# Groundwater management in Dar Es Salam coastal aquifer (Tanzania) under a difficult sustainable development

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*Abstract:* - This paper deals with the approach and the consequent results referred to some activities carried out in the framework of the Adapting to Climate Change in Coastal Dar Es Salaam (ACC-DAR) project, to evaluate quantitative and qualitative evolution of groundwater in this coastal aquifer. The aim of the project was to enhance the capacities of Dar's municipalities to adapt to climate change (CC). In 2012 it was carried out a monitoring campaign of groundwater, in order to evaluate CC effects and anthropic influences on groundwater resources, and to highlight the critical aspects of groundwater management in the area that could suggest consequent adapting measures. The data collected included precipitations, land cover and chemical composition of groundwater. Field data were analyzed and compared with historical data of the last ten years.

*Key-Words:* - Tanzania, Groundwater overexploitation, Seawater intrusion, Climate Change, Groundwater recharge

## 1 Introduction

The Adapting to Climate Change in Coastal Dar Es Salaam (ACC-DAR) project is a cofounded research project, granted by the European Union, leaded by the Sapienza, University of Rome, in cooperation with Ardhi University of Dar es Salaam. The aim of the project is to 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 unserviced coastal settlements. In order to provide a series of enhanced methodologies for improving municipal activities in the water management sector, it was investigated the evolution of groundwater quality and availability in the principal coastal aquifer of Dar es Salaam in the period 2001-2012. During the period considered the city has undergone a considerable population growth, with a consequent increase of the urban areas, soil consumption and increased demand for water, which, given the scarcity of surface water resources, is largely satisfied by withdrawing the groundwater. Access to clean water is a major problem for Dar es Salaam, since only one third of the households received piped water available at their dwelling. The rate of groundwater extraction is expected to grow due to growing rate of demographic expansion.

## 2 Problem Formulation

In the last two decades, Dar Es Salaam coastal plain has undergone a very strong change, due to the large increasing of urban and peri-urban settlements, which have caused, and nowadays is still causing, a huge modification in soil use. This evolution is strongly due to residential people increasing, which have doubled in the same period, and it is estimated to grow up in the next ten years. In the same period this fast urbanization has not been followed by development of water supply networks. Most of the settlements were of peri-urban type, and they changed quite often, in this same period, so the water demand up going has been so quick to not allow the building of this water supply networks. As a matter of fact in the aim to satisfy the water demand growing up, they were built hundreds and hundreds of boreholes in the aim of exploiting groundwater. Unfortunately in this area, as it happens in many coastal plains all over the world, not only in Africa, groundwater belong to a coastal aquifer, where freshwater, exploited for domestic uses, is supported by seawater. Freshwater and seawater are not definitively separated, but a mixing zone, made of brackish water is between them. In these aquifers a special natural balance is set up among these three types of water, and if, for any reason, freshwater decreases, brackish water and seawater come up. In many cases, like Dar es

Salaam one, two factors contributed to freshwater decreasing. The first is the fast modification of soil use, which, in the last two decades, deducted large areas to the natural infiltration of precipitations, due to controlled and uncontrolled urbanization, and made smaller the annual groundwater recharge. The second factor is represented by the increase of groundwater exploitation, by private and public wells, in the aim of satisfy domestic water demands. As a consequence of these two processes the principal coastal aquifer of Dar Es Salaam is under increasing danger of salinization. Further problems are caused by health risk, as many shallow wells, drilled for private supply and for selling of the water, are exposed to contamination from pit latrines. The target of the study was to investigate groundwater availability and quality evolution into Dar Es Salaam's coastal aquifer, as a consequence of seawater intrusion and urbanization processes, in the framework of Climate Change (CC) effects. They have been driven some estimations on domestic water demand as for nowadays as for the next ten years, taking in account that these demands could increase as for people growing up as for everyone demand due to general welfare improvement. The aim is to set up an integrated approach to evaluate CC effects on groundwater resources, in coastal plain affected by seawater intrusion as a consequence of high development of Dar es Salam, and to better manage these important natural resources.

## 2.1 Study Area

The United Republic of Tanzania is a country in Sub-Saharan Africa and Eastern Europe. It borders the Kenya to the North and the Uganda, Rwanda, Burundi and the Democratic Republic of the Congo to the West while the Zambia, Malawi and Mozambique to the South. The city of Dar es Salaam is the largest urban center of Tanzania, with a population of about 3 million people and a growth rate of 4,3%. The region of Dar es Salaam is divided into the three districts of Ilala, Kinonondoni, Ilala and Temeke. The study area covers a surface of approximately 260 $km^2$. It extends along a 40 km stretch of coastline to the north of the city center, and includes a part of the city center, and some peri-urban areas. The study area was selected based on hydrogeological boundaries. These are the Indian Ocean to the East, the Dar es Salaam Plateau, which rises west of the Ocean along the entire study area up to the Pugu Hills to the West, the Mzinga River and the Nyakasangwe River to the south and to the north, respectively [5].

The geological setting of the study area includes unconsolidated sediments of Neogene and Quaternary ages. The alluvial deposits and coastal plain deposits are of Pleistocene to Recent age. They are present moving from the coast towards the mainland within the river valleys. The main part of the study area corresponds to this valley. These deposits consist of sand, clay, gravels and pebbles. Fine to coarse-grained sands occur widely within valleys creeks, deltas and mangrove sites of the Mzinga, Kizinga and Msimbazi Rivers. The groundwater reservoir is located within the coastal plain in the quaternary sediments, having higher hydraulic conductivity than the underlying and surrounding Miocene sequence, including clay intercalations. The aquifer system of the study area is made of two main aquifers, both from Quaternary: an upper unconfined sand aquifer and a lower semi-confined sand aquifer, separated by a clay aquitard.


Fig.1, Study area.

## 2.2 Materials and methods

The current state of groundwater quality in the coastal aquifer of Dar es Salaam was studied through the implementation of various methods, tailored to the available set of climatic and hydrogeological data. Two main activities were carried out: collection of historical data from a variety of existing sources, and the execution of two groundwater monitoring campaigns in June and November 2012. Climatic and anthropogenic influences on hydrogeological dynamics were investigated through the analysis of temporal evolution of the Average Annual Groundwater Recharge (AAGR). Seawater intrusion was evaluated by hydrochemical methods, through physical and chemical testing of a monitored network of representative boreholes. All historical data, coming from 400 georeferenced boreholes, have been collected and organized in a database, the ACC-Dar Borehole Monitoring Database http://www.planning4adaptation.eu/042_Maps.aspx. In the database, technical data on the boreholes can be accessed and updated. A subset of boreholes, from the database of 400 georeferenced ones, was chosen for the monitoring campaign network of 2012, with consideration for uniformity of spatial distribution: the network consists of 79 boreholes, uniformly distributed with a frequency of about 1 borehole per 3 $km^2$ [5].

