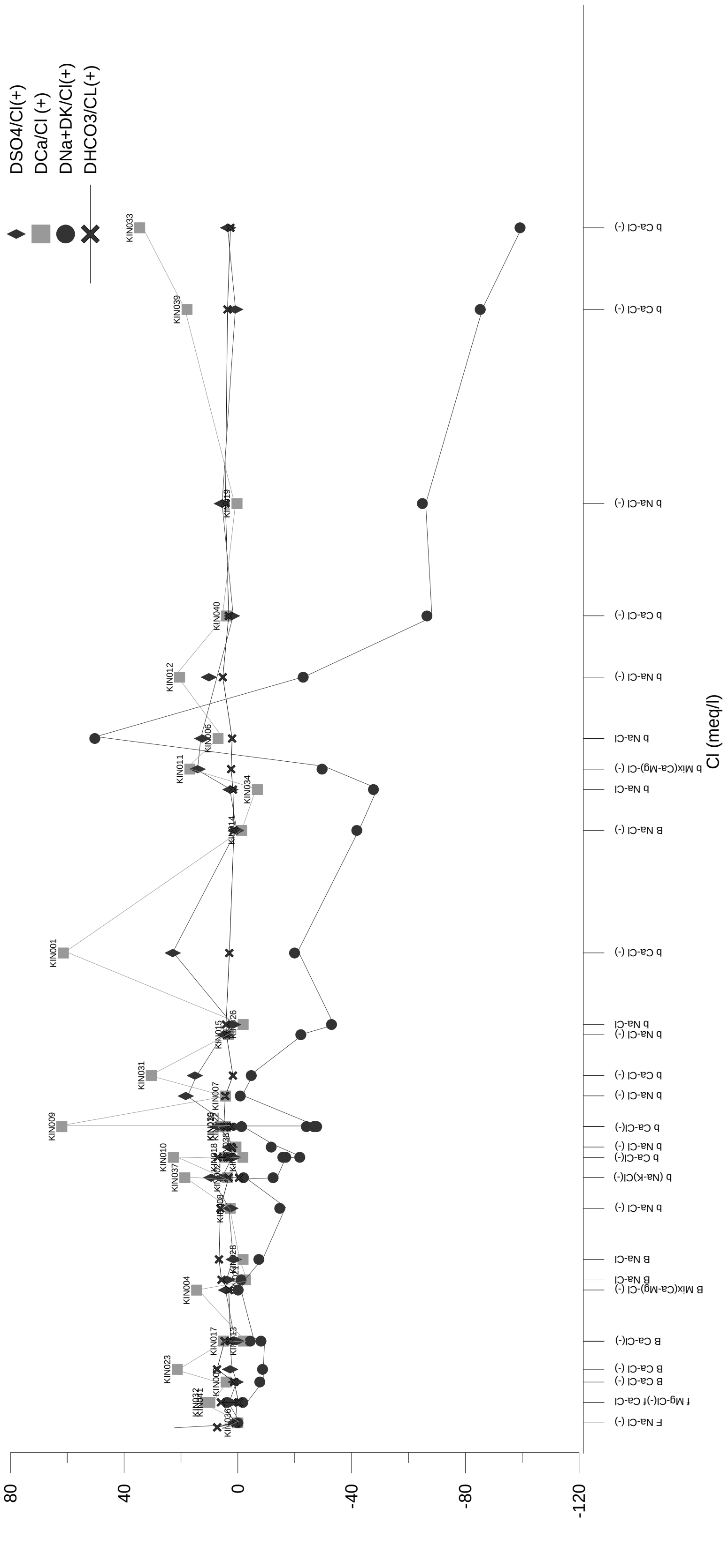


Figure 16 - Ionic delta versus chloride increase for Kinondoni district

A majority of the samples indicate a positive ΔCa, while the ΔNa + ΔK is negative. Moreover, this behaviour is even more evident as the chloride ion content increases, and it is very clear in areas subjected to a process of seawater intrusion: specifically, boreholes KIN001, KIN009 and KIN012 in the north and KIN033 and KIN039 in the south. It is interesting to observe the water types of these samples: all of them, according Stuyzfand's classification are bCa-Cl(-), that is:

- a brackish-salt water, due to a salinity content greater than1000 mg/l;
- belonging to the calcium-chloride family, with a negative ΔNa, typical of a water resulting from an inverse cationic exchange.

On the other hand, samples coming from boreholes KIN014 and KIN019 show a bNaCl water type, indicating a simple mixing phenomenon.
Results of the ionic delta analysis, carried out in the whole study area, suggest that the ionic exchange that occurred in the clays in contact with salty water significantly involves only Ca, Na, and K. With this approach, it seems clear that when ΔCa positive is compared with the amount of ΔNa and ΔK, a linear relationship is obtained. However, when these parameters are compared graphically (Figure 17) to confirm whether this process is actually responsible for the observed variations regarding the theoretical mixture, ΔCa values are greater than the sum of ΔNa + DK. It follows that there is an excess of Ca, which cannot be justified by ion exchange processes.

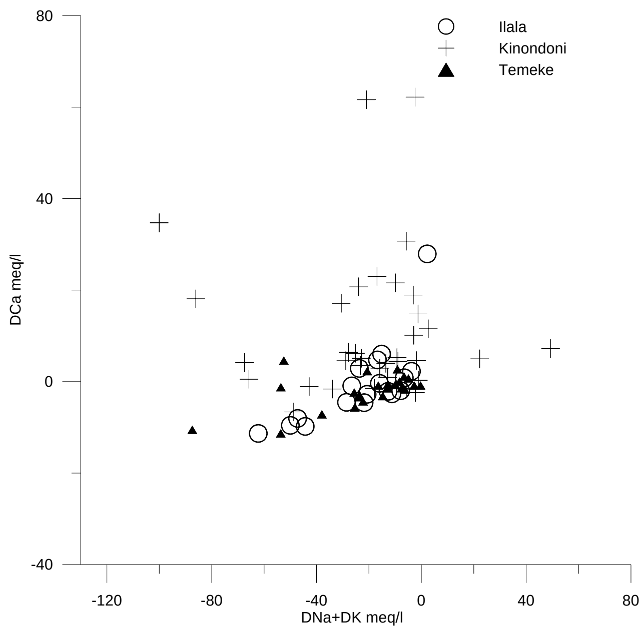


Figure 17 - ΔCa vs ΔNa+ΔK in samples referred to the study area

In order to determine the possibility that such excesses relate to process of carbonate solution, the contents of Ca have been compared with HCO3 concentrations in all waters.

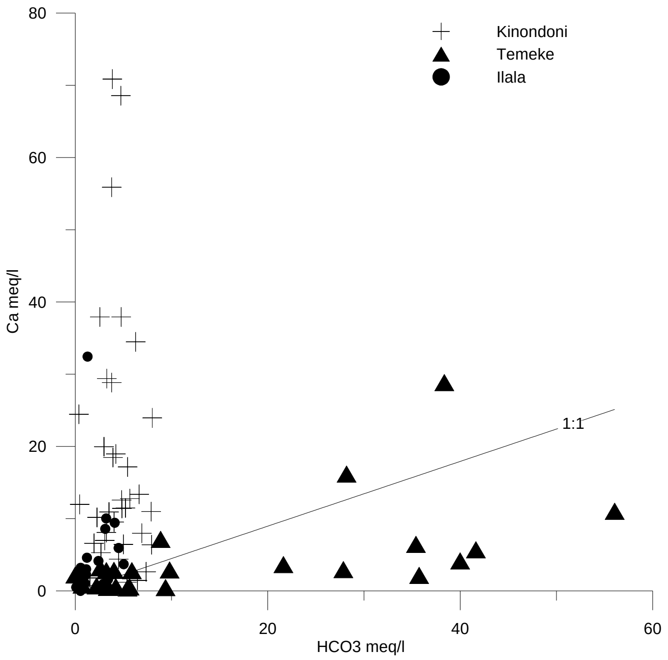


Figure 18 - Relationship between the content of Ca and HCO3

Most samples, especially in the Kinondoni district, are located straight above the 1:1 line, which defines the presence of dissolution of CaCO3.

<u>The Historical evolution</u>

In order to analyze the temporal evolution of the phenomenon of seawater intrusion into the Dar es Salaam aquifer, the available historical data have been grouped by year, thus allowing for a sufficient number of samples and to cover the whole area study. The analyses described above were also carried out for the available historical data, particularly for the group of years 2001-2002-2003. According the plots shown in Figure 19, the areas affected by intrusion according to 2012 data were already subject to the same processes in the three years 2001, 2002, and 2003.

The lack of systematic historical data and the fact that very few samples of historical analysis correspond with those of wells investigated in 2012, require further considerations, which are shown below in order to highlight in detail the evolution over time and the exact spatial extent.

Figure 20 plots the wells of the 2012 campaign for which historical chemical analyses are also available for 2001,2002 and 2003 or 2006, 2007, 2008, and 2009.

Although they represent specific situations, their distribution in individual districts and the general behaviour of their TDS, Cl, and SO4 content allow for the recognition of an evolutionary trend characterized by an increase in salinity in the study area (Figure 21, Figure 22, Figure 23).

Figure 19 - Sectors affected by seawater intrusion (2001)

Figure 20 - Boreholes where samples were taken in 2012 and in previous years

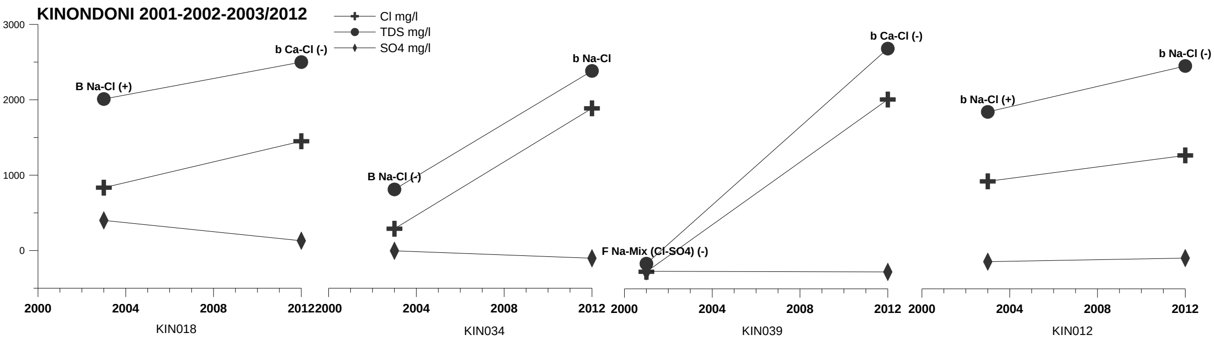


Figure 21 - Increasing concentration of Cl, SO4 and TDS in boreholes of Kinondoni, with samples analyzed as in 2012 as in previous years

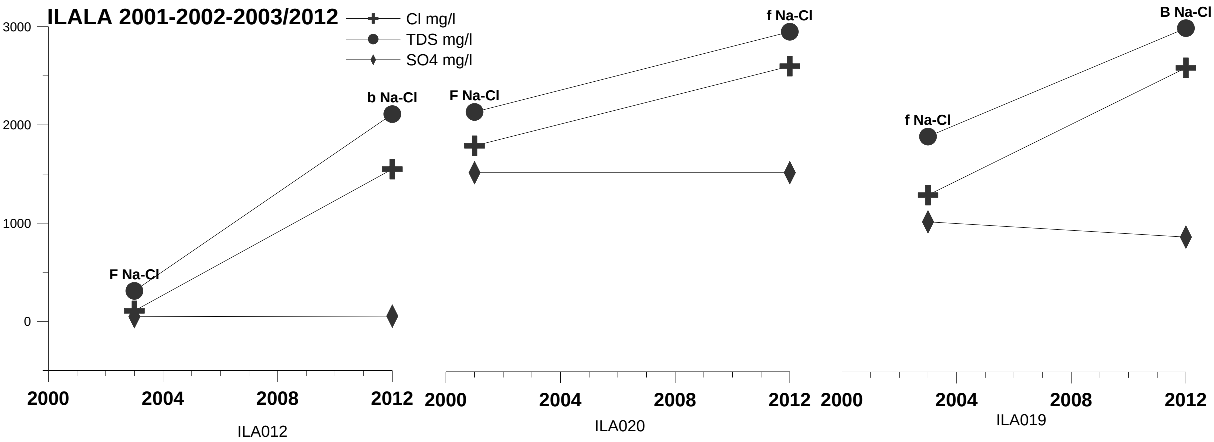


Figure 22 - Increasing concentration of Cl, SO4 and TDS in boreholes of Ilala, with samples analyzed as in 2012 as in previous years

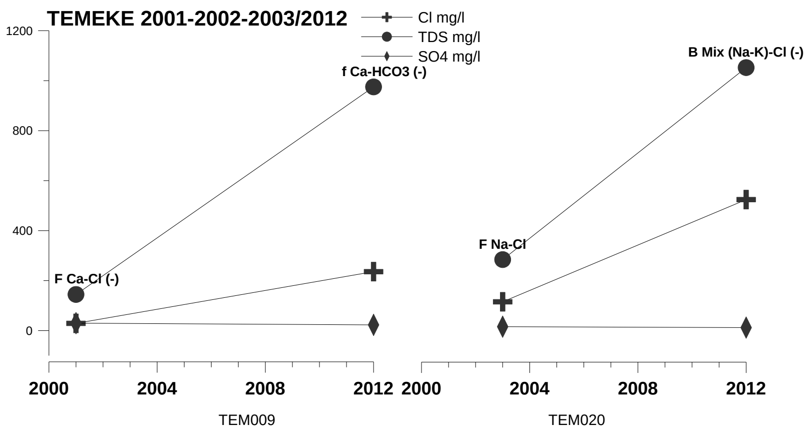


Figure 23 - Increasing concentration of Cl, SO4 and TDS in boreholes of Temeke, with samples analyzed as in 2012 as in previous years

This is particularly evident in the Kinondoni district where wells were monitored over three different groups of years (Figure 24). The evolutional trend of TDS is progressively accompanied by an increase in Cl from 2004 to 2012.

Moreover, in some of the wells described above, it is very clear the change of facies of groundwater, as a typical process of an ongoing saltwater intrusion, over the years. For instance, KIN018 (in Msasani), which was already salinizated in 2003, and KIN039 (in Makurumula), with a lower chloride content in 2001, have become a BCA-Cl (-) water in 2012 (Figure 21). Even faster is the change of facies referred to wells KIN08 (in Kunduchi ward) and KIN014 (in Kawe ward): both of them starting from a fresh watertype, acquire a salt water types during the last 7-8 years (Figure 24).

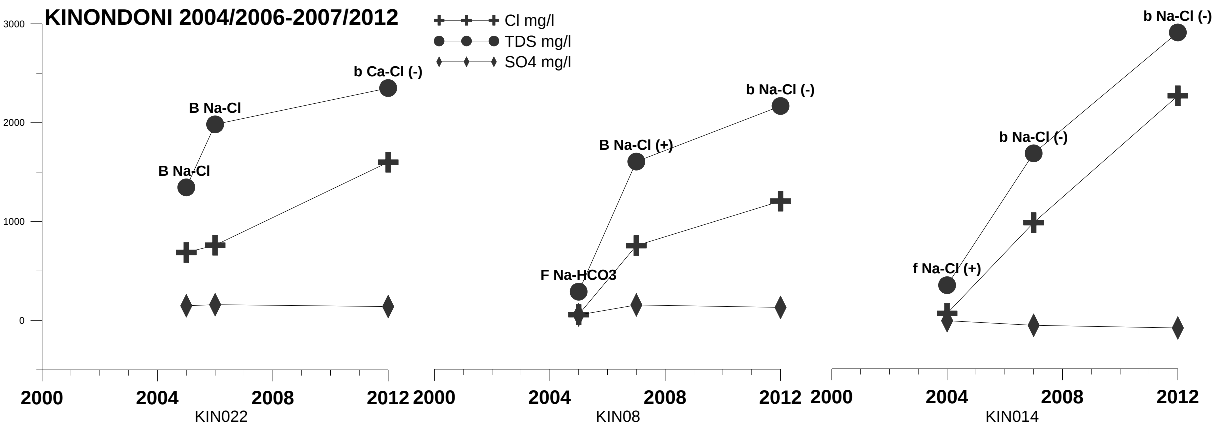


Figure 24 - Increasing concentration of Cl, SO4 and TDS in 3 boreholes of Kinondoni, with samples analyzed as in 2012 as in previous years

Based on the set of all available historical data, four series of maps have been developed in order to depict the temporal evolution of saltwater intrusion that affects the study area from a spatial point of view.

The iso contents of TDS, Cl, SO4, and Electrical conductivity, are represented for the following groups of years: 2001-2002-2003, 2004-2005, 2006-2007-2008-2009, 2012 (Appendix A).

In all of those groups, the chloride iso content lines are well suited to represent TDS distribution, indicating that the process of seawater intrusion is the main cause of the increase in the salt content of the water.

The more salinized areas, characterized by values increasing over time, are in the northern and south-western sectors of Kinondoni and the north-western sectors of Ilala.

These areas correspond in broad outline with SO4 iso content and EC lines, which indicate the greatest increase in the northern sector of Kinondoni.

It is important to highlight that the high values of TDS, recorded in the southern sector of the study area (corresponding to the district of Temeke), could be due, not only to the phenomenon of saltwater intrusion, but also to high concentrations of nitrates, as shown in the map below (Figure 25). Nitrates are likely contributed by pollution originating from the use of pit-latrines and fertilizers for urban agriculture (Mjemah, 2007).

