Groundwater modelling simulating under human activity and climate change in Great Maputo aquifer, Mozambique

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1. Study area

1.1 Base information

The Great Maputo coastal aquifer system is located in southern Mozambique, which has an area of about 5,900 square kilometers. The aquifer contains the four most populous cities in Mozambique, namely: Maputo, Matola, Xinavane and Manhica (Fig. 1).

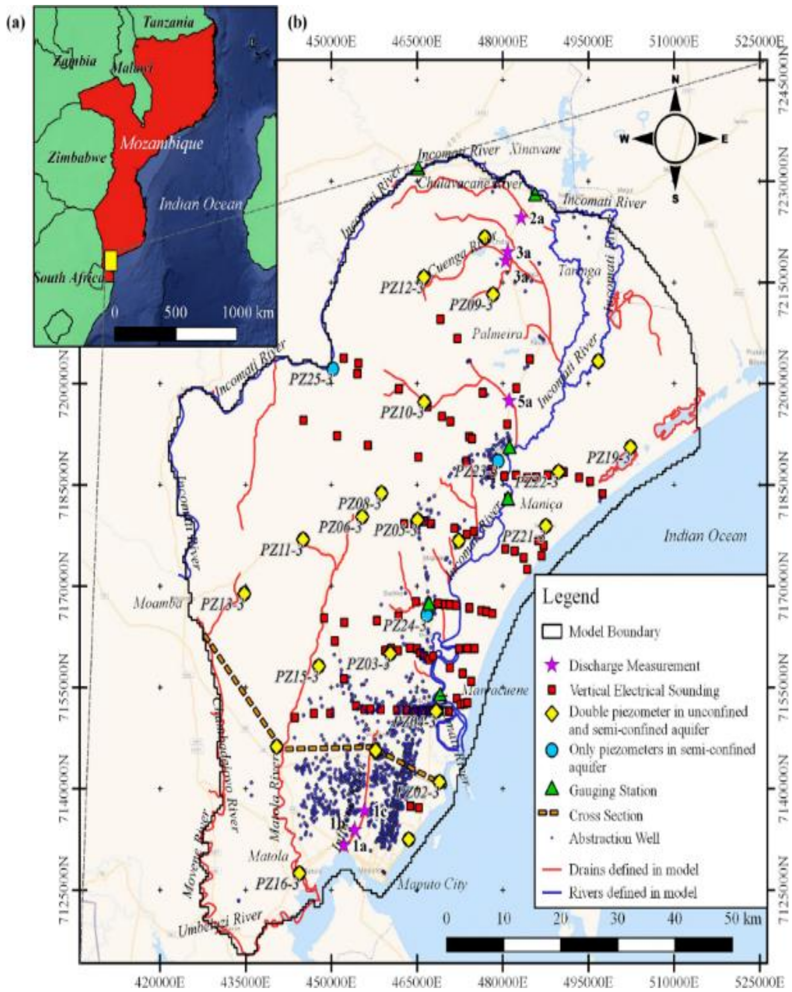


Fig. 1 Map of the study area (Alberto Casillas-Trasvina 2019)

The Indian Ocean is located on the southeast boundary of the aquifer, ridge Libombos is the western boundary, while Incomati river is the northern boundary. In 2016, the population of the area was approximately 2.4 million. Due to the large population growth caused by urban expansion, sanitation services and water supply cannot keep up. At the same time, the amount of available fresh water and potential for exploitation have been affected by the problem of inland salinization. The altitude of the area ranges from 0 to 125 meters and most of the terrain is flat.

1.2 Climate

The seasons in this area are divided into wet and arid, with high temperatures, moderate rainfall, and mild winters, which belongs to the tropical savanna climate. The average annual rainfall in the area is around 600 mm, rainfall is mainly concentrated between November and March. Meanwhile, the highest temperature is in January (27^{o}C), while the lowest temperature is in July (17^{o}C). However, the annual potential evapotranspiration is greater than the average rainfall value (Fig.2).