### 2.2.1 Groundwater recharge evolution analysis

It was evaluated the contribution to AAGR coming from direct infiltration in the area under study, using the Hydrogeological Inversed Budget Method (Civita and De Maio, 2001) as modified by Sappa, Trotta, and Vitale (2014) [6]. This method involves a spread parameters approach, based on the discretization of the study area in cells, and on the estimation, for each cell, of climatic, topographical and hydrological input parameters usually available and involved for the evaluation of the hydrogeological budget. The study area was divided in 500m x 500m square meshes. Precipitation records for the previous 50 years, from 1960 to 2010, were collected in three meteorological stations in Dar es Salam: JNIA, Wazohill, and Ocean stations. The values of Average Annual Precipitation (AAP), to be assigned to each cell, were set up by the Annual Average Precipitation values recorded in the gauging stations, through the Inverse Distance Weighting (IDW) method, which is a simple method of spatial interpolation. In the IDW method the neighboring points are identified for each cell, and a weighted average is taken of the observation values within these neighborhoods. The weighting function is the inverse power of distance d: $w(d) = 1/d^p$ , so that the weights are a decreasing function of distance, the further away are the points of observation, the less is their weight in helping define the unsampled location. Given a number of neighboring observations n(u), the estimated value $\hat{z}$ at an unsampled location u is

$$\hat{z}(u) = \frac{\sum_{i=1}^{n(u)} \frac{z(u_i)}{d_i^p}}{\sum_{i=1}^{n(u)} \frac{1}{d_i^p}} \qquad (1)$$

where $z(u_i)$ are the observations at location i, and d is their distance from the point of estimation u. The value of power p specifies the amount/rate of influence of each point of observation. As the weighting power p increases, the weights of each observation value decrease more rapidly with distance (i.e. the region of influence of each point of observation decreases, the closer points are more influential, so the estimated grid node value approaches the value of the nearest point). For a smaller power, the weights are distributed more evenly among the neighboring data points. In this case, it was chosen for p the value 2, as it permits to take into account of all the contribution of the observed values. The choose was made in consideration of the substantial uniformity of topographical elevation of the study area, which is all included within the coastal plain, and due to the limited relative distances of meteorological stations. In fact, although this approach often results less performing, in terms of accuracy of estimation, if compared with more sophisticated methods [1], it is efficient, when it is applied to spatially omogeneous contexts, relatively to the properties of interest.

Due to the absence of temperature values necessary for the calculation of evapotranspiration, but also to the land cover properties, the application of the method was performed, as suggested by the authors, enclosing the effects of evapotranspiration and runoff, directly in the Potential Infiltration Factor (PIF). The PIF represents the infiltrating amount of rainfall, which contributes to groundwater recharge, ranging between 0 and 0.55, depending on land cover characterization. Values of PIF associated to the different land cover outcropping in the study area, are reported in Table 1 [6]. The values of Average Annual Infiltration (AAI), given to each cell, expressed in mm, were calculated as a product of the PIF and the AAP, multiplied by the area of each cell. The amount of AAGR, referred to the whole study area was obtained by the addition of values, assigned to each cell.

| N | Land cover | PIF |
|---|---|---|
| 1 | Out of city | 0,15 |
| 2 | Unclassified | 0,15 |
| 3 | Full Vegetation | 0,3 |
| 4 | Mostly Vegetation | 0,4 |
| 5 | Continuos Urban | 0,1 |
| 6 | Discontinuos Urban | 0,2 |
| 7 | Soil | 0,3 |
| 8 | Water | 0,55 |

Table 1, Potential Infiltration Factor (PIF) values.

#### 2.2.2 Geochemical analysis and seawater intrusion

It was carried out the analysis of water quality evolution in the period 2001-2012 with data analysis methods, including elaboration of distribution maps for various parameters (TDS, Cl, $SO_4$, and EC), Piper diagram, Stuyfzand classification [10], and data analysis using Cl-Y diagrams related to the theoretical freshwater-seawater dilution line. The mixing lines that appear in the diagrams were built by two end-member of freshwater and seawater collected in October 2013. The boreholes concerned with monitoring campaign are used commonly to satisfy civil private demand. For many of them depth was unknown, and as they were all equipped with a pump, the samples collected from them cannot be referred to a specific depth, therefore they are representative of the average thickness of the aquifer crossed through. The results of the monitoring campaign of 2012 were compared with historical data measured in the previous decade (2001-2012). Water type classification based on chloride content, according to Stuyfzand classification system [10], was carried out on water samples analyzed in 2012 and on available historical data. The analysis of average monthly values of precipitations, registered at JNIA station, during the last 50 years, let us infer that groundwater recharge mainly occurs during the long rainy season (March to May) and to a lesser amount during the short rainy season, i.e. between October and December. Based on monitoring campaign driven in June and in November 2012, a geochemical analysis allowed identifying some seasonal variations of chemistry of groundwater, which are possible indicator of processes underway in the area. Interpretation was based on scatter diagrams of principal ions and Stuyfzand's Base Exchange Index (BEX) [10], which is:

$$BEX = (Na^{+}+K^{+}+Mg^{2+})\text{corrected} = (Na^{+}+K^{+}+Mg^{2+})\text{measured} - 1{,}061Cl \ (\text{meq/l}) \quad (2)$$

This parameter represents the difference between principal marine cations, which are found in the sample, and the expected values of them for seawater. The definition of BEX index is based on the description of the ionic exchange process that occurs when seawater intrudes in a fresh-water aquifer, which is described by the following reaction, where a,b,c,d represents molar concentrations, with the balance in milliequivalents: 2a = b+c+2d;

$$aCa^{2+} + [bNa^{+},cK^{+},dMg^{2+}]\text{-Ex} \leftrightarrow [aCa^{2+}]\text{-Ex} + bNa^{+} + cK^{+} + Mg^{2+} \quad (3)$$