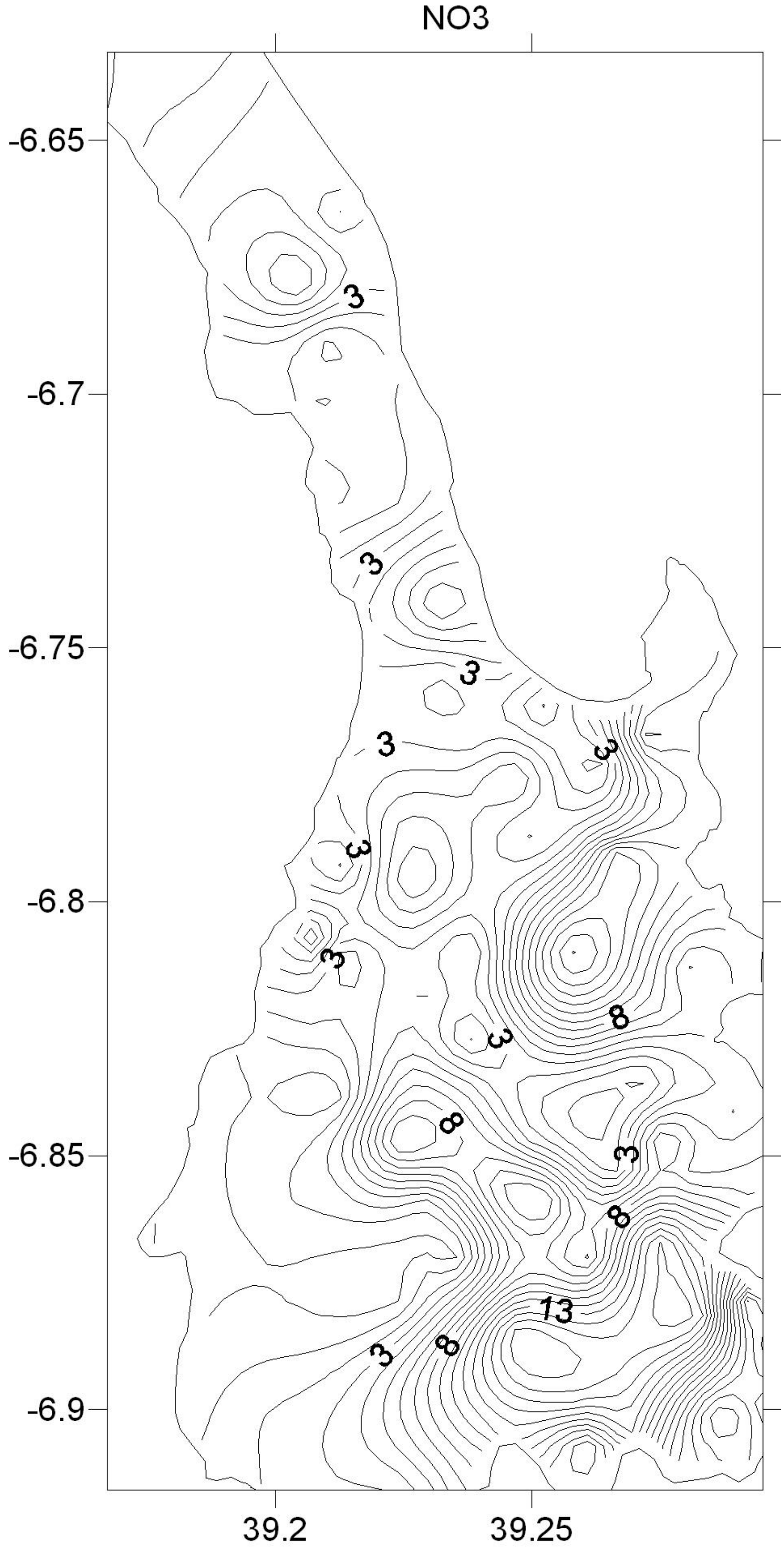


Figure 25 - Nitrates distribution (2012)

On the basis of the analysis carried out so far, and in light of the differences in chloride and electrical conductivity, calculated between the years 2001 and 2012, the following priority sectors of the study area that need systematic monitoring can be identified:

- Kunduchi and Kawe, in the north;
- Ubungo, Mabibo,Manzese,Tandale,Ndugumbi and Makurumula in the centre;
- Mikocheni and Msasani on the eastern coast;
- Keko, Miburani,Yombo Vituka ,Mbagala and Kurasini, in the south.

3.3 Climatic and anthropogenic influences on hydrogeological dynamics

3.3.1 Historical evolution of groundwater table

The findings discussed in the following are supported as by the historical piezometric surface analysis, based on local evidence derived from the comparison between measurements referring to the same point in different years.

There are very few boreholes where the measurements of static water level have been repeated at least once in the last ten years. This is one of the reasons that it was so difficult to set up comparable piezometric surfaces referred to different years, using only GIS supported software. Moreover, in an urbanized area the real static level is rarely determinable, as the measured level can be affected by groundwater exploitation via nearby wells. On the other hand, the hydrogeological assessment of the area under study, reported below, outlines the presence of a deeper, semi-confined aquifer as well as a shallower, unconfined one. As the boreholes are of very different and sometimes unknown depths, in many cases the measured static water level of the aquifer was unclear. Since this is an area with a scarce number of piezometric measures, they may not be enough to set up a piezometric surface (Van Camp et al., 2012).

For most years, the selection of measurements from the same year was not enough to set up a piezometric surface. Instead, three piezometric surfaces were constructed: one based on 2003 data (Figure 26) and two based on the measurements carried on in 2012 (Figure 27 and Figure 28)

The two more recent maps have been plotted to check the correct interpretation of the piezometric trend in the area under study and to identify variations of static groundwater level in different seasons. In spite of the problems outlined above, interesting considerations regarding piezometric evolution in the area under study can be formulated.

As a matter of fact, the comparison between the piezometric levels, plotted for 2003 and 2012 reveals a decrease in groundwater resources over the last decade.

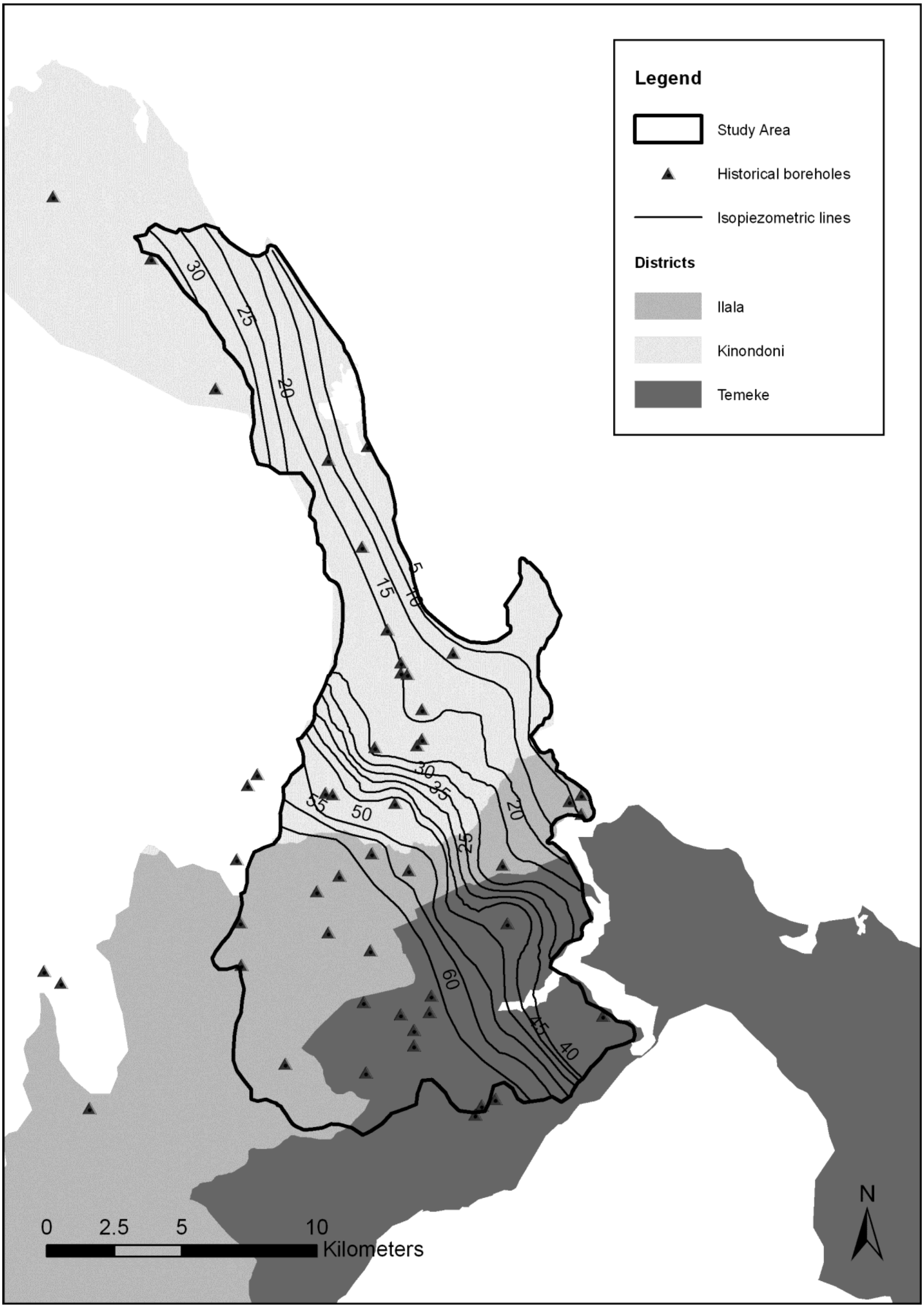


Figure 26 - Piezometric map (2003)

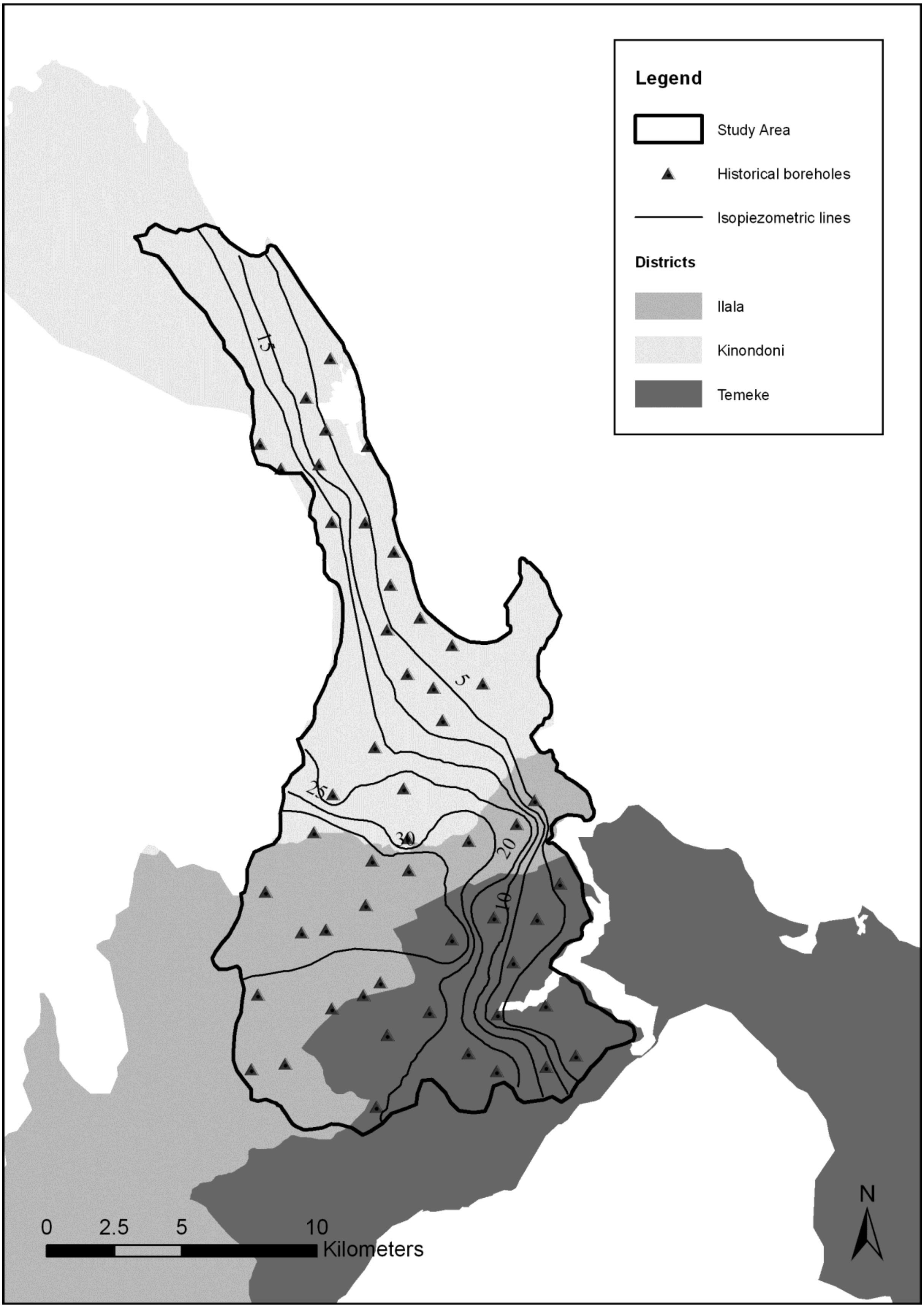


Figure 27 - Piezometric map (June 2012)

Figure 28 - Piezometric map (November 2012)

Starting from the north part of the area, for instance, it is quite clear that the isopiezometric line of 5 m.a.s.l., which was quite close to the coastline in 2003, had receded about 600minland from the coastal line in 2012. If we estimate the piezometric gradient is about 8*10-3in this area, a value very close to the one given in the literature (Mjemah, 2007), this means that there has been a groundwater level drawdown of about 5 m in the last ten years. This trend is locally confirmed by the difference of about 2 m between the value recorded in 2004 and 2012 in borehole KIN006. On the other hand, the comparison between measurements from June and November 2012 shows that in this part of the study area under is lower than 0.5 m. In the middle part of the study area, the regional withdrawal of isopiezometric lines is confirmed, and locally it is more pronounced than in the north. In fact, the 2012 static level in borehole KIN039 was 22 m.a.s.l., while in 2001 it was 30 m.a.s.l.. The seasonal difference between June and November is never more than 0.6 m. In southern part of the area under study, the groundwater table level shows the same drawdown trend as in the more northern parts. However, in the area farther from the coast line the drawdown of the groundwater table seems to be greater, with a difference of more than 10 m from 2001 to 2012 based on the values for borehole ILA020, which had dropped to 28.72 m.a.s.l. in June 2012, while in 2001 it was at more than 40 m.a.s.l.. In this part of the area under study they have been calculated differences in seasonal measurements of static groundwater level till 2 m.

The overall comparison between measurements from June and November of 2012 indicates that in 75% of the monitored boreholes the difference in static groundwater level was less than 1 m. If these two monitoring months can be considered the end members of the annual groundwater cycle, the value of 1 meter can be considered the average annual variation of groundwater level. As mentioned before, it may be that the large gap between values recorded in different years for the same borehole could be affected by the exploitation, ongoing or otherwise, of surrounding boreholes. As such, the numbers referred to above should be considered more as a trend, in the last ten years, of continuous decrease in the water table and, consequently,, of declining groundwater resources, and not as an exact evaluation of how much groundwater has been lost in the last ten years. On the other hand, one must also consider that the groundwater table drawdown could be related to seawater intrusion, and to the mixing processes between fresh water and seawater, especially in the zones close to the coastline. In fact, increasing transition zone thickness in coastal aquifers, due to improved breaking processes of fresh water, has been shown to drive drawdown of the groundwater table level (Tulipano, 2008). This may also be the case in the study area, especially in the north. So, the results referred to above should be interpreted as a possible result of over exploitation of groundwater, combined with drawdown due to seawater intrusion in the same area.

3.3.2 Evolution of Active Groundwater Recharge

The hydrogeological assessment of the area under study as it is sketched previously on the basis of recent references (Mjemah, 2007) reports that the active groundwater recharge of the aquifer occurs, in large part, through coastal plain infiltration. It may also occur partially through uplift from the deepest flowpaths from the Miocene geological formations of the internal hill chain, beyond the fault dividing the Pugu Hills from the same coastal plain aquifer. Elaborations and results regarding contributions to active groundwater recharge coming from the direct infiltration in the area under study are presented below. Although the

values discussed may only be part of the total active groundwater recharge of the area, this aspect should not affect the conclusions drawn.
Precipitation records for the previous 50 years, were collected in 3 meteorological stations in Dar Es Salam: JNIA, Wazohill, and Ocean stations. Unfortunately, only the JNIA station, close to the International Airport of Dar, had data for every one of the 50 years, so it is the only data set considered for in following elaborations. Other authors have taken the same approach when studying the Dar area (Van Camp et al., 2012). An Inverse Hydrogeological Budget (Civita and De Maio, 2001) was constructed by elaborating the precipitation measurements recorded at the JNIA station. In the aim of analyzing the climate change impact on active groundwater recharge in the study area, the average precipitation data for all 50 years was first considered. Data were then grouped into 5-year sets, for which average annual precipitation and average annual thermometric data were calculated. By smoothing the average values, the evolution of precipitation during the last 50 years is represented in Figure 29, which outlines a decreasing trend in annual precipitation in the last ten years and a decrease in average annual precipitation as compared with the 50-year average value.