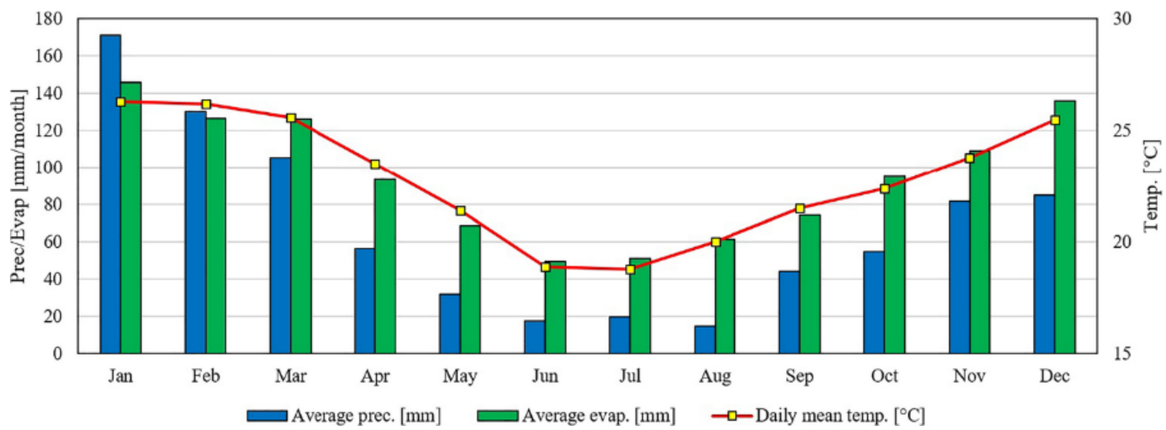


Fig. 2 Average monthly precipitation, temperature and potential evapotranspiration for the Great Maputo region, for the years 1961–1990 (Alberto Casillas-Trasvina 2019)

1.3 Hydrology

There are many perennial and ephemeral river sand streams in the area. In the model, the largest Incomati River is used as the river to simulate the water exchange between the river and groundwater. The study area is bordered by many countries, resulting in most of the freshwater being used for urban and agricultural irrigation.

1.4 Hydrogeology

In the aquifer, it is divided into an unconfined aquifer composed of fine-to-moderate sand dunes in the Quaternary, and a lower semi-closed aquifer composed of fine-to-coarse sand partially cemented and rich in calcium carbonate. There are about 1238 groundwater abstraction wells distributed around the cities of Maputo and Matola, while in other areas, the number of wells is very small, and the total annual abstraction rate is about 22Mm^3.

2. Methodology

2.1 Modelling objectives

In this modelling study, the objectives were to analyze underground flow system and identify recharge and discharge area, to simulate the effects of saltwater intrusion under natural and pumped conditions, and to assess future groundwater development potentials.

2.2 Modelling framework

In order to achieve the above objectives, and since the main factor restricting groundwater development is the risk of saltwater intrusion, a groundwater flow and saltwater transport model with coupled density were used. Since chloride is a conservative component and easy to measure, so chloride concentration is often used as an indicator for brine transport models.

However, chloride concentration measurements have only been possible in certain observation wells and 2017 extraction wells. The extraction of large amounts of groundwater began in 1968 and may have triggered saltwater intrusion. To simulate the possible impacts, the chloride transport model needs to be run between 1968 and 2017. The initial condition of chloride concentration in 1968 should be specified. Since there was no data for chloride measurement in 1968, a chloride precipitation model was used to create chloride concentration. Starting from the assumed saltwater source, the chloride evolution model was run from 1869 to 1968 until an equilibrium chloride distribution was reached. Therefore, in this study, a step-by-step modelling approach was adopted. First, establish a steady-state groundwater flow model with an average net recharge and discharge calculated, and use the measured hydraulic heads and measurements of discharges to calibrate. Second, construct a chloride transport model to simulate saline groundwater evolution in the last 100 years, from 1869 to 1968, under different assumptions about the origin of saltwater under natural conditions. Assume the steady-state natural groundwater flow condition for the simulation period. The chloride evolution model creates the initial conditions for a subsequent 50-year transport model from 1968 to 2017 under pumping conditions. Compare the computed Cl concentrations (from other papers) with measurements of recent years. Third, construct scenarios analysis models to assess groundwater development in relation to groundwater availability and saltwater intrusion impacts under different natural and artificial conditions.