When salt water intrudes an aquifer containing fresh water, in the early stages of seawater intrusion, generally, an ion exchange process takes place, sodium replaces calcium on the aquifer's clay particles through ion exchange before significant chloride increases are observed. This involves a Na+ concentration decreasing in groundwater, and a $Ca^{2+}$, parallel increasing. Conversely, when seawater is flushed by freshwater, most abundant ions in freshwater such as $Ca^{2+}$ expel and replace the Na+, adsorbed in the solid matrix, and sodium is released into the water. Therefore seawater intrusion leads to negative values of BEX index, and sample has to be considered of Class 1, according to Table 2.

| $(Na+K+Mg)_{CORRECTED}$ (meq/l) | Class |
|---|---|
| $(Na+K+Mg)_{CORR} < -\sqrt{0{,}5Cl}$ and $(Na+K+Mg)_{CORR} < -1{,}5(\Sigma cat - \Sigma an)$ | 1 |
| $\Sigma cat = \Sigma an$ and $\lvert (Na+K+Mg)_{CORR} + (\sqrt{0{,}5Cl})*(\Sigma cat - \Sigma an)/\lvert\Sigma cat - \Sigma an\rvert\rvert > \lvert 1{,}5(\Sigma cat - \Sigma an)\rvert$ | 2 |
| $(Na+K+Mg)_{CORR} > \sqrt{0{,}5Cl}$ and $(Na+K+Mg)_{CORR} > 1{,}5(\Sigma cat - \Sigma an)$ | 3 |

Table 2, Definition of BEX index ($(Na+K+Mg)_{CORRECTED}$) in Stuyfzand's classification.

### 2.3 Results

It was estimated a range of possible values of present AAGR for the study area. The values were estimated considering AAP values calculated on the basis of the 52-year data set, and the land cover for the year 2011 (29% soil, 65% urban, 6% vegetation). In order to determine the AAP values for each gauging station, it was carried out the statistical analysis of the 52-year rainfall data set. It was verified the data's adaptation to theoretical distributions through the method of moments. Only the Gaussian distribution passed the Pearson test

(Chi-square test). The values obtained in the Pearson test are reported in Table 3. Consequently, the range of values of AAP was defined as the range that corresponds to the 68% of probability of happening in a Gaussian distribution, that is defined by the mean (μ) and the std.dev (σ) as (μ-σ) and (μ+σ). These values of AAP became the input data for spatial interpolation and for the evaluation of AAGR. The correspondent minimum, medium and maximum values of AAGR estimated are, respectively, $4{,}0x10^7$, $5{,}2x10^7$ and $6{,}4x10^7$ $m^3$. These values spread on an area of 260 km2 correspond to about 200 mm/year, which seems very similar to result coming from previous studies, giving 198 mm/year [3].

| Probability level (%) | Expected Chi-square statistic |
|---|---|
| 90 | 36,8 |
| 95 | 33,9 |
| 99 | 28,9 |

| Observed Chi-square statistic | |
|---|---|
| Gauss | 21,5 |
| Lognormal | 87,2 |
| Gumbel | 2553,3 |
| Frechet | 2,9 E+11 |

Table 3, Results obtained in the Chi-square test to verify the adaption of the rainfall statistical distribution to the theoretical distributions.

It was analyzed the evolution of AAGR in the period from 2002 to 2011, considering the AAP and land cover data of each year. The analysis has shown that AAGR decreased by about 20% over the last ten years (2001-2012), which is almost 5% for each year. The analysis of the rainfall evolution (mm) in the last decade referred to the study area showed that, although for all of the monitored stations, the AAP decreased over the last decade, the changes have been slight in the last five years and AAP appears to be almost the same with values between 900 and 1000 mm/y. Thus, in recent years most of the decrease of groundwater active recharge was likely originated by land cover modifications. The interpretation of land cover data permitted to assess the evolution of urbanization in the study area in the period of observation (2002-2012). Urban land, as both continuous urban and discontinuous urban land, increased from 40% to 65%, as following a linear trend. In the meanwhile, soil, which is the land cover type with the maximum PIF value, has decreased by 20%, from about 47% to about 27%. The increase in urban areas transformed the region to be less permeable to rainfall. Because of it, many areas, now, are less contributing to the recharging process than before [6]. A prediction was made of AAGR volumes evolution from 2013 to 2020, assuming that the rate of precipitation will be constant (the analysis has been carried out, by the mean estimated values for each station) and assuming a linear trend of urban land cover increasing. It was estimated for 2020 a recharge value of 5,0 $x10^7$ $m^3$, representing a 14% decrease in AAGR across the timeframe considered 2012-2020 [7].

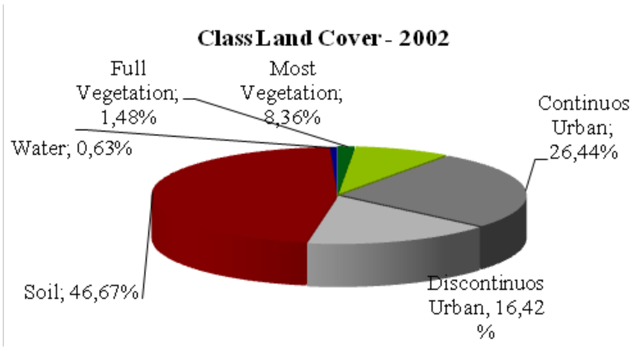



Fig.2, Land cover 2002

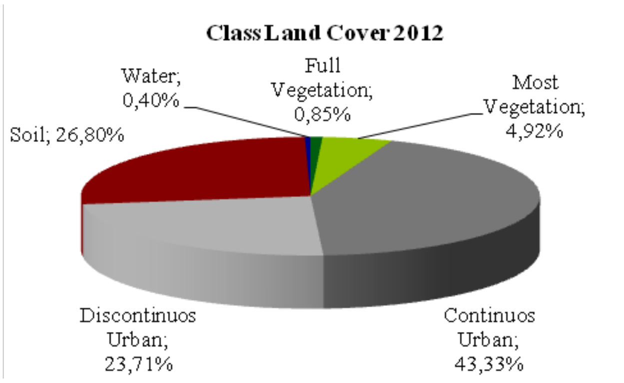



Fig.3, Land cover 2012

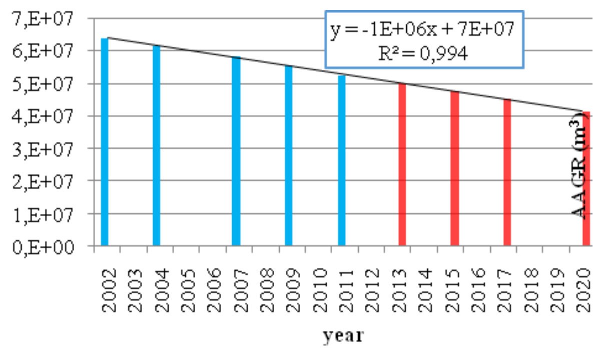



Fig.4, Evolution of Average Annual Groundwater Recharge (AAGR)