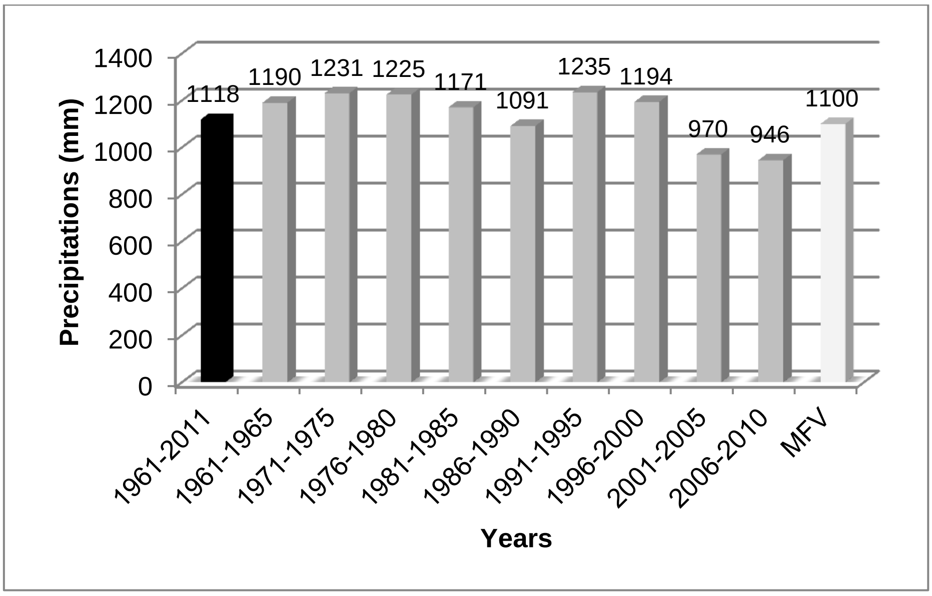


Figure 29 - Evolution of precipitations in the 1961 – 2010 period

In fact, the AAP (Average Annual Precipitation) value for 2001-2005 is 13% lower than the 50-year average, and 19% lower than the average of the previous 5 years (1996-2000). The AAP for the 5 years between 2006 and 2010, is 15% lower than the 50-year average, and 21% lower than the value for the 5 years from 1996-2000. With respect to the following elaborations, the Most Frequent Value of Precipitation (MFVP) for the 50 years of measurements was considered, because the analysis of precipitation evolution in the last 50 years as shown in Figure 29 suggests that precipitation cycles in this period seem to be about 20 years long. This means that the decrease noted over the last ten years could be reversed in the next ten. As such, the assumption that this data indicates a continuous decrease of precipitation may lead to incorrect conclusions. Application of the Inverse Hydrogeological Budget to the study area did not require the evapotranspiration. In stead, effective infiltration was calculated directly from annual precipitation values.
To evaluate the impact of climate change on active groundwater recharge various land cover conditions were also considered, as this is the second most important factor affecting infiltration and, consequently, active groundwater recharge. Land cover scenarios for 5

different years were considered. Land cover evolution in the years considered changes the infiltration capacity of the soil. Figure 30 and Figure 31 depict the difference in distribution percentages of land cover in the area under study between 2002 and in 2012. Over the last 10 years, soil, which is the land cover type with the maximum PIF value (potential infiltration factor), has decreased from 46.7% in 2002 to 26.7% in 2012.

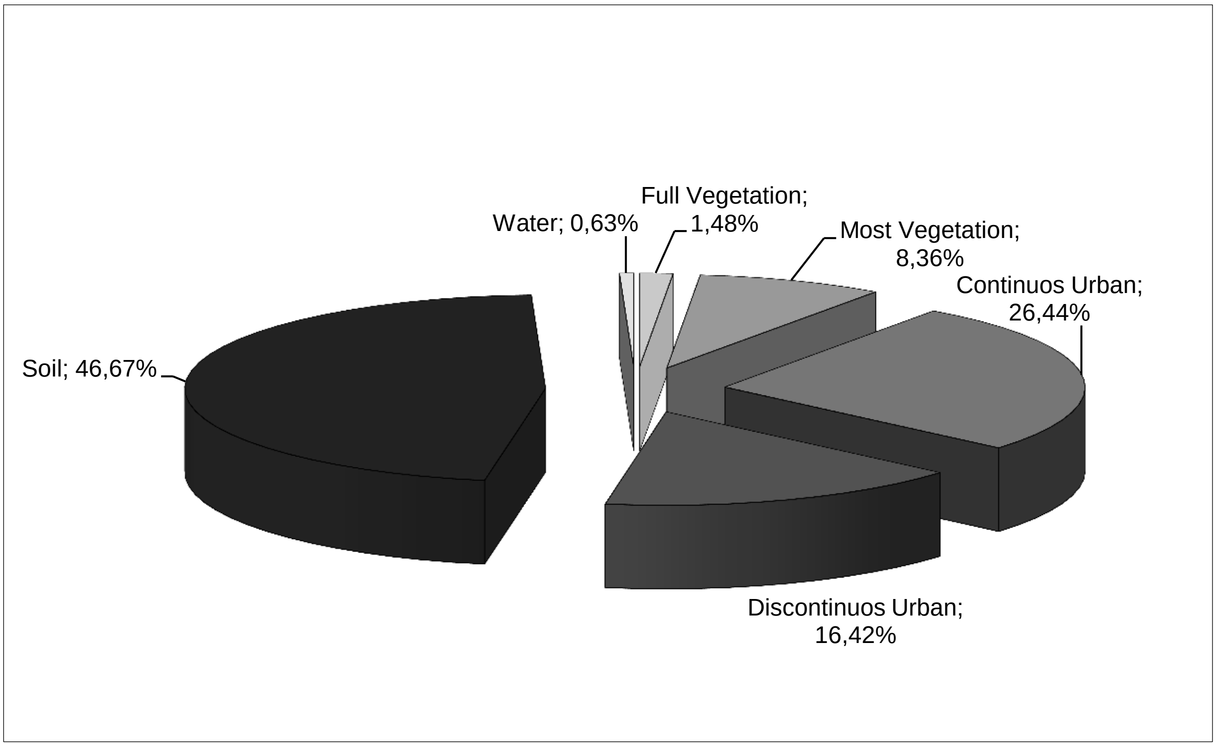


Figure 30 - Land cover distribution in 2002 (Congedo et al., 2013)

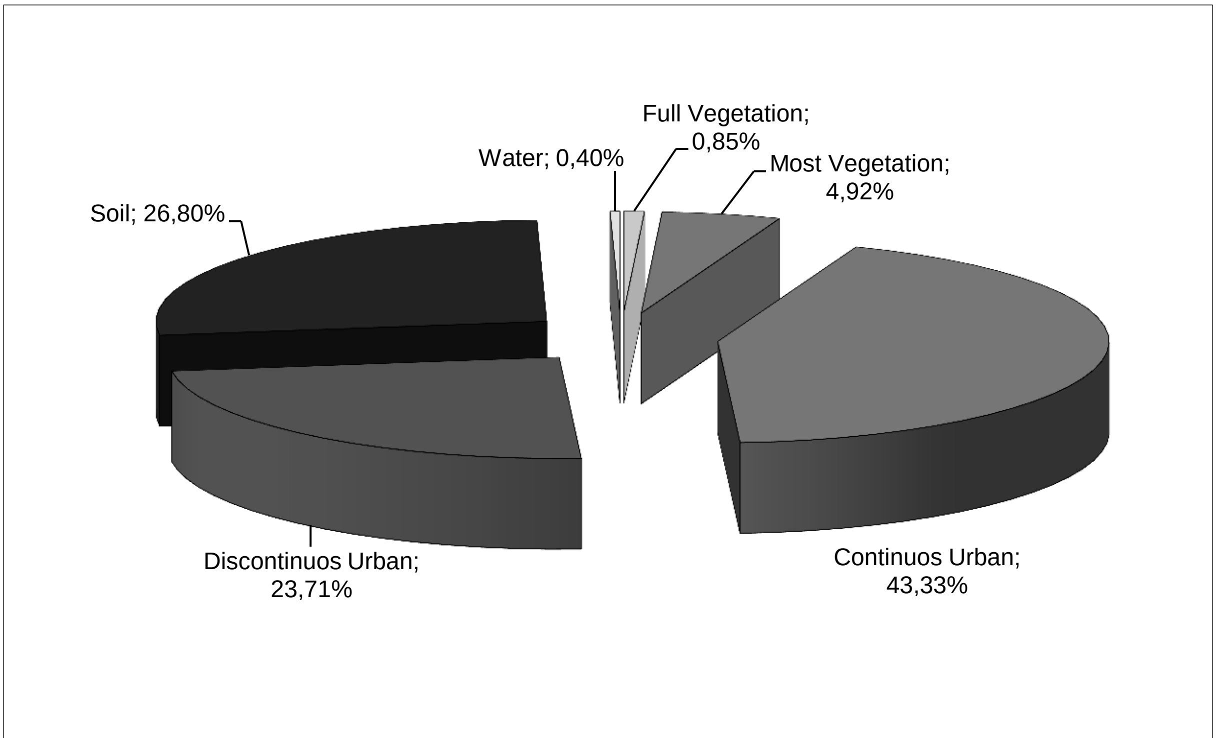


Figure 31 - Land cover distribution in 2012 (Congedo et al., 2013)

The data indicates that soil as a land cover type has decreased to less than half of its original value. Table 4 reports the Potential Infiltration Factor values of different kinds of land cover and the extension of those areas in the considered years.

Land Cover Class	Potential Infiltration Factor
Full Vegetation	0,3
MostVegetation	0,4
Continuos Urban	0,1
Discontinuos Urban	0,2
Soil	0,3
Water	0,6

Table 4 - Potential Infiltration Factor values, given to the different land cover class

In order to evaluate infiltration in the study area the following scenarios were considered. First, the Most Frequent Annual Precipitation Value, which is 1100 mm, was applied to 5 land cover different scenarios (Figure 32), with results indicating that there has been a continuous decrease in infiltration and a consequent decrease in active groundwater recharge over the last ten years. This decrease is estimated at 18.6% for that same period. Since the same precipitation value was applied for each year, corresponding to Most Frequent Value for the last 50% (and therefore the most probable) the decrease in the infiltration percentage is attributable exclusively to land cover changes.

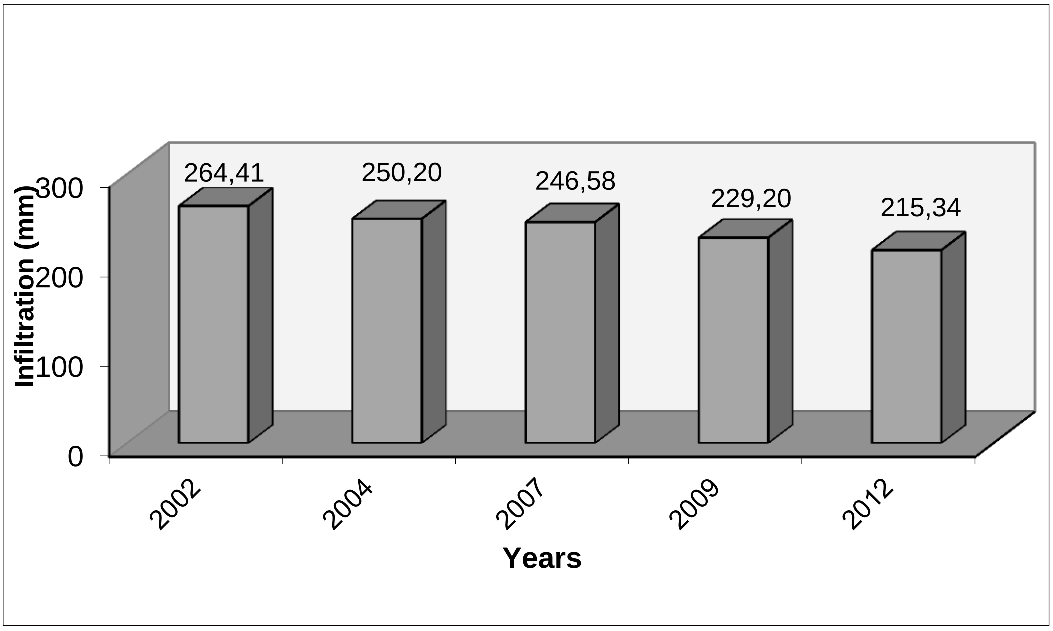


Figure 32 - Infiltration evolution depending on different land covering with the most frequent value of precipitations

For the purpose of comparison, effective infiltration in the study area, the AAP for 2001-2005, was correlated to land cover distribution referred to the years 2002 and 2004, and the same correlation was applied to the AAP for 2006-2010 and the land cover outputs for the years 2007, 2009, and 2012. The results are shown in Figure 5, which applies this deterministic method for infiltration evaluation and demonstrates that in the last ten years the loss of infiltration, due both to land cover changes and to decrease in precipitation, was 20.6%, with an average annual loss of 2%. It is interesting to note that the application of a half-statistical approach, like the first analysis, and a deterministic approach, as mentioned above, produced results very similar those obtained in the second, with a difference between the two of less than 10%.

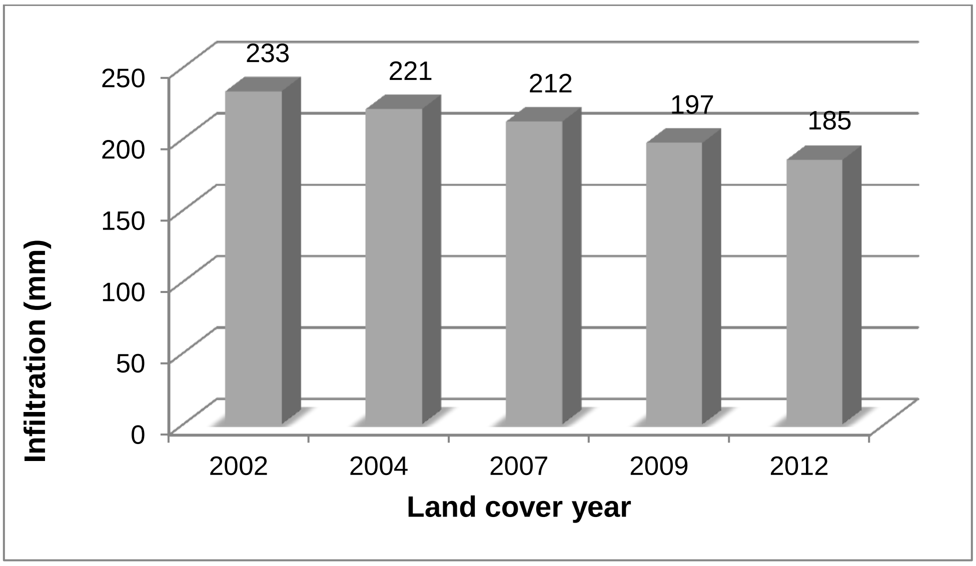


Figure 33 - Infiltration evolution depending on different land cover distributions

As regards what could happen in the future, if the infiltration trends identified through the foregoing elaborations are confirmed in the coming years, two different phenomena are likely to occur. First, the evolution of land cover, noted over the last ten years, will be likely to continue over the next ten, at the same rate. Figure 6 depicts what future infiltration values will be if the Most Frequent Annual Precipitation Value for the last 50 years, according to JNIA station data, is applied to the trend of land cover evolution recorded over the last ten years.

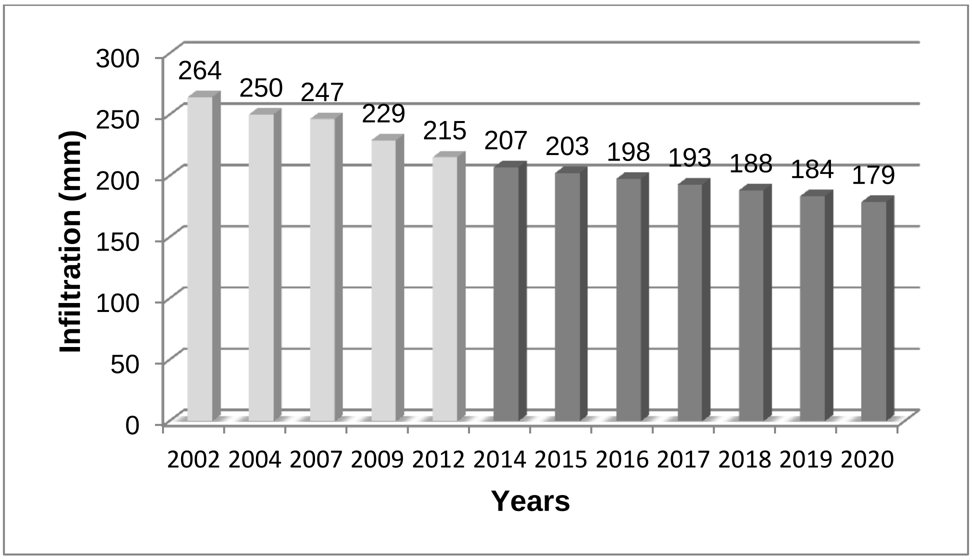


Figure 34 - Infiltration trend for the future with the MFPV and the land cover distribution trend of the last ten years

Results indicate that by 2020 there will be an infiltration loss of about 32% as compared with 2001 values, and of about 17% as compared with 2012. Also, the infiltration trend identified for the last ten years is projected to continue for the next ten. Results are presented in Figure

7, which indicate that the loss of infiltration would be of 37% with respect to 2002 values, and about 20%, if the recent trend is confirmed.