The rapid increase of urban population in Dar es Salaam is mostly due to migration from rural areas. Migration is one of the most critical issues in urban areas in Tanzania as in many other parts of the world [12]. The rate of migration exceeds the existing services and exacerbates the existing urban problems such as inadequate clean water supply, poor sanitation, poor health services and unemployment. Access to clean water and sanitation are major problems for Dar es Salaam's poor, and contribute to widespread illness, including cholera and malaria. Groundwater plays a major role in providing water for domestic use and agriculture. The rate of groundwater extraction is expected to grow, due to growing rate of demographic expansion. It was estimated the evolution of groundwater demand in the study area, in the period 2002-2011, in order to compare the estimated AAGR with the rate of groundwater extraction.
For 5 years between 2002 and 2011 (2002, 2004, 2007, 2009, 2011), they have been defined four possible values of the annual demand of groundwater. The values are based on estimate of demographic evolution and types of water supply, for the period between 2002 and 2011 (found in Ricci et al., 2012 and Congedo et al., 2013 [4]). The four values correspond to different percentages of population using groundwater and different daily demand per capita: 45 l/d (scenario A1 and B1) and 60 l/d (scenario A2 and B2), corresponding respectively to the quantities indicated in Sappa et alii, 2013 [6]). The two different daily demand allow to represent the possible increase of water demand due to the expected socio-economic development in different sectors. It resulted that water demand has already reached, nowadays, the amount of AAGR. This should advise the need for adequate and integrate interventions to contrast excessive depletion of groundwater resources.

| | Scenario A | Scenario B |
|---|---|---|
| Kinondoni | 50 | 60 |
| Ilala | 70 | 80 |
| Temeke | 80 | 90 |

Table 3, Definition of scenarios.

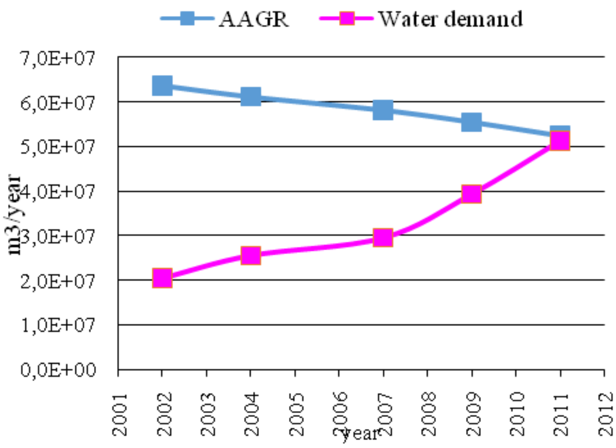


Fig.5, AAGR and water demand evolution between 2001 and 2012

The main parameters that indicate the groundwater salinization rate are electrical conductivity (EC) and chloride (Cl-) concentration [2],[9]. EC depends on total salt concentration, which is the major quality factor, generally limiting the use of saline waters for crop production. The guidelines of FAO and WHO indicate that waters with high EC are not suitable for drinking nor for irrigation. Results of the chemical analysis of groundwater in June 2012 (79 samples), showed that 25.3% of the samples were not suitable for drinking and irrigation according to FAO guidelines for EC (2000 µS/cm), 36.7% according to the WHO classification (1500 µS/cm) [13]. The analysis of the evolution of EC and $Cl^-$ content of groundwater in the period 2001-2012 was carried out regarding to boreholes for whom measures in different years were available. The wells available for this type of processing were, in the whole, 15, 10 of which in Kinondoni area, 2 in Ilala, 3 in Temeke. The analysis revealed high percentage increases in EC in some boreholes (Fig.9). Chloride is the most abundant ion in seawater (seawater contains approximately 35,000 mg/l of dissolved solids, which include about 19,000 mg/l of chloride, while fresh-water generally contains less than 30 mg/l). To assess if EC increasing is related to seawater evolution, it has been analyzed the parallel increase of chloride concentrations. Boreholes with the highest percentage increases in EC had also the highest percentage increases in chloride content (Fig.10). Diagrams of (Cl + SO4) vs. (Ca + Mg) show the comparison between the content of principal ions of marine origin and principal ions of continental origin. All the diagrams revealed, for nowadays, higher concentrations of marine ions than ones observed in the previous decade. In Fig.6, it is reported the diagram for the district of Kinondoni, with the largest symbols representing the more recent data [9].

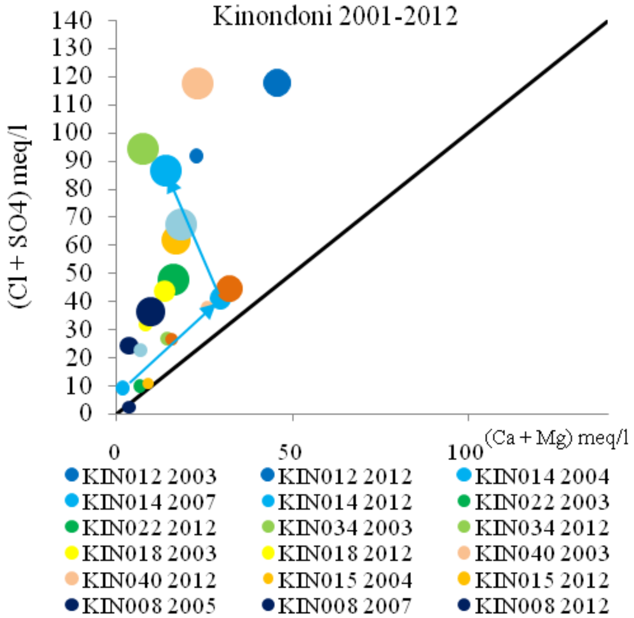



Fig.6, Diagram of (Ca+Mg) vs. ($Cl+SO_4$)

Chemical analysis were carried out on 79 samples collected in June 2012 (representing the end of the main wet season), and on 71 samples collected in November 2012 (representing the peak of the minor wet season). The analysis of diagram of TDS vs $Cl+SO_4$ (Fig.7) has shown that the salinity of a majority of the samples depends mainly on $Cl^-$ and $SO_4^{2-}$ ions, which are predominant anions in seawater.

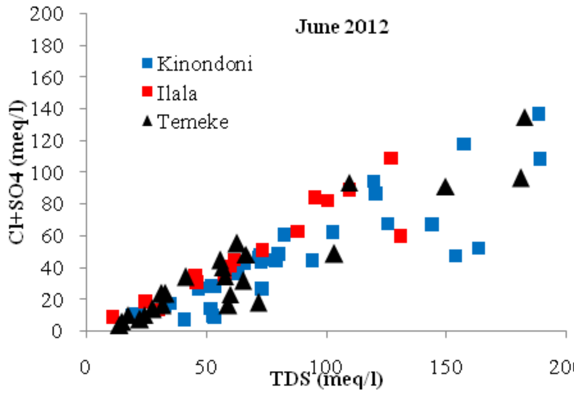
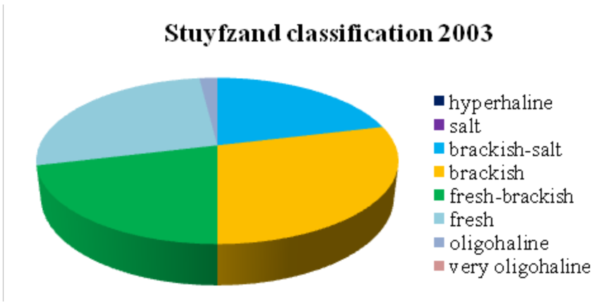
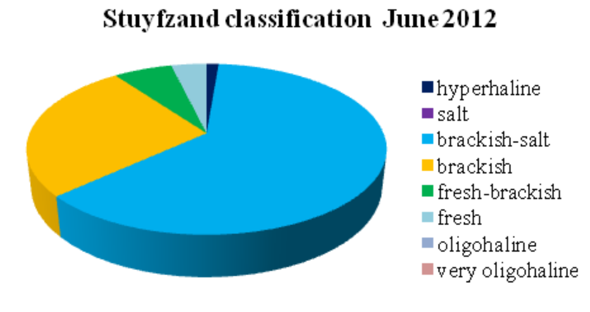



Fig.7, Diagram of TDS vs. ($Cl+SO_4$)



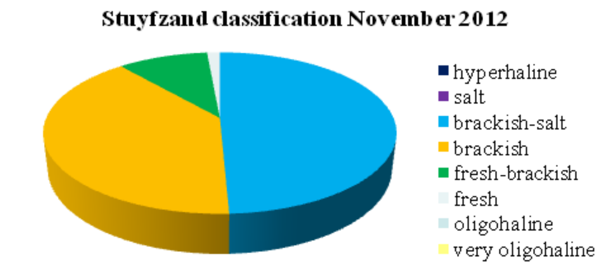




Fig.8, Stuyfzand classification: variations 2001-2012

The analysis of Stuyfzand's classification for boreholes for whom measures in different years were available showed a significant increase of the percentage of waters classified as brackish and brackish-salt, and a reduction of samples classified as fresh water. Diagram of Cl vs. $Cl/HCO_3$ is used to evaluate the level of salinization. In the diagrams of Fig.11 ad Fig.12, the lower line represents a typical value of the Cl/HCO3 ratio expected for fresh waters, which is 0,5. When waters exhibit values of the ratio exceeding this value they have to be considered affected by salinization. Line at 6,6 represents a typical value indicating high salinized waters [9]. Diagram of Cl vs. $Cl/HCO_3$ shows that almost all samples, referred to both months of investigation, are affected by salinization. In June boreholes of Temeke present the minor salinization and chloride content, while in November all boreholes appear salinized [9].

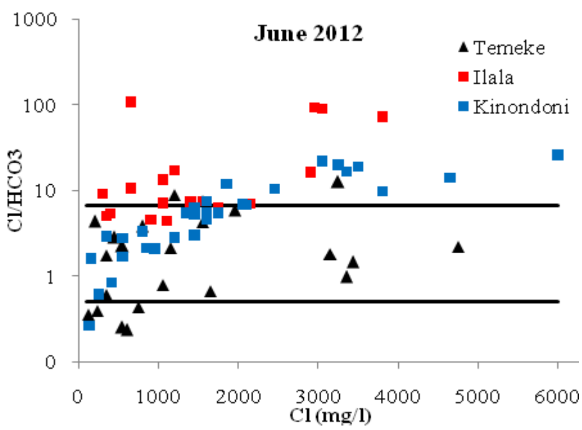


Fig.11, Diagram of Cl vs. (Cl/HCO3), June 2012

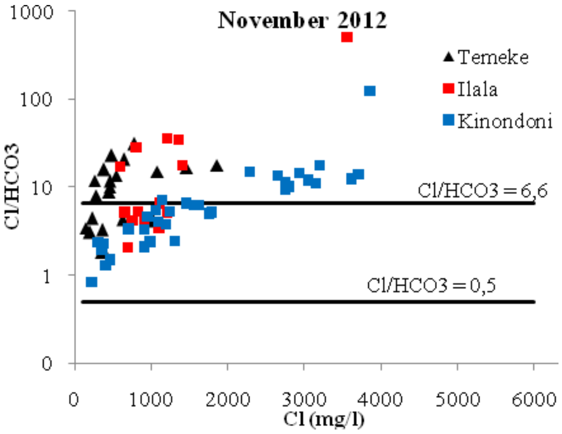



Fig.12, Diagram of Cl vs. ($Cl/HCO_3$), November 2012

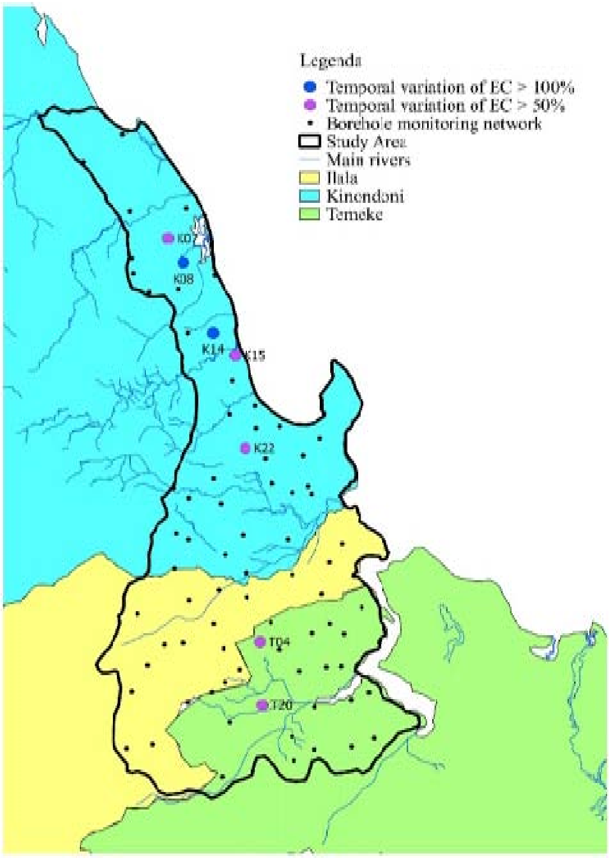



Fig.9, Evolution of EC (2001-2012)