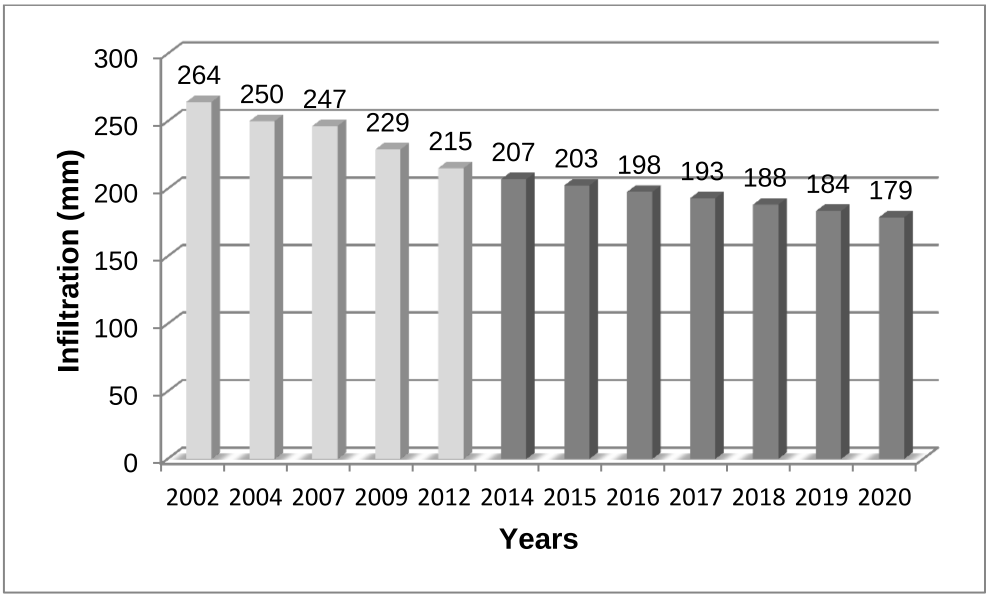


Figure 35 - Infiltration trend until 2020 applying the evolution of the last ten years

The application of these two procedures produced results that differ by about 15%. All calculations of infiltration were transposed into Active Groundwater Recharge, AGR, using the product of all these values and the extent of the study area, which has been estimated to be 254 km2. The amount of groundwater available in the study area in light of infiltration estimations is depicted Figure 36 and Figure 37.

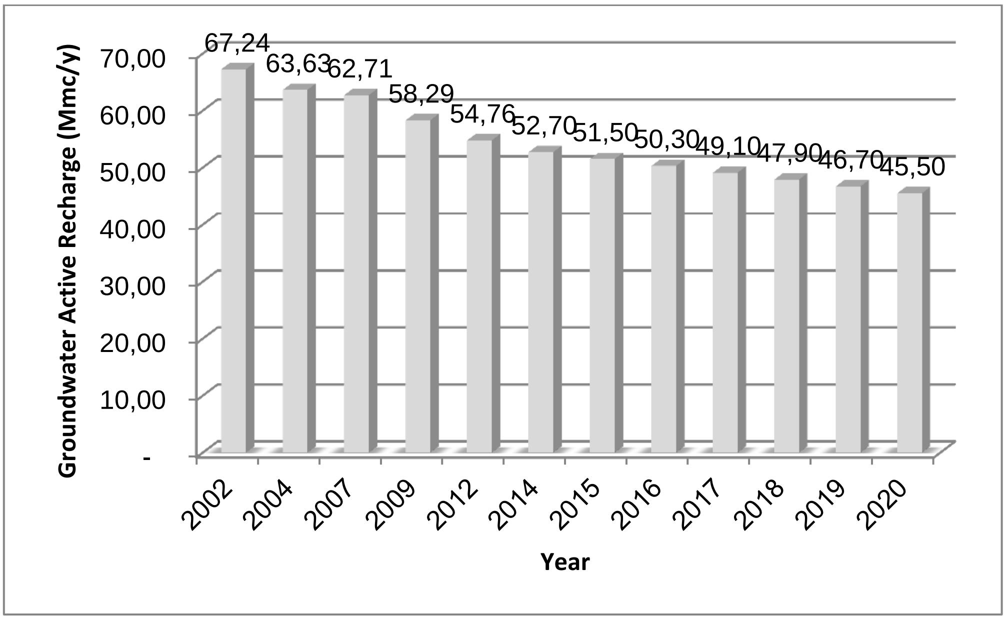


Figure 36 - Groundwater Active Recharge evolution until 2020 following the trend of the last ten years applying the MFPV

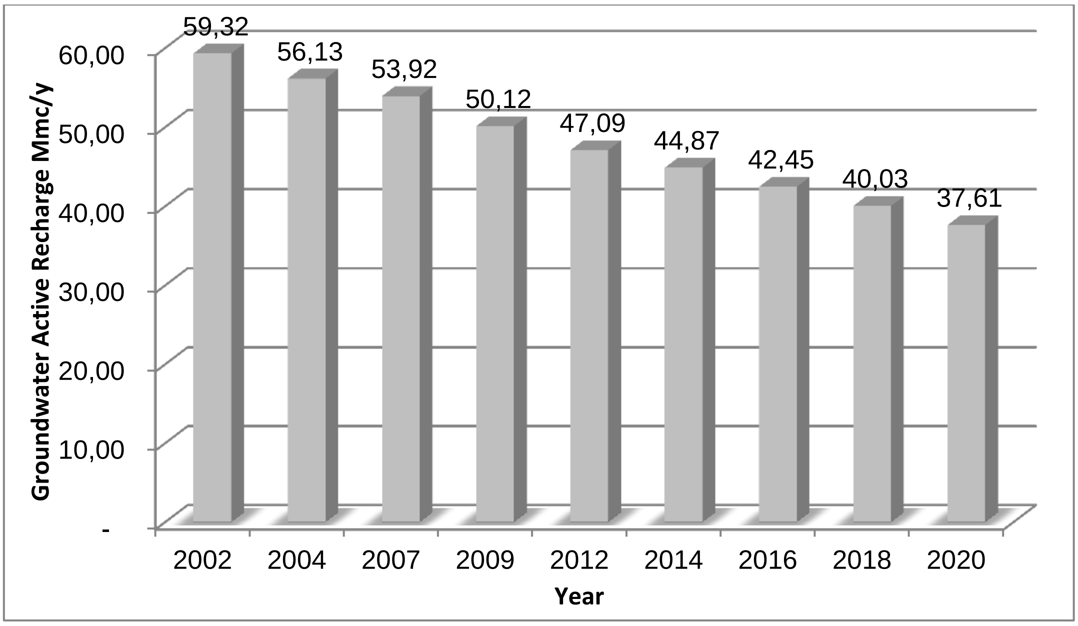


Figure 37 - Groundwater Active Recharge evolution until 2020 following the trend of the last ten years

The 2002 AGR was estimated at $67*10^6$ mc by applying the Most Frequent Precipitation Value to the land cover for that year, while it was estimated at $59*10^6$ mc by applying AAP values for the period 2001-2005 to the land cover for to 2002. Since the analysis in terms of percentages produces to same infiltration values, it is interesting to note that application of the first method produces a GAR for 2012 estimated at $47*10^6$ mc, meaning a loss in ground water recharge of about $12*10^6$ mc in the last ten years, while application of the second method indicates a loss in ground water recharge of about $13*10^6$ mc over the last ten years. For 2020, estimated loss of available groundwater is, in the first case, about $20*10^6$ mc, and in the second case, about $22*10^6$ mc.
The differences between the results produced through application of the two methods suggest that these data should be considered more as indicators of a trend, rather than a precise evaluation of the decrease in groundwater availability.

3.3.3 Water demand evolution

Demand for water in the study area depends on many factors and is satisfied in part by the water network and in part through groundwater exploitation. The present study is interested in estimating the evolution of the latter over the last ten years. Unfortunately, information on the wells in the study area is scarce (Van Camp et al., 2012) and not sufficient for setting up a numerical or statistical model capable of producing an acceptable estimation. Nevertheless, in order to reach an estimation demand for groundwater in the study area among the people living there from 2002 to 2011 was evaluated according to the demands of individuals, which have been provided in recent reports addressing the same problem (Dodi Moss et al., 2012; JICA, 2012). First, the number of people that satisfy their water demands through groundwater exploitation was estimated on the basis of information on population evolution (from 2002 to 2011), and water provision types in coastal Dar es Salaam, provided by other activities of the project (Ricci et al., 2012; Congedo et al., 2013); two scenarios were then considered, as reported in Table 5.

	Existing City[3]	Coastal plain – Existing city	
		Scenario A	Scenario B
Kinondoni	10%	50%	60%
Ilala	10%	70%	80%
Temeke	10%	80%	90%

Table 5 - Percentage of people served by groundwater exploitation in existing city and coastal plain in the parts of municipalities included in the study area.

Figure 38 depicts the estimates of the number of people in the study area who satisfy their water demands through groundwater

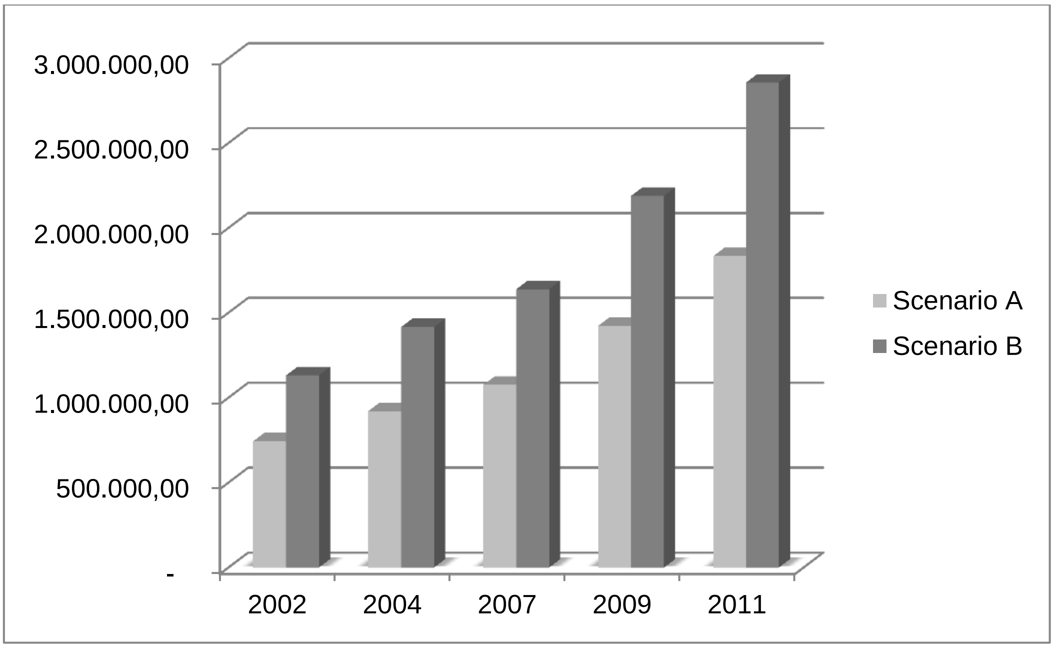
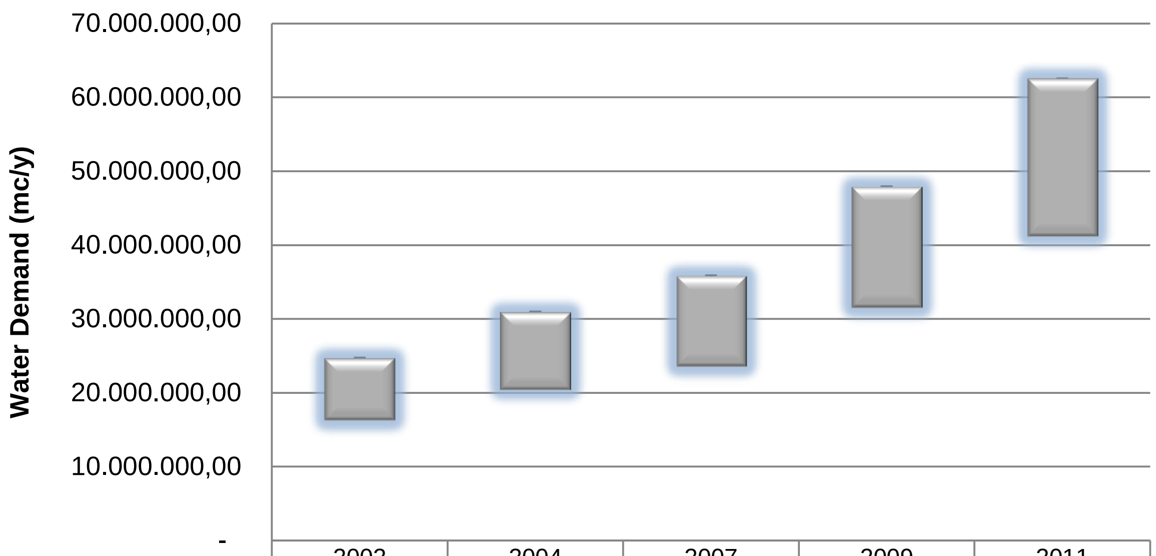


Figure 38 - People evolution in the study area in the last ten years

On the other hand, previous reports suggest two different per capita water demand values have been assigned. One is 45 l/day per person (WDPC01), as indicated by JICA (2012). The other is 60 l/day per person (WDPC02), as indicated by the most recent Master Plan of Dar (Dodi Moss et al., 2012). Four values of groundwater exploitation for each considered year have been estimated on the basis of those suggested amounts in Figure 39.

[3] Existing City: The existing urbanised area within Nelson Mandela and Sam Nujoma roads (Dodi Moss et al., 2012). It includes the city centre and the strictly neighboring areas.



	2002	2004	2007	2009	2011
Scenario A WDPC02	16.413.024,3	20.518.252,5	23.696.317,9	31.604.401,9	41.226.906,0
Scenario A WDPC02	18.579.417,8	23.255.769,5	26.914.257,9	35.954.251,0	46.920.778,4
Scenario B WDPC01	21.884.032,4	27.357.670,0	31.595.090,5	42.139.202,5	54.969.208,0
Scenario B WDPC02	24.772.557,0	31.007.692,7	35.885.677,2	47.939.001,4	62.561.037,9

Figure 39 - Groundwater exploitation evolution estimation in the study area

According to these calculations, groundwater exploitation has increased by over 150% for any considered scenario over the last ten years, and the average estimated value for groundwater exploitation in the study area in 2011 is very similar to the value obtained for Active Groundwater Recharge in 2012, as calculated and presented in Figure 36 and Figure 37. The maximum estimated groundwater exploitation value for 2011 seems to indicate that the groundwater extraction now exceeds estimated active recharge. As mentioned above, these results should be considered a general trend rather than a precise quantification. Nevertheless, they are enough to complete an assessment of the effects of the ongoing evolution in Dar es Salaam coastal plain.

4 Conclusions

With reference to the overall objective, the study allowed to qualitatively assess the current evolution of the Dar es Salaam's coastal aquifer sensitivity to seawater intrusion through the analysis of its hydrogeological evolution and of the groundwater physic-chemical characteristics.

Moreover, the main climate and anthropogenic dynamics, which have influenced the evolution of the phenomenon, were assessed through the analysis of Active Groundwater Recharge, parameter that regulates the availability of groundwater resources depending on both meteorological and land cover variables.

As regards the seawater intrusion analysis, the study was able to identify the areas where the saline intrusion must be referred to the seawater and that may become priorities for vulnerability assessment and adaptation action implementation.

They are in details (Figure 40):

- Kunduchi and Kawe, in the north;
- Ubungo, Mabibo,Manzese,Tandale,Ndugumbi and Makurumula in the centre;
- Mikocheni and Msasani on the eastern coast;
- Keko, Miburani, Yombo Vituka, Mbagala and Kurasini, in the south.

At the same time, the comparison between historical piezometric data and those from the 2012 surveys showed an important lowering widespread throughout the study area and locally related to the effect of seawater intrusion, because of the enlarging of the transition zone in the coastal areas.

Concerning the study of the temporal evolution of Active Groundwater Recharge, the temporal analysis of climatic and land cover data for the last ten years allowed to define a decreasing trend in the groundwater availability; in fact, the aquifer recharge is directly related to the precipitation portion that can infiltrate into the soil: this aspect clearly depends on precipitation and land cover.

Moreover, both of these factors have a relationship with climate change, as the first one evolution is a direct effect of it, while the urbanization dynamics partially reflect the population adaptation strategies to cope with it.

The resource availability decrease on the one hand and the increase in the estimated groundwater withdrawal on the other, point out that unplanned and uncontrolled groundwater exploitation is a significant factor of hydrogeological imbalance, which can be related to a general increase of the aquifer sensitivity to seawater intrusion phenomenon (Figure 41).

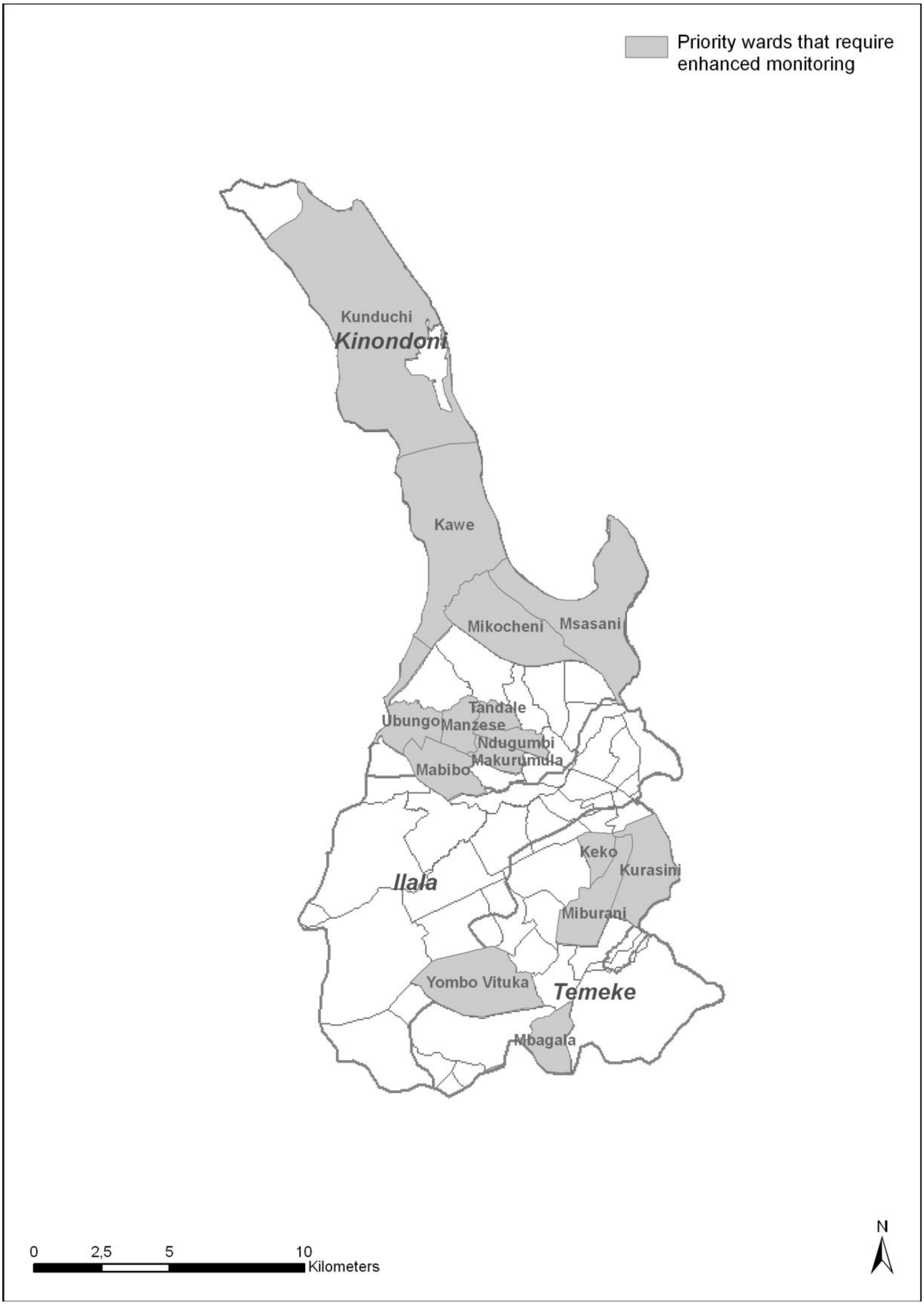


Figure 40 - Priority wards that require enhanced monitoring

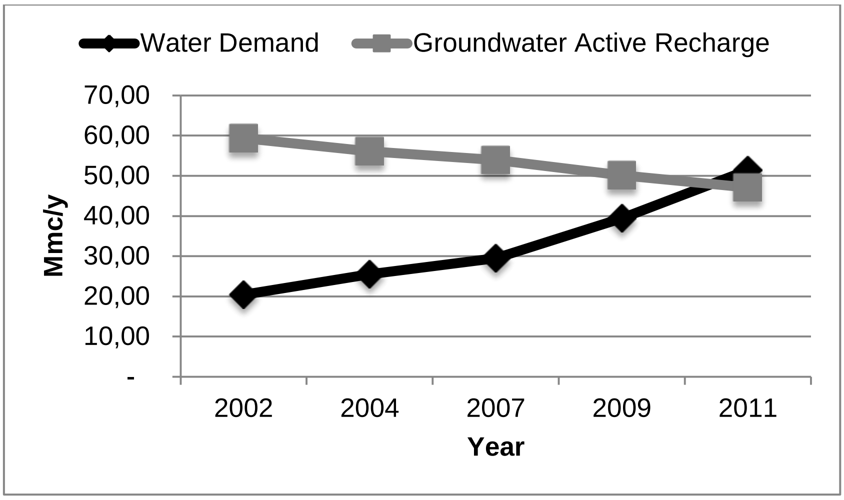


Figure 41 - Groundwater Active Recharge vs Water Demand in the last ten years

Moreover, since this assessment has been carried out on the whole coastal area, the hydrogeological unbalance, expressed in term of piezometric drawdown and seawater intrusion, could even occur in a faster and serious way at a local scale, considering the influences of the concentrated withdrawals in the areas with higher population density.

4.1 Limitations

The methodologies and tools defined and adopted in this study have proved suitable for the purposes and for the typology of available data; nevertheless some limitations can be pointed out, preventing a rigorous assessment and definition of aquifer sensitivity and groundwater availability evolutionary scenarios.

First, the activity faced with a lack of systematic historical data for the definition of the state marine intrusion in the past. The large amount of data that has been found and analyzed is referred to previous studies completely unrelated to each other: in fact, although in absolute many historical information are available, very few are the wells where measurements have been replied in time.

Since the phenomenon, by its nature, evolves slowly as expected from every hydrogeological process, the use of historical data reliable and referable to the same monitoring point would have allowed a deeper knowledge about the evolution of the aquifer sensitivity.

At the same time, for a detailed understanding of the seawater intrusion dynamics and a more accurate correlation with environmental and anthropogenic causes, it would be desirable a rigorous monitoring activity of all the levels constituting the multilayer coastal aquifer, through the use of well-made boreholes with known technical features and available for deep measurements.

On the contrary, the monitoring campaign was mainly based on private wells with unknown technical features (pump depth, number and depth of screens, etc.) and not available for deep measurements (wells equipped with pumps and pipes); this allowed to investigate just the groundwater mixing the different aquifer layers, without the possibility to analyze the parameters logs all along the aquifer depth.

In this regard, it could be useful for the local institutions to take in account the arrangement of some monitoring points for the zones identified as the highest sensitive ones, consisting of well executed wells with separate screens on each aquifer levels. This would enable to

register in continuous the logs of some of the most important parameters characterizing the groundwater evolution, like SWL, EC, T, TDS, pH, Cl.
Together with the methodologies and tools for data storage and management provided by the study, that arrangement would enable the institutions to address the above mentioned limitations and to reduce the effort required for the implementation of future widespread monitoring campaigns following the one started within this study.

4.2 Recommendations

The methodologies and the tools identified in the framework of this study are a first step to support the local institutions in identifying adaptation strategies aimed to design new water management plans as a consequence of the people vulnerability to seawater intrusion.
In detail, the project started up a first survey of the coastal aquifer specifically designed for the analysis of the seawater intrusion, with the help of specific tools for systematic data collection and management as the ACC-Dar Monitoring Boreholes Database.
This tool could be a reference for the storage of the future monitoring activities results in order to assure the standardization of the data collected and their preservation over time, as suggested by Prof. D. Fidelibus in her evaluation report.
In this way, and on the contrary to what happened so far, the level of knowledge and understanding of the phenomenon will grow over time, making the local institutions able to update and refine the analysis of seawater intrusion evolution and to explore likely scenarios of aquifer sensitivity.
At the same time, the integrated use of the methodologies proposed in this study withthe information provided by other activities of the project (Ricci et al., WP 1.1, Congedo et al., 2013, WP 2.1), related to the evolution of urban phenomena and the degree of dependence of the population from groundwater resources, will enable local authorities to use the mere scientific monitoring outputs in the framework of a broader assessment of population's vulnerability, aimed to assist the identification of the adaptation actions to be mainstreamed in water management plans and strategies.

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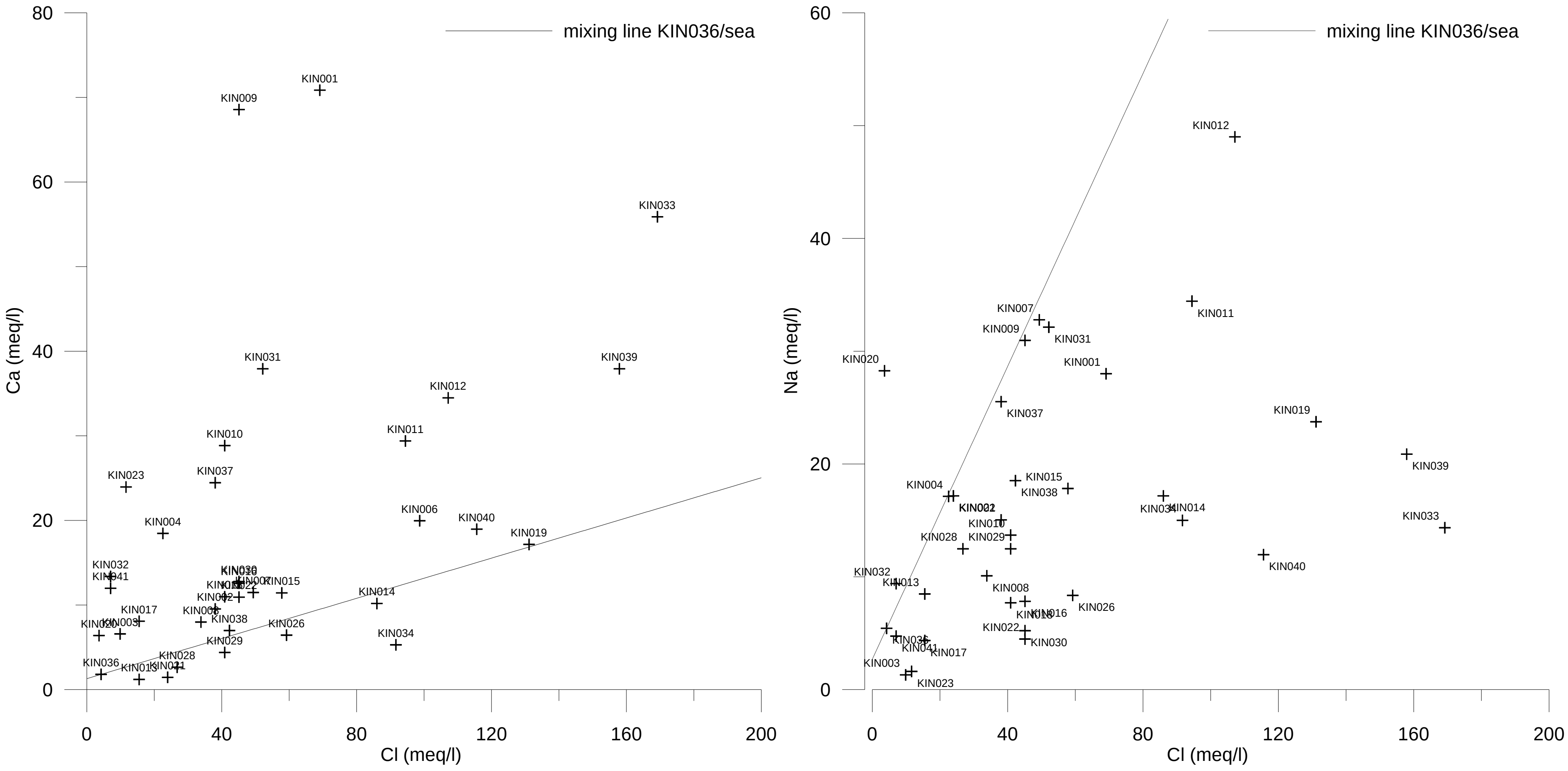
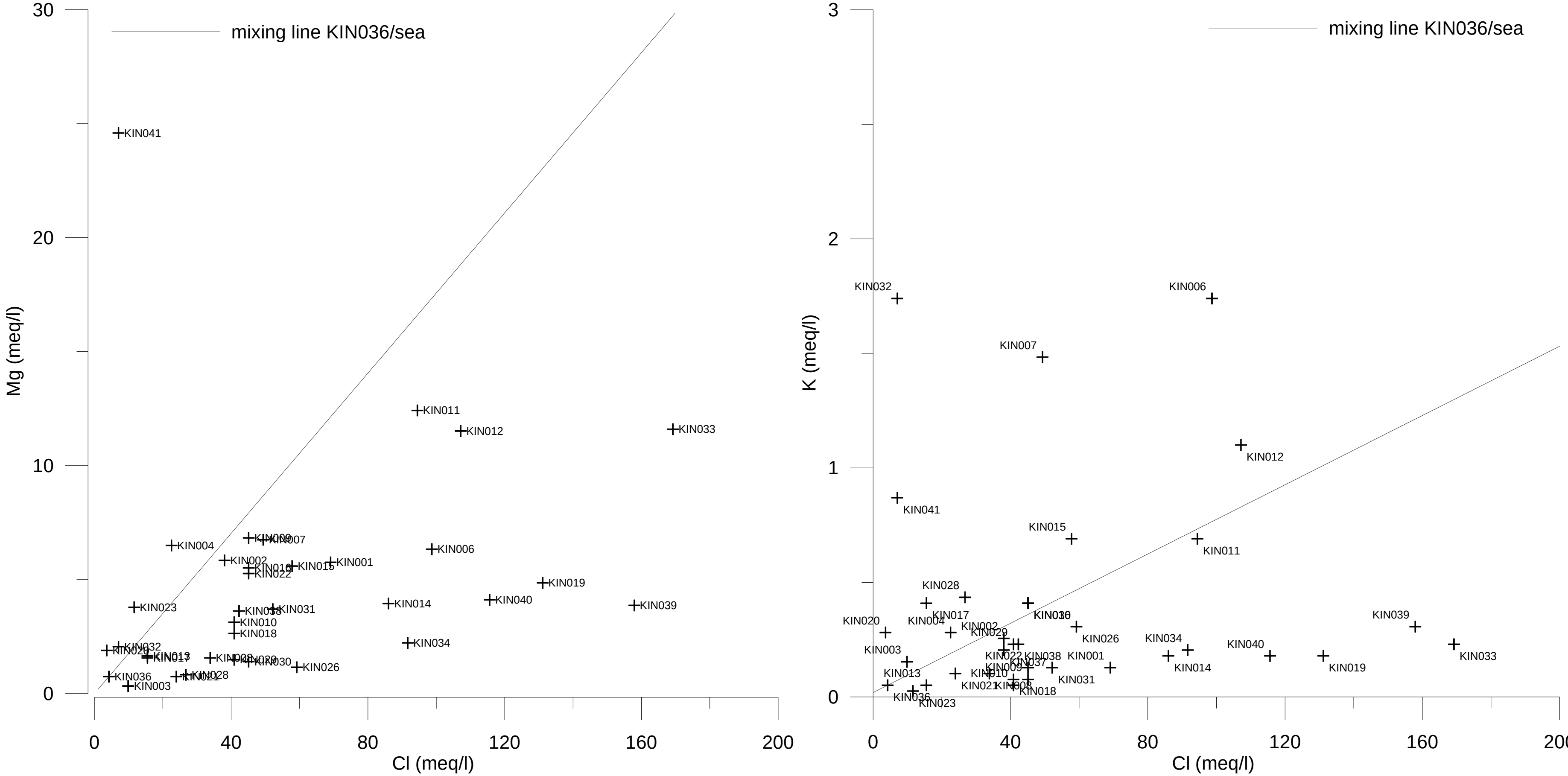
Appendix 1 – Hydrochemical Framework

Kinondoni 2012

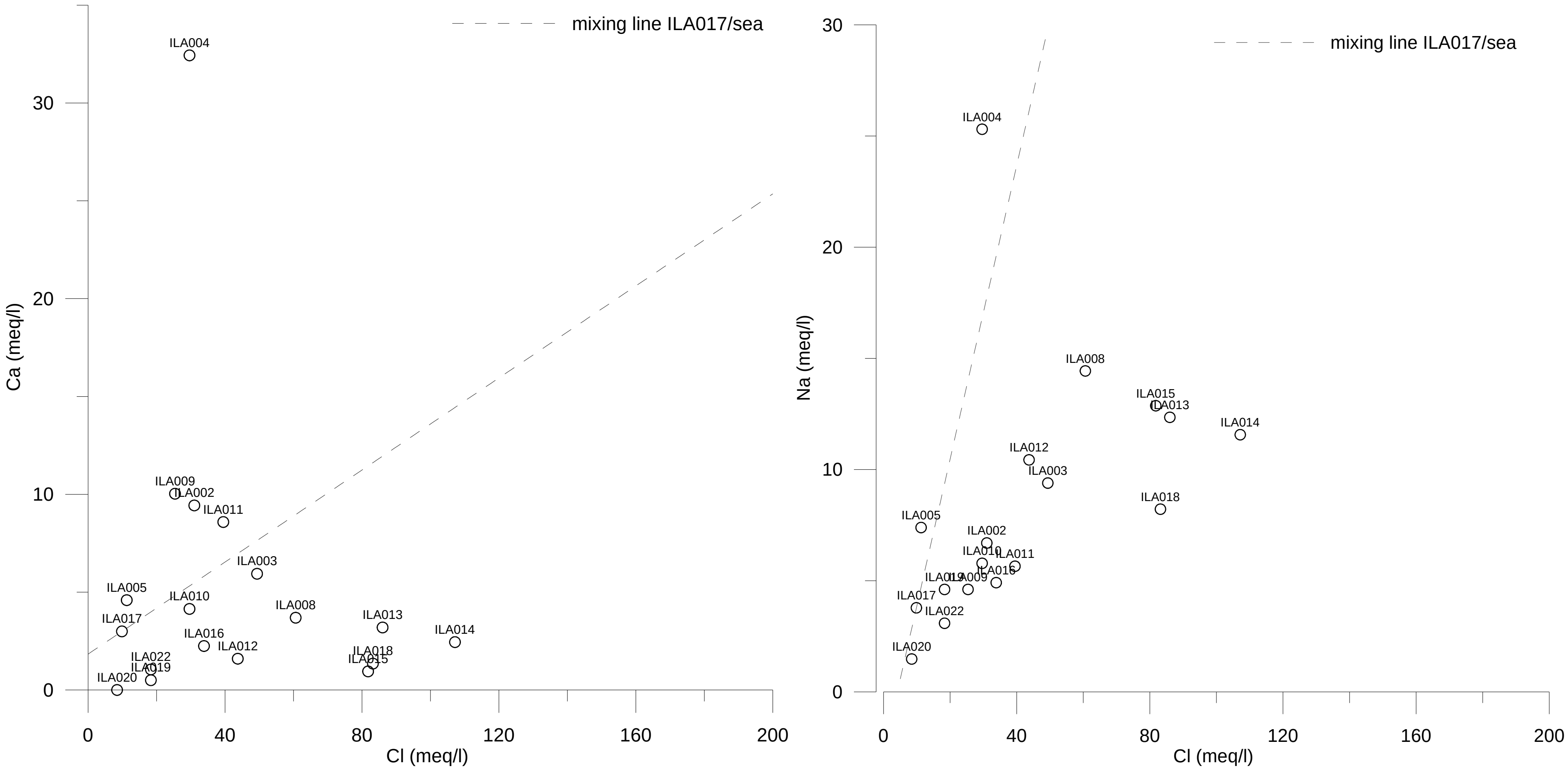


Appendix A 1 - Ca and Na vs Cl concentration of the 2012 campaign data, Kinondoni