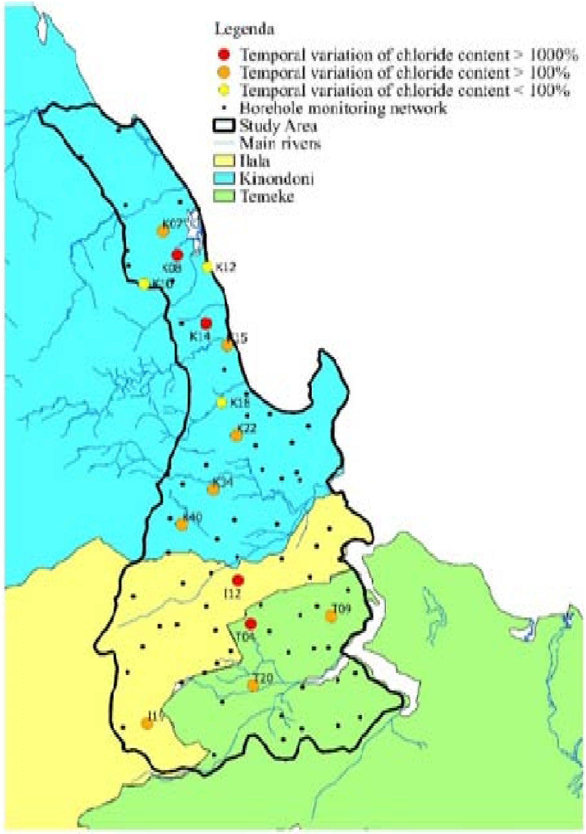



Fig.10, Evolution of chloride content (2001-2012)

Chloride can be considered like a conservative tracer, and it is representative of the proportion of seawater intruding into the aquifer, because it is not involved in ionic exchange processes. The analysis of graphic correspondences between Cl- and the other major ions, like Ca and Na, relatively to the simple mixing lines, is useful to identify additional processes, as ionic exchange, annexed to the mixing phenomenon. Dilution lines in the diagrams represent the theoretical gradual (linear) transition from one water-type to the other one, which occurs in the transition zones in coastal aquifers. They can be drawn starting from the knowledge of composition the two end-members, freshwater and seawater. In this case, the mixing lines were built by two end-member of freshwater and seawater collected in October 2013.

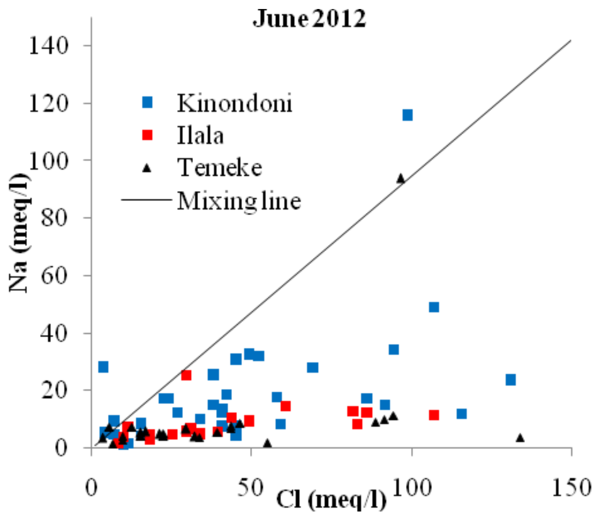



Fig.13, Diagram of Cl vs. Na, June 2012

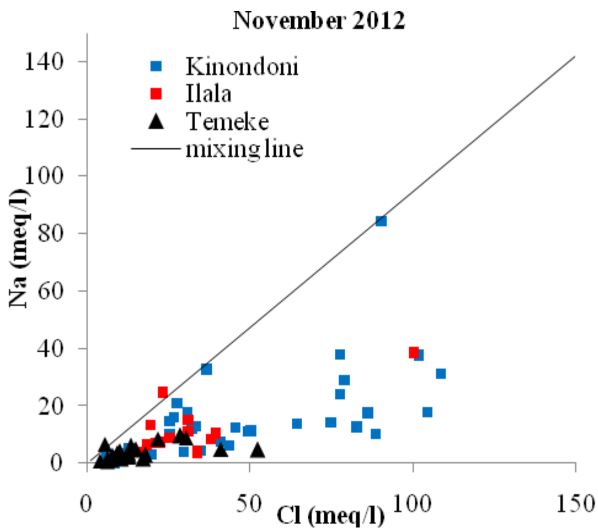



Fig.14, Diagram of Cl vs. Na, November 2012

The concentrations of major constituents present in the sampled waters were compared with corresponding values of dilution lines. In Fig.13, and in Fig.14 diagram of Cl vs. Na, almost all samples are under the dilution line, meaning that sodium concentrations are lower than the expected quantities in the presence of simple mixing with marine waters.

This result is a possible indicator of the presence of the process of ionic exchange associated with seawater intrusion. It was analysed sample's distribution in Ca vs. HCO3 diagram (Fig.15 and Fig.16). This diagram is used to reveal the presence of carbonate's dissolution process. It describes the proportion between calcium and bicarbonate concentration when the dissolution process takes place. It corresponds to the equation of the chemical reaction:

$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$

In the diagram it can be seen that almost all samples in the district of Ilala and Kinondoni present excess of calcium respect to the theoretical lines of the process.