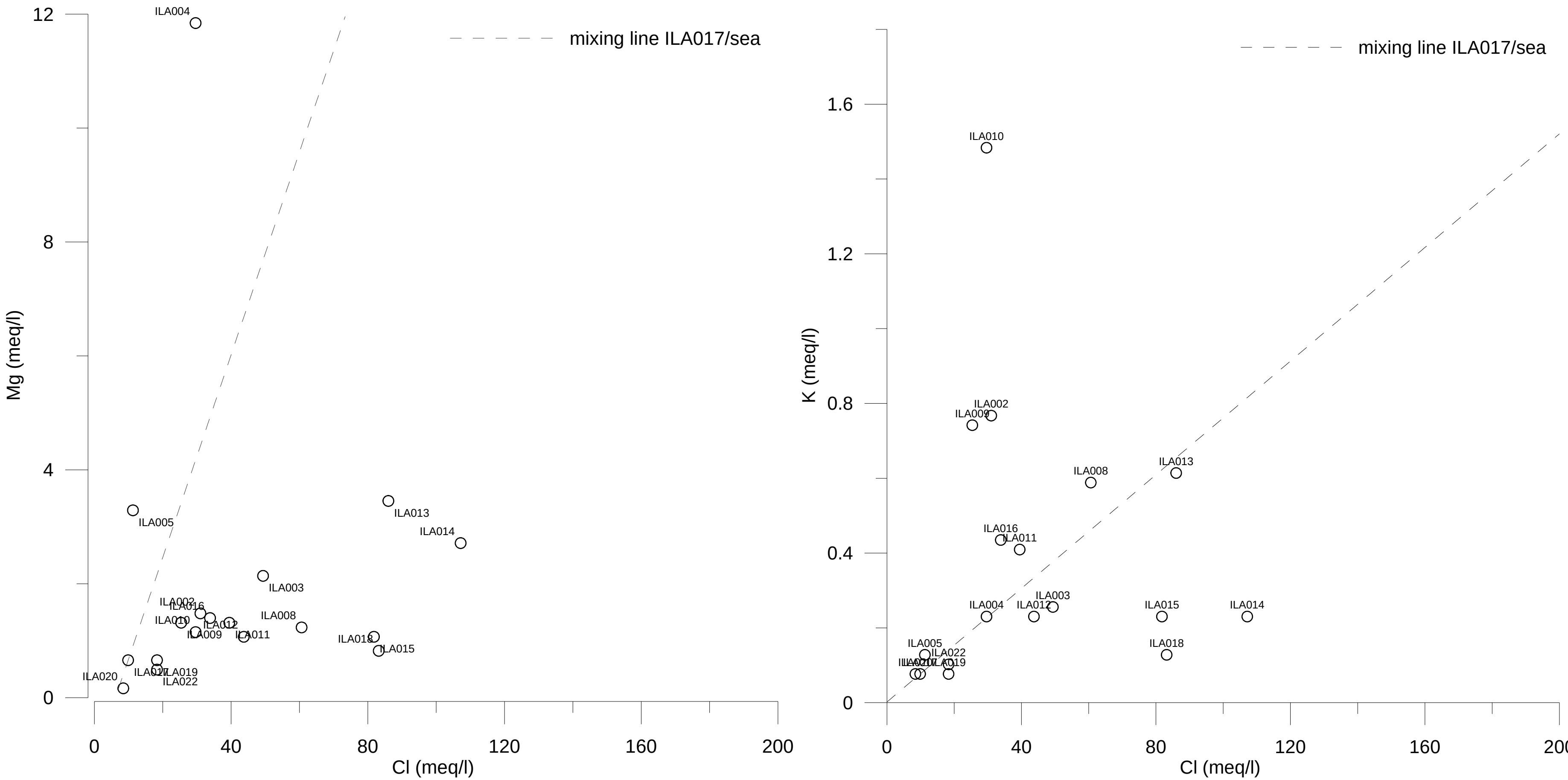


Appendix A 2 - Mg and K vs Cl concentration of the 2012 campaign data, Kinondoni

Ilala 2012

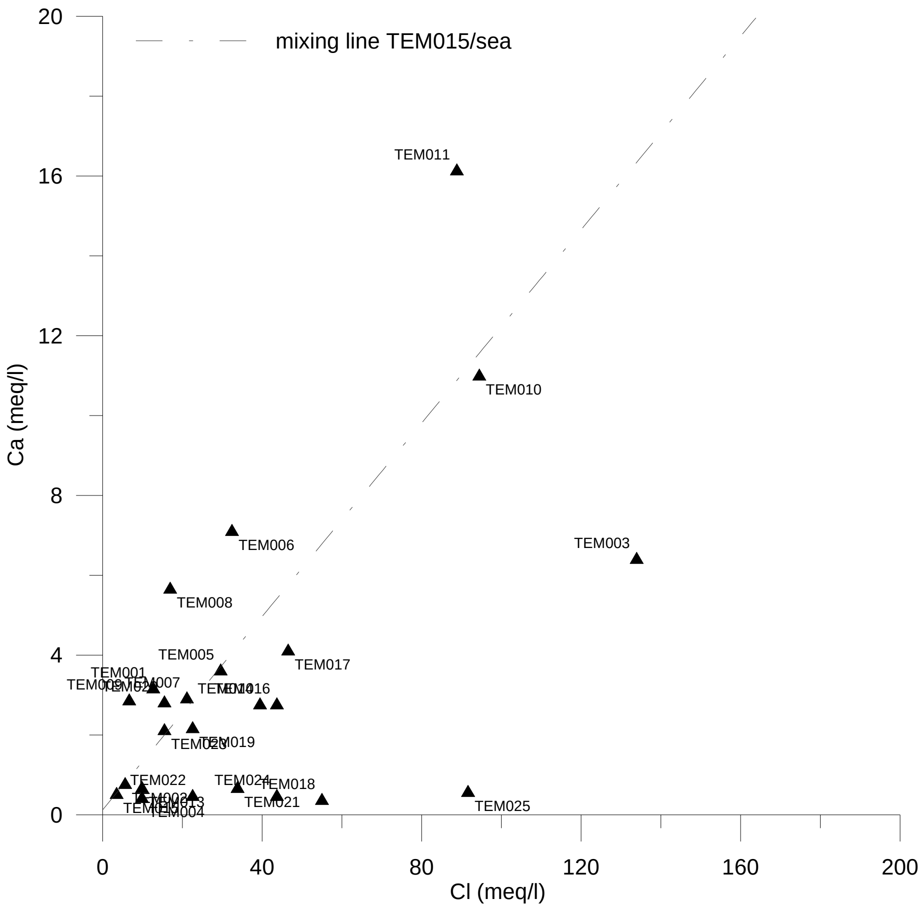


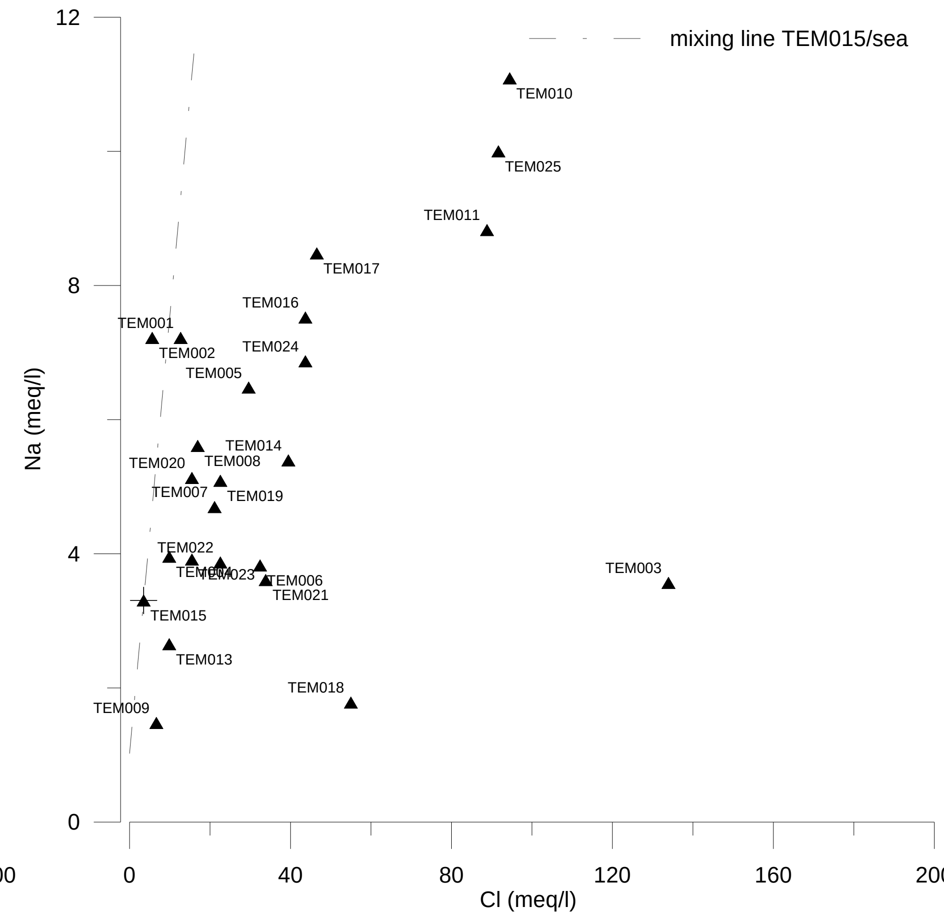
Appendix A 3 - Ca and Na vs Cl concentration of the 2012 campaign data, Ilala



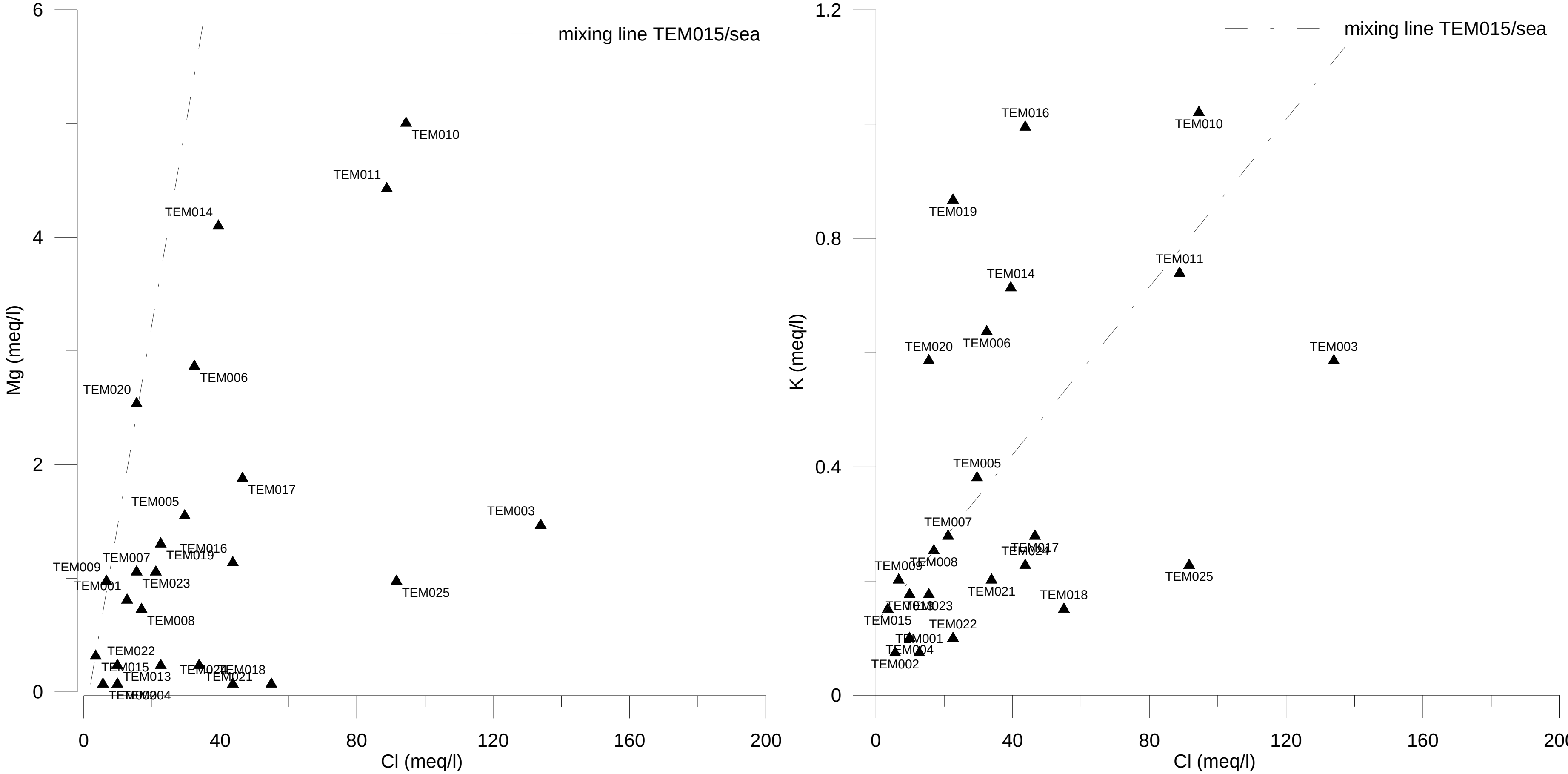
Appendix A 4 - Mg and K vs Cl concentration of the 2012 campaign data, Ilala