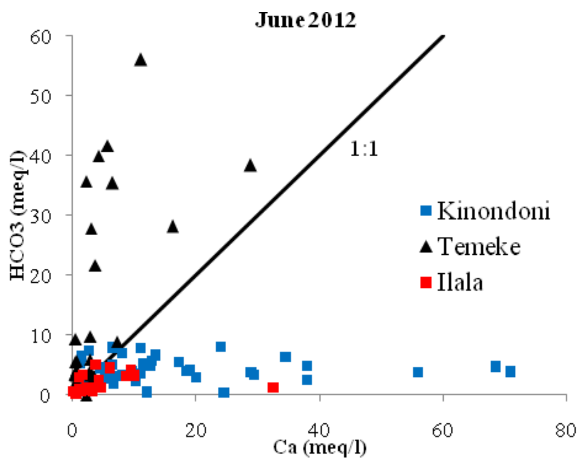



Fig. 15, June 2012: diagram of $Ca^{2+}$ vs. $HCO_3^-$

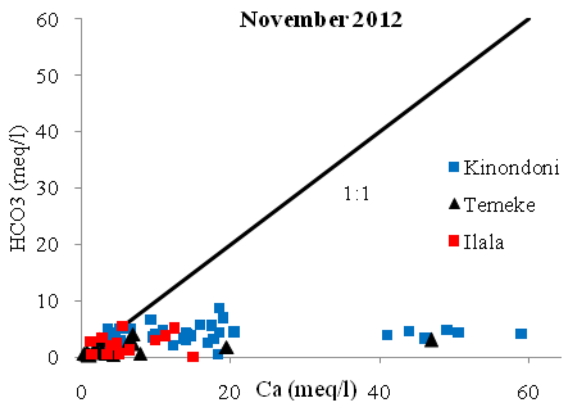



Fig. 16, November 2012: diagram of $Ca^{2+}$ vs. $HCO_3^-$

It is known the presence of limestone formations in the northern coastal area of Dar es Salaam, in the north of the study area, this explain the presence of the process of dissolution of carbonates. The excess of calcium, respect to the theoretical line in diagram, indicates the presence of additional processes underway in the area, such as ionic exchange.

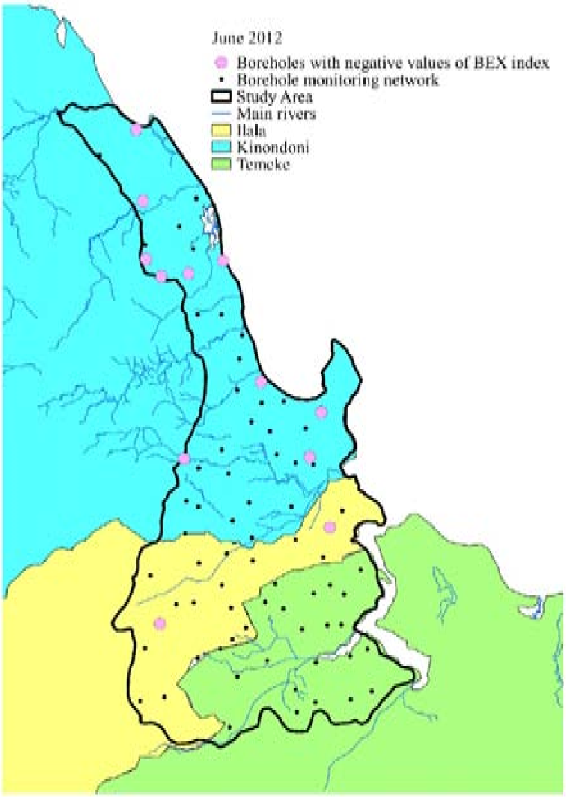



Fig.17, Stuyfzand classification: distribution of samples of Class 1 in June 2012.

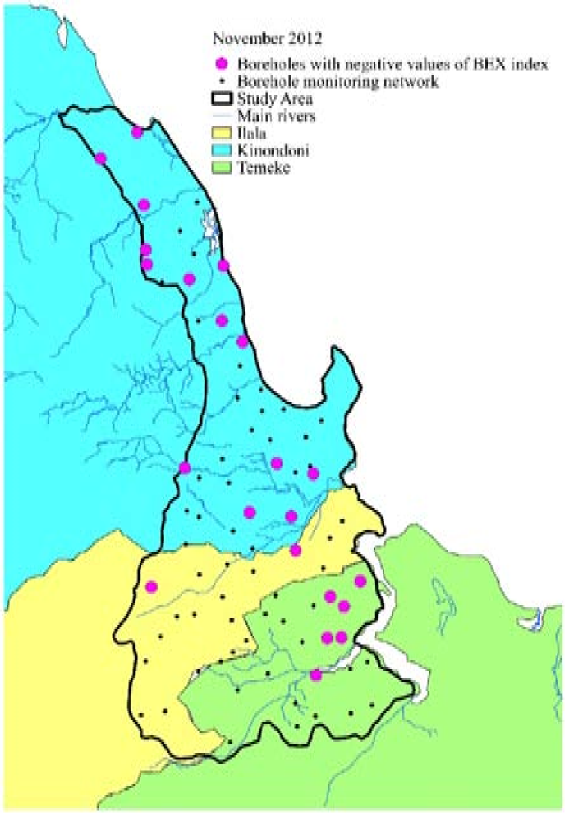



Fig.18, Stuyfzand classification: distribution of samples of Class 1 in November 2012.

This agrees with the depletion in sodium that occurs in previous diagrams of Na vs. Cl, thus the excess of Ca can be explained as a consequence of both the dissolution of carbonates and the ionic exchange process associated with seawater intrusion.

Concerning to Stuyfzand classification, analytical results show a slightly different distribution of samples in various classes for the two months of investigation. It can be seen a decrease in November of samples classified as brackish-salt (72.7% in June and 60% in November), but also (Fig.17 and Fig.18), a major number of samples with negative values of BEX index (21% in June, 33.3% in November), signifying an increase of number of boreholes with signals of seawater intrusion.

This occurs in particular in many boreholes in Temeke's districts and in some boreholes of the southern districts of Kinondoni, in the centre of the study area. The analysis of time series of rainfall data showed that the amount of rainfall has not decreased significantly over the period observed, so the decrease of the infiltration component in the water budget is primarily due to the reduction of infiltration areas, because of the increasing of urbanized area percentage. The geochemical analysis showed, for most of the sampled wells, an increase in the salinity of the water. The origin of this salinity is difficult to determine, because it may depend on several factors, including the punctual contamination from anthropogenic sources. However, analyzing the data with appropriate geochemical methods it was noted a significant presence of marine ions in the waters sampled, presumably due to sea intrusion in the coastal aquifer of Dar es Salaam.

This let us presume that seawater intrusion 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 depends.

The chemical analyzes have allowed to detect the effect of the alternation of periods of recharge and discharge for the aquifer in which, also because of more intense withdrawals, due to the lower availability of surface water, the salinization is more pronounced. Some differences in the chemical composition of water, recorded in certain areas of the study, could be attributed as to the lithology of the coastal aquifer, as to the use of the soil.

In particular, it was possible to notice some differences between a northern residential area, urbanized and equipped with primary services, and a southern area, more densely populated and characterized by a strong presence of informal settlements and agricultural areas. In the former, the salinization of groundwater is present in both seasons, this is due to urbanization, but, also, the origin of the salinity is, at least in part, attributable to the limestone composition of the aquifer. In the southern area, the fragmentation of the urban fabric makes more evident the effect of the alternance of seasons on the chemical composition of the waters, which are less salinized at the end of the rainy season and show more evident signs of seawater intrusion at the end of the dry season.

# 3 Problem Solution

In order to limit the aquifer over-exploitation, to make full benefit of groundwater potential and to protect groundwater quality, it would be beneficial the realization of dedicated groundwater monitoring networks. This could improve knowledge on safe yields of groundwater withdrawals, and could guarantee safety control on water quality. For example it could help the establishment of safety distances between human activities and boreholes used for domestic use. An adaptive water management plan for the city of Dar es Salaam, should integrate both centralized and decentralized approaches. It would be opportune the realization of an efficient water distribution network, which should be feed by freshwater coming from the uplands, appropriately collected through specific infrastructures and interventions, like dams and tanks. Moreover, based on specific knowledge gathered within the ACC-DAR project, the realization of some rainwater harvesting (RWH) interventions could be a valuable tool for adaptation to climate change, in some peri-urban areas of Dar es Salaam, where urbanization is not yet present in a continuous manner and local agriculture is an important source of livelihood for the population. RWH practices represent a decentralised and thus more flexible management approach. The use of the techniques of RWH in situ would have the effect of supporting the growth of crops, thus supporting the local economy. The creation of small infiltration basins would increase the amount of surface water that annually reaches the water table, thus enhancing this resource by improving its quality, obtainable using the filtering capacity of the soil, which promotes the reduction of pathogenic bacteria and contaminants.

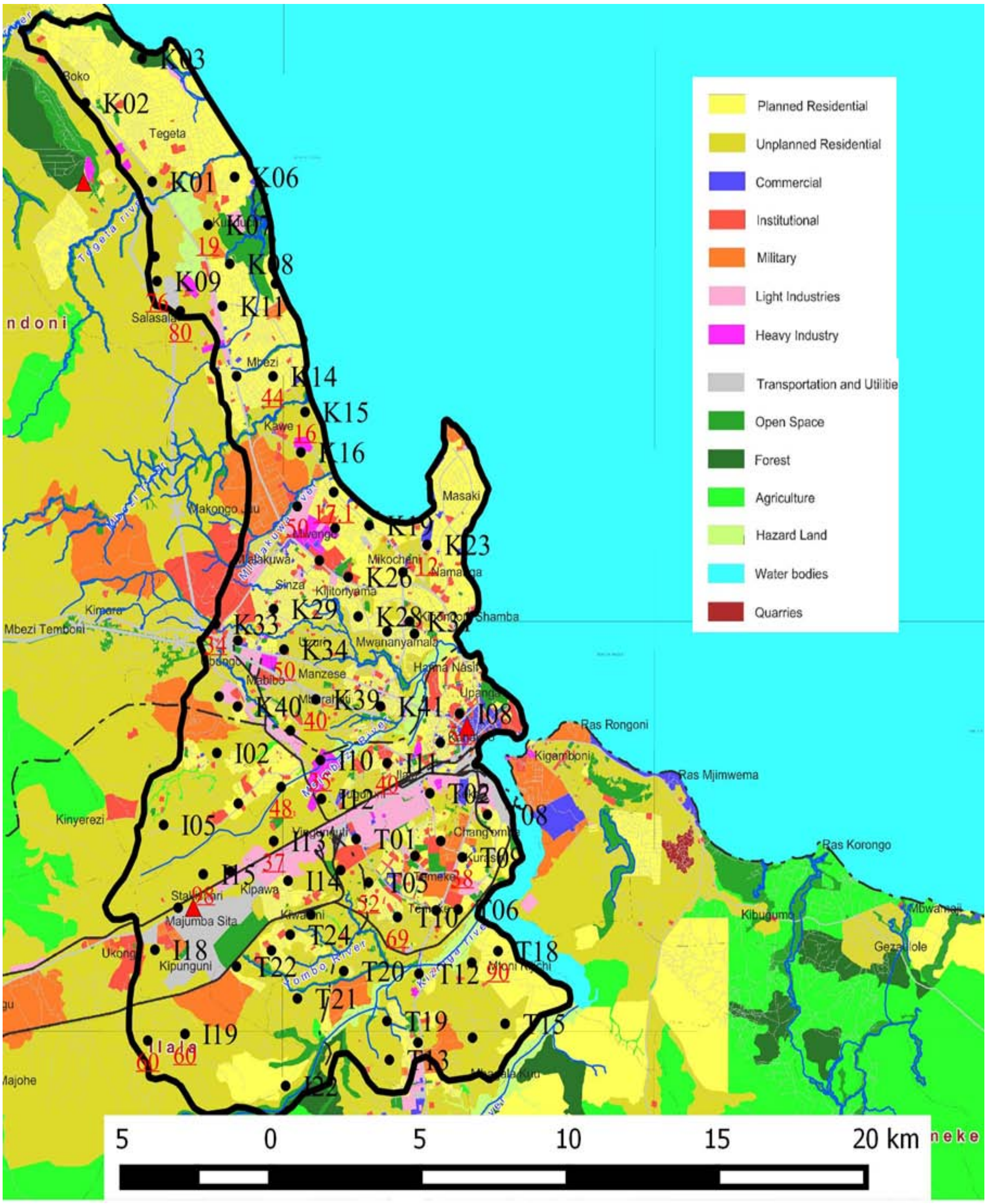



Fig. 19, Land cover

## 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.

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 groundwater availability decrease, on the one hand, and the increase in the estimated groundwater withdrawal, on the other one, 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.

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