Temeke 2012



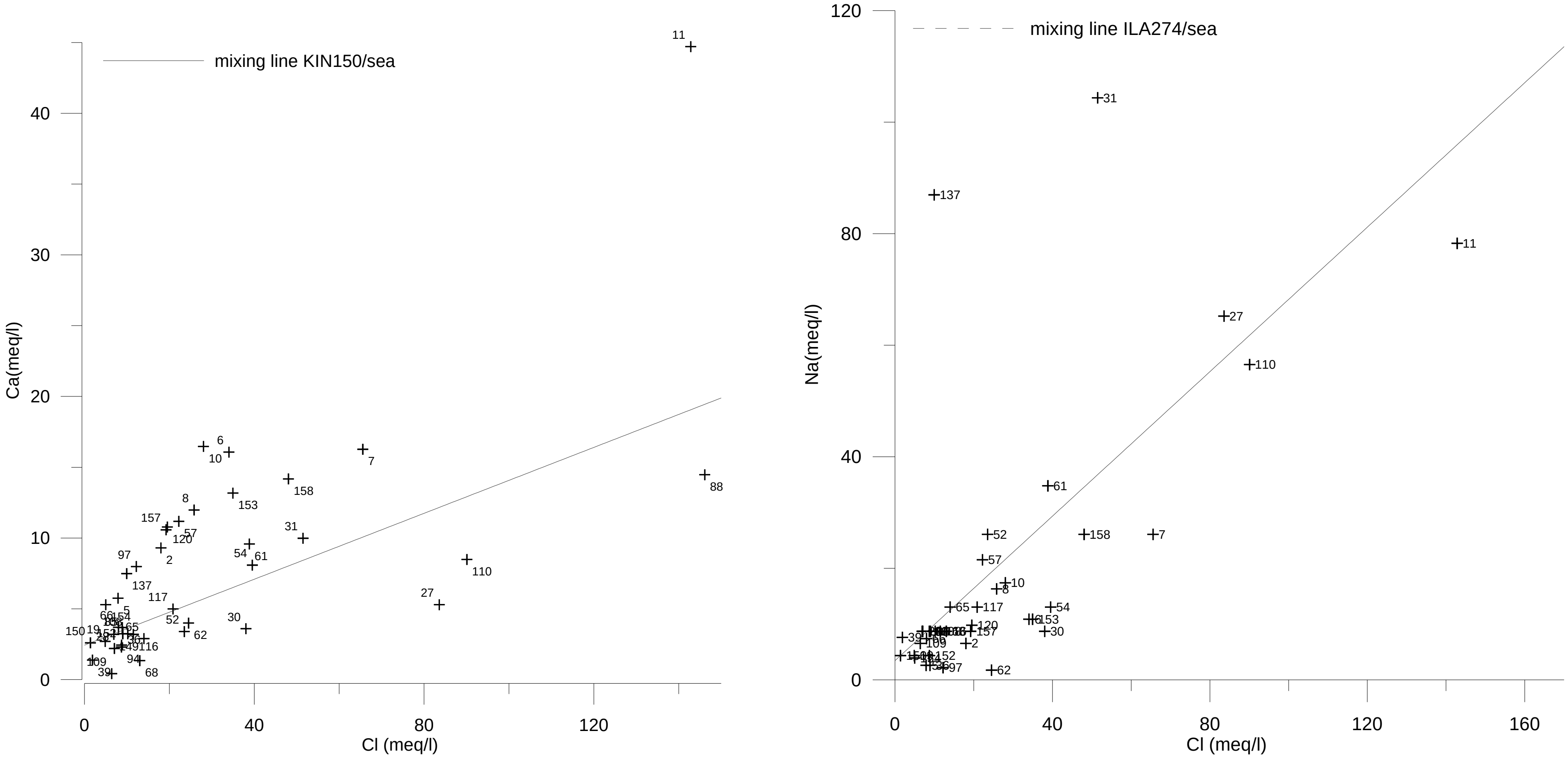


Appendix A 5 - Ca and Na vs Cl concentration of the 2012 campaign data, Temeke

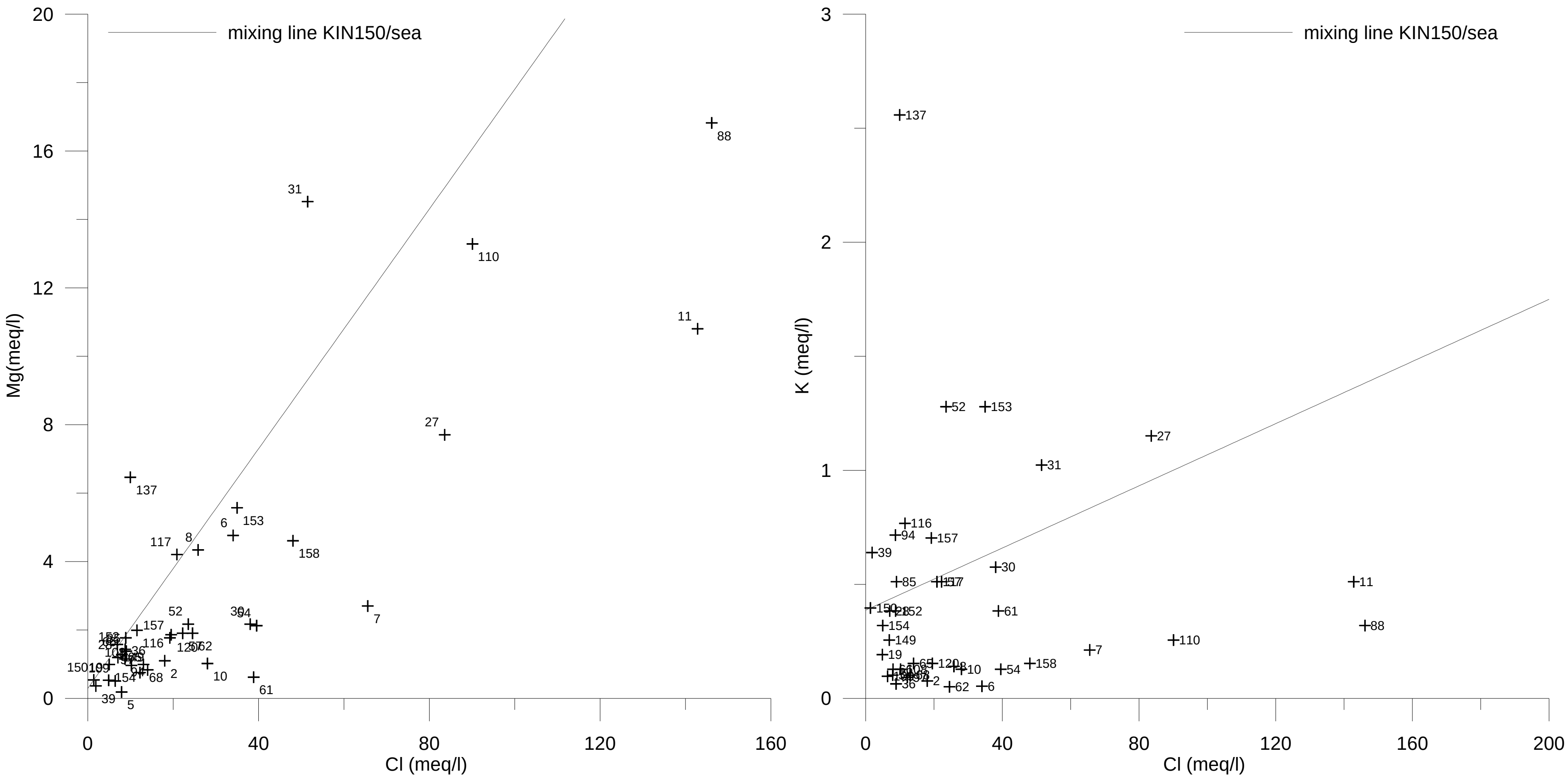


Appendix A 6 - Mg and K vs Cl concentration of the 2012 campaign data, Temeke

Kinondoni 2001

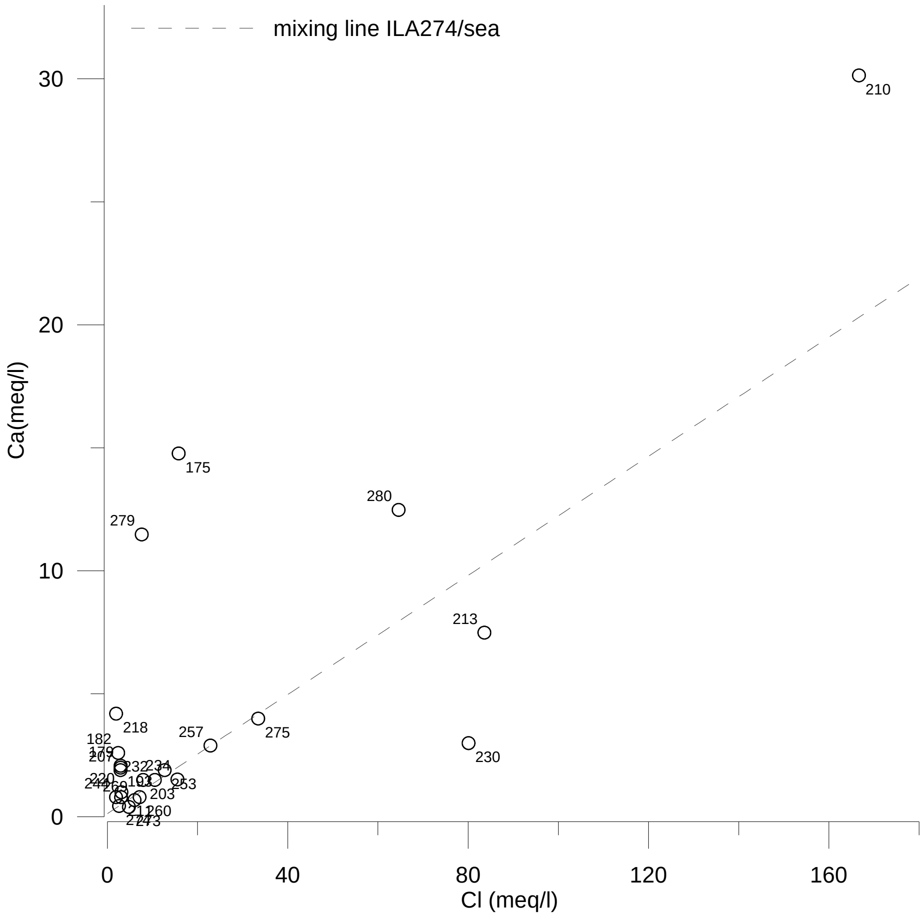


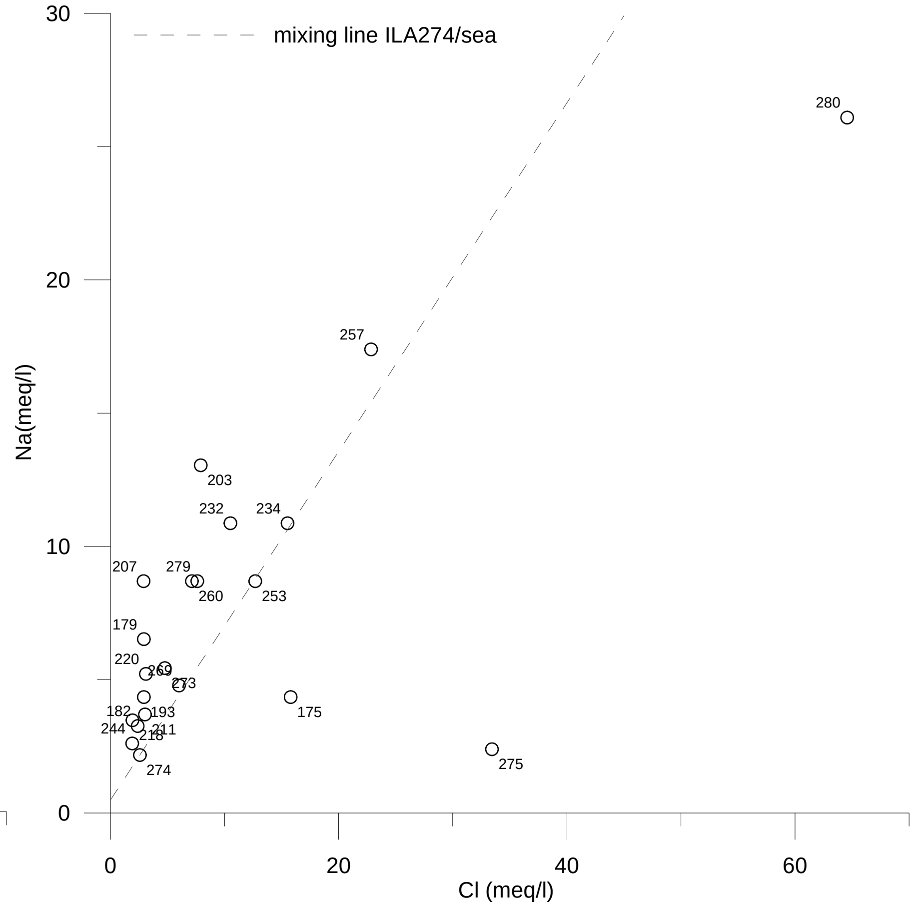
Appendix A 7 - Ca and Na vs Cl concentration of the 2001-2002-2003 campaigns data, Kinondoni



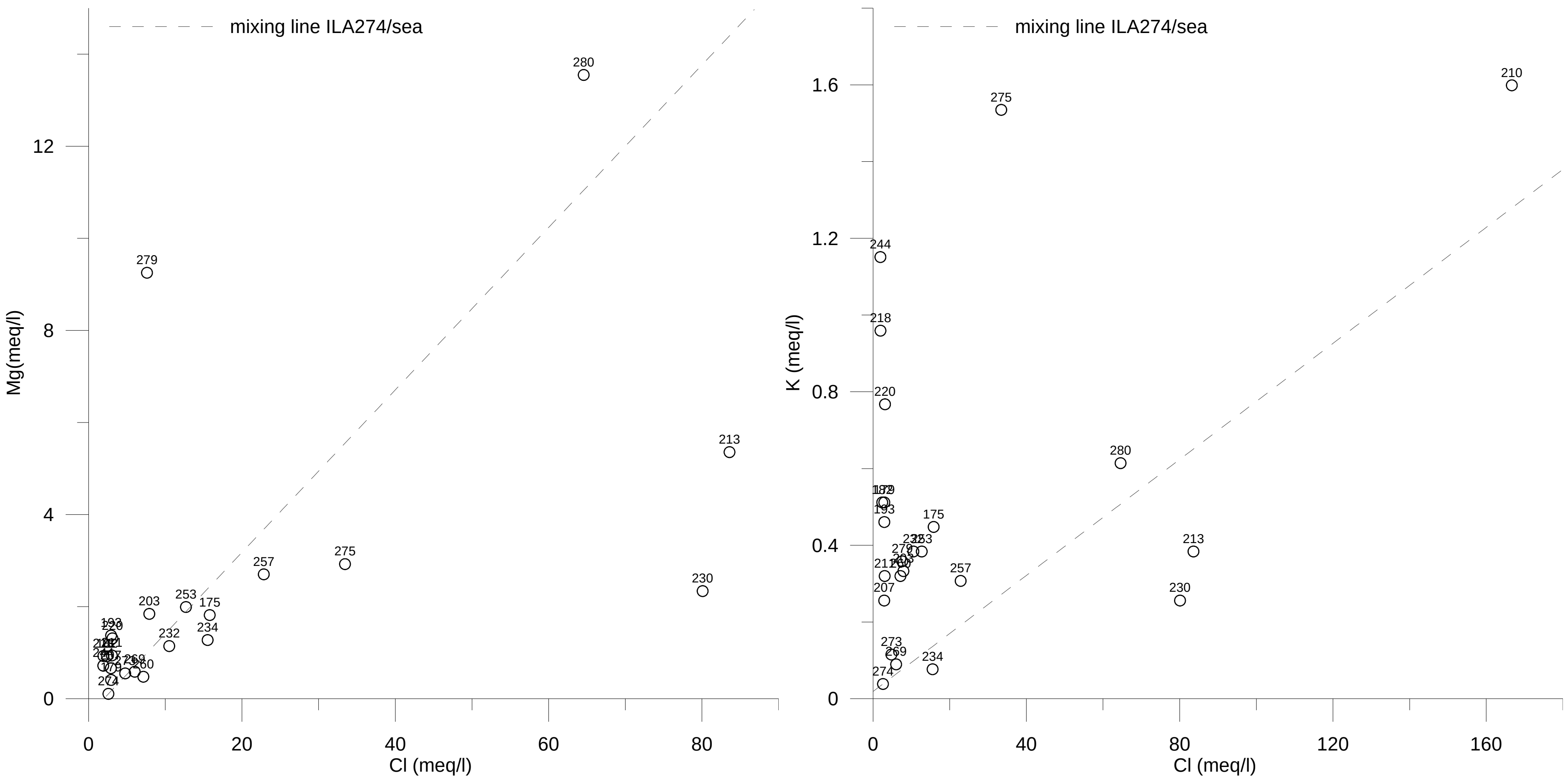
Appendix A 8 - Mg and K vs Cl concentration of the 2001-2002-2003 campaigns data, Kinondoni

Ilala 2001



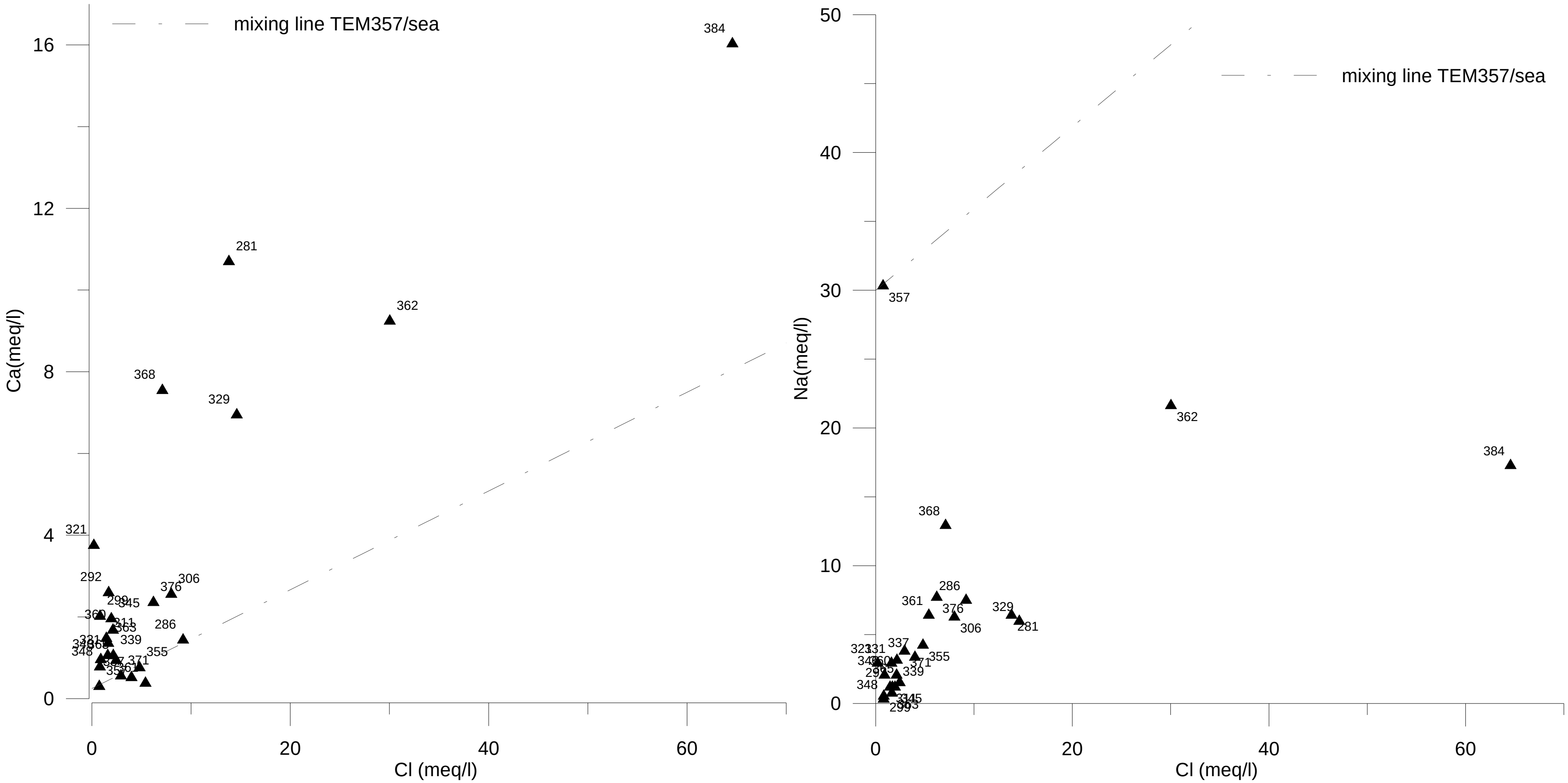


Appendix A 9 - Ca and Na vs Cl concentration of the 2001-2002-2003 campaigns data, Ilala

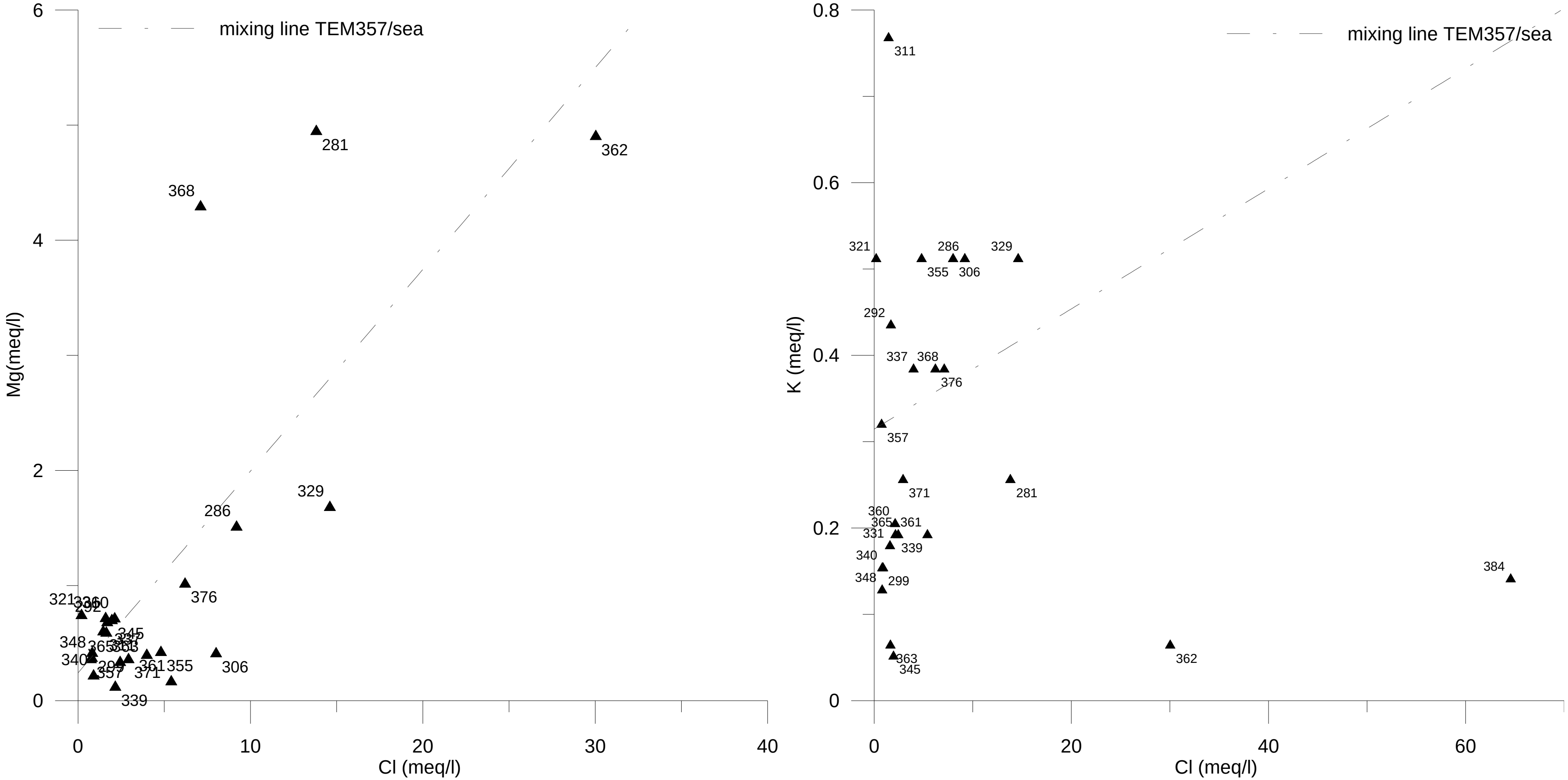


Appendix A 10 - Mg and K vs Cl concentration of the 2001-2002-2003 campaigns data, Ilala

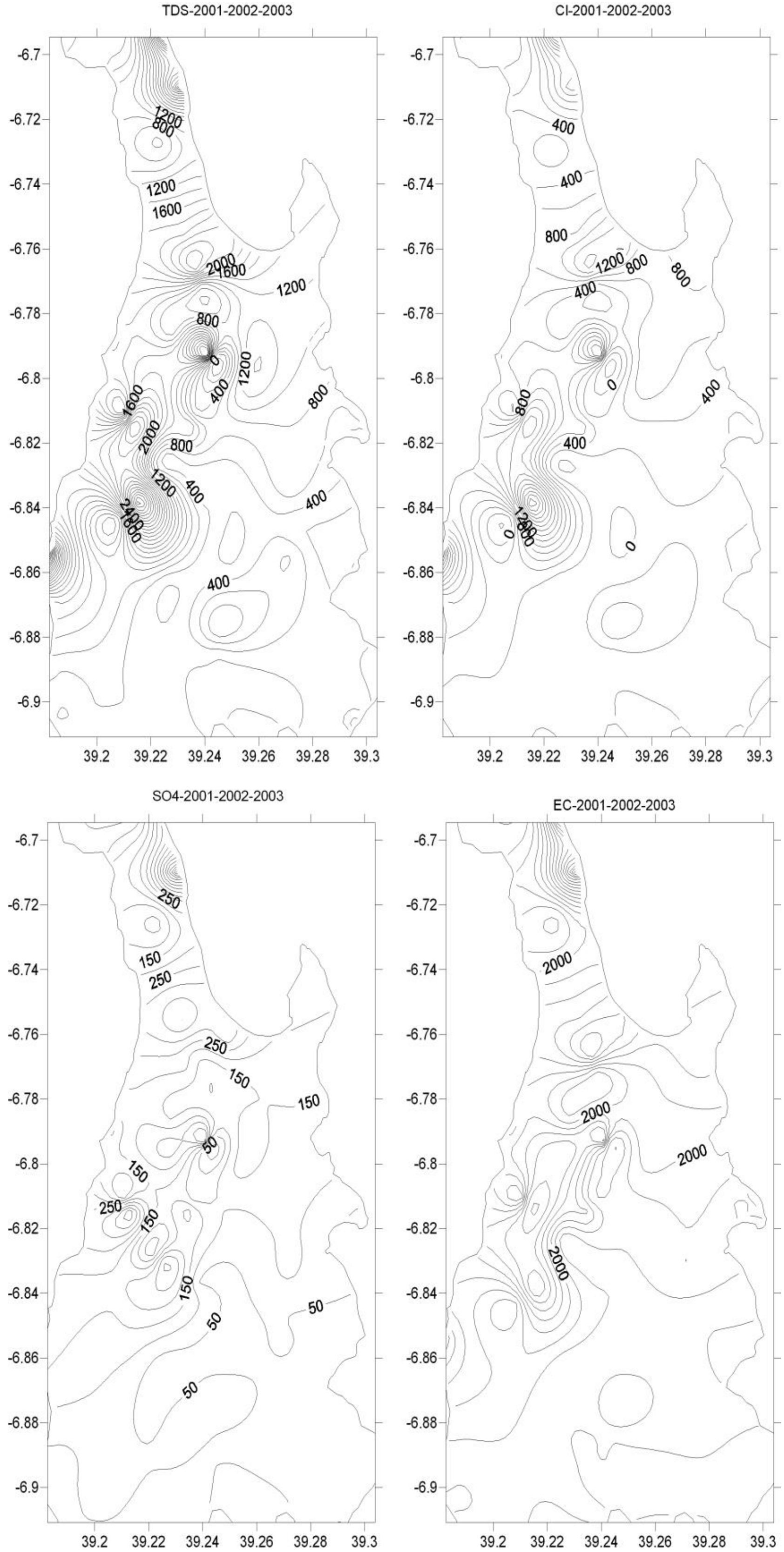
Temeke 2001



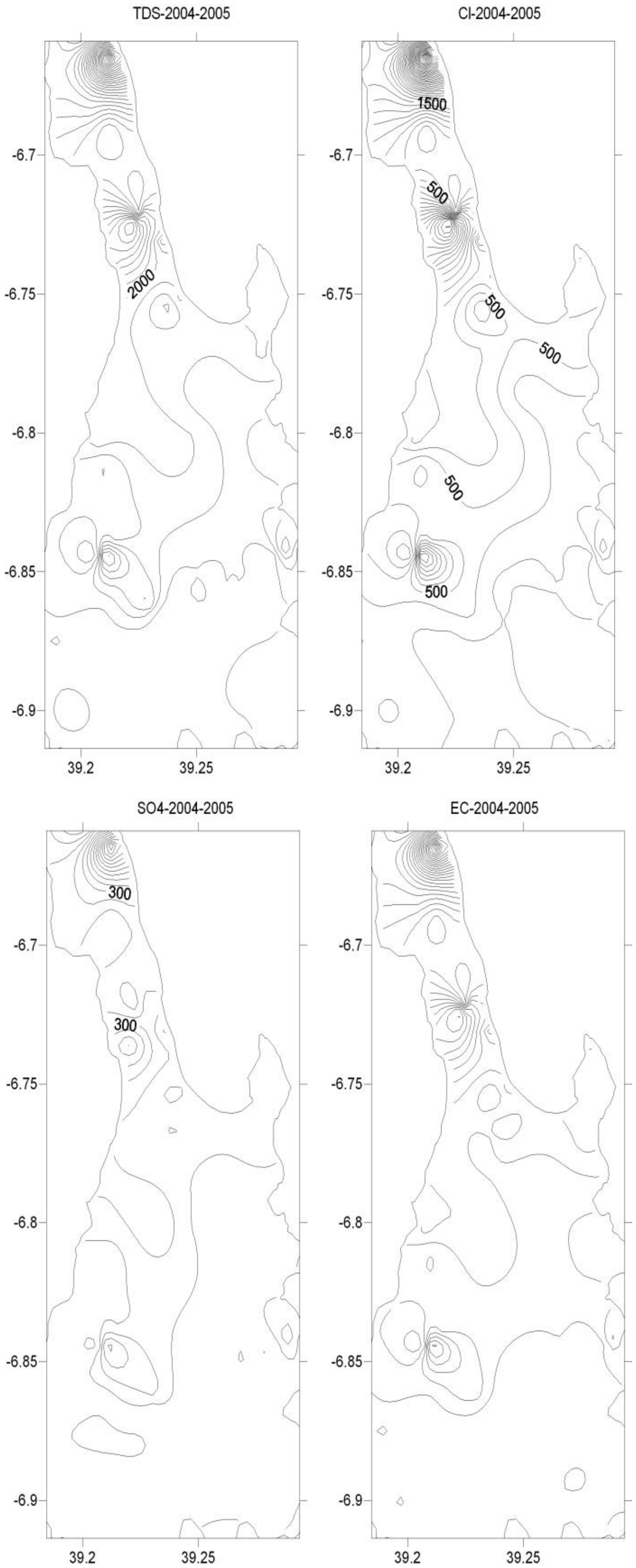
Appendix A 11 - Ca and Na vs Cl concentration of the 2001-2002-2003 campaigns data, Temeke



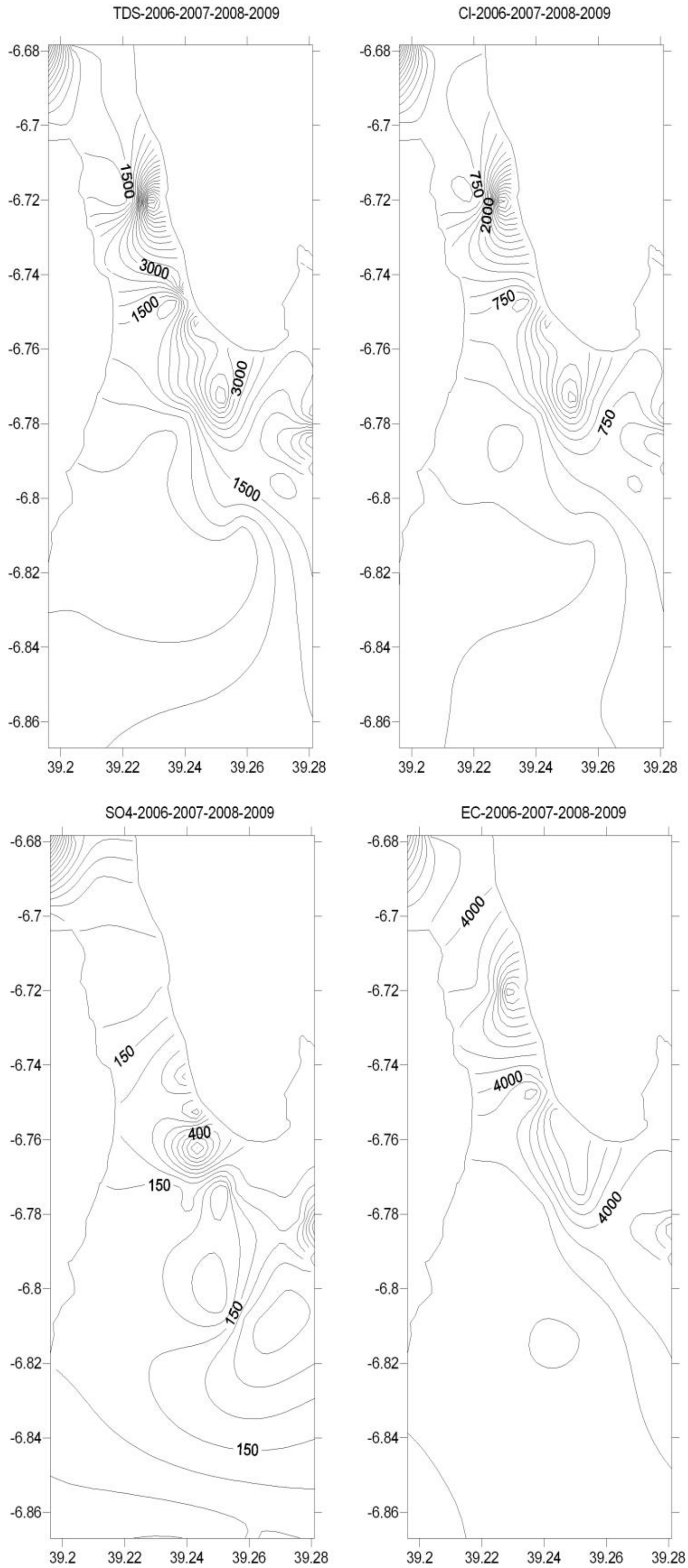
Appendix A 12 - Mg and K vs Cl concentration of the 2001-2002-2003 campaigns data, Temeke



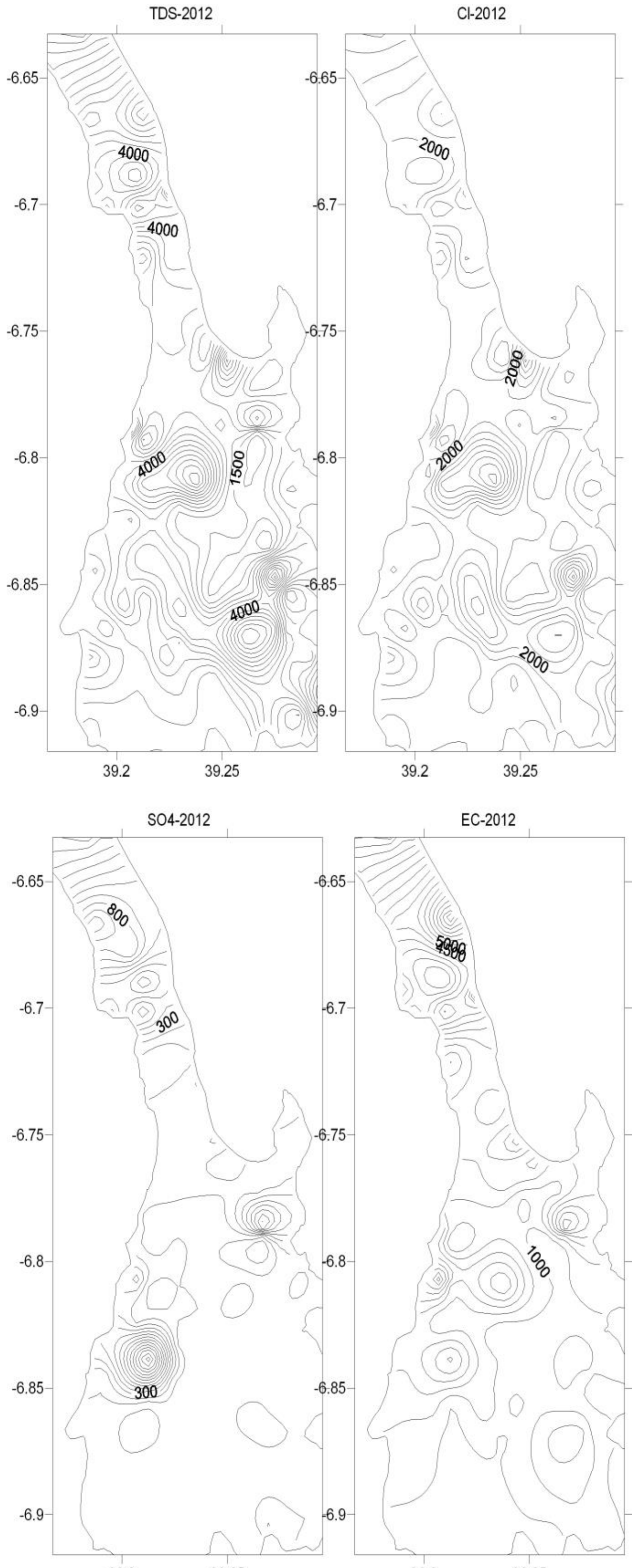
Appendix A 13 - Comparison 2001-2002-2003



Appendix A 14 - Comparison 2004-2005



Appendix A 15 - Comparison 2006-2007-2008-2009



Appendix A 16 - Comparison 2012

Appendix A 17 - Cl differences

Appendix A 18 - EC differences

Project title:

Adapting to Climate Change in Coastal Dar es Salaam

Project acronym:	**ACC Dar**
Contract number:	**2010/254-773**
Project duration:	**01/02/2011 – 31/01/2014**
Grant Contract Beneficiary:	**DICEA Sapienza University of Rome**
Contact Person:	**Silvia Macchi**
Partner in the Action:	**Ardhi University Dar es Salaam**
Associate in the Action:	**Dar es Salaam City Council**