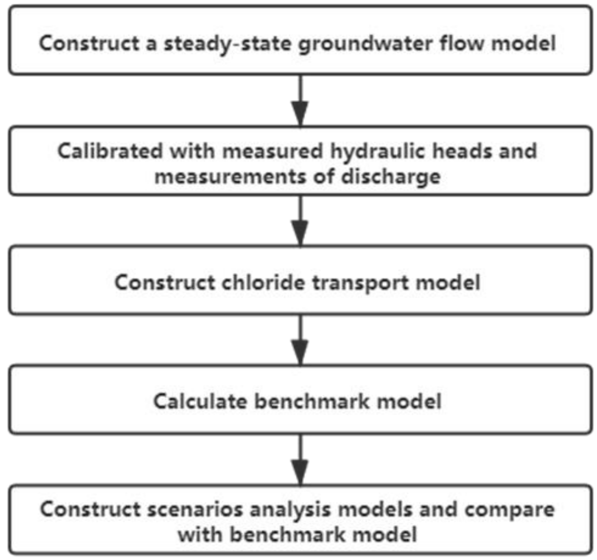


Fig. 3 Framework of the step-by-step modelling approach

2.3 Conceptual hydrological model

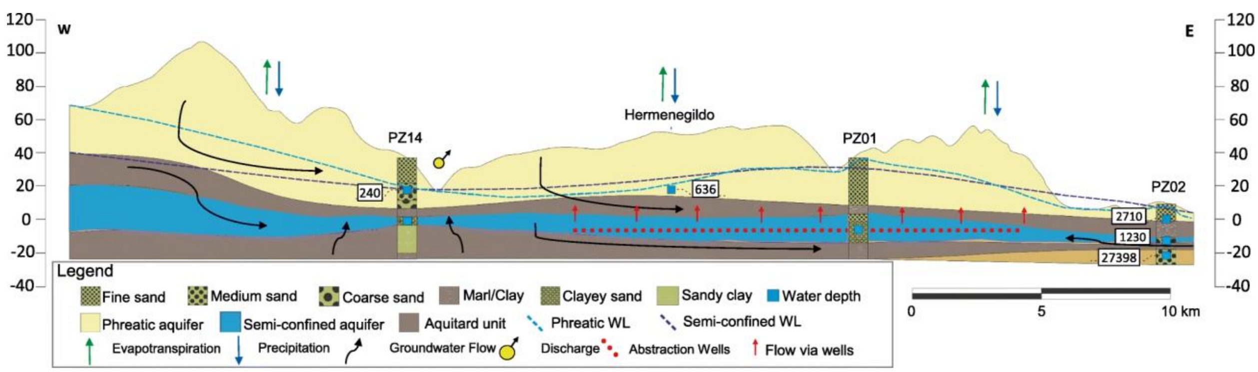


Fig. 4 Conceptual model profile of the groundwater system West to East (adapted from Nogueira 2017)

Based on a previous research (Hydroconseil and We-Consult 2011) and other hydrochemical information, Nogueira (2017) conceptualized the aquifer system into four hydrogeological layers (Fig. 4). The top layer constitutes a regional phreatic aquifer, including young sand dunes, clay-rich alluvial layers and old sand dunes. A regional aquitard built up of clay and silt is found below the phreatic aquifer. A semi-confined aquifer, consisting of fine-to-coarse sands rich in calcium carbonate, separates the regional aquitard from the bottom aquitard of clays and silts.

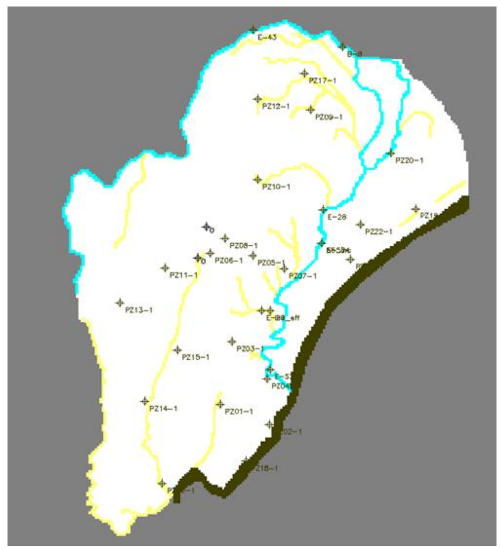
2.4 Model construction

2.4.1 Model domain and boundary condition

Firstly, a regular model grid with 224 rows and 248 columns has been formed by scattering the model area, which the size of cells is 500m*500m. Therefore, a new layering definition was carried out. Following the conceptualization of the area, 4 layers are varying in thickness. The elevations of these layers were determined relative to the surface.

Using these mapping tools, and carrying out the Kriging statistical interpolation method to get the elevations by using the software Surfer. It can produce a user-user defined spaced grid from XYZ given data, which is irregularly spaced (Golden Software 2014).

There are four model layers, which can represent the top phreatic aquifer, the first aquitard, semi-confined aquifer and the bottom aquitard. The thickness of layers was obtained from 97 vertical electrical soundings technology and 1131 geological boreholes data by using the Kriging interpolation method. Representation of spatial distribution of each layer is based on 4 factors. (1) The 25 lithological wells records. (2) 8 cross-section. (3) 97 geophysical measurements presented by WeConsult (2013) and ARA-Sul (2011), and (4) 30-meter Digital Elevation Model (DEM). Elevation of each layer was relevant with the surface elevation, which obtained from the 30-meter DEM (Casillas Trasvina, J.A. 2018).



The constructed model can be regarded as the regional groundwater flow and transport model. This model is enough to simulate the flow of simulated regional and transport mode.

The model boundary is shown in the graph. Among them, the north boundary follows the Incomati River and was simulated as a head-dependent flow boundary using the MODFLOW River package in the first model layer, while the other model layers were defined as no-flow boundaries. The east and south boundaries follow the coastline, which was viewed as a head-dependent flow boundary in the first layer using the MODFLOW GHB package (General-head boundary (GHB Package), which can be used to simulate the ocean at the South to South-eastern margins, and this can representing an of the part of Indian Sea.), and other layers in this section as a constant head boundary. The western border of all layers was defined as a no-flow boundary. To simulate the flow field a lot of boundary condition and parameter needs to be considered, such as constant head boundaries. Modflow will use these flow package to show the boundary conditions and put them into the aquifer stress.

2.4.2 Model Parameters

According to the geology and borehole data and we separated the six parameters zone in these two aquifers. The units reported by (WeConsult 2013) is taken from the regional hydrogeological map. This unit is the base of zonation and initial value for the horizontal hydraulic conductivities. Since there is no information about the change of K values with direction, the horizontal isotropy is assumed. That is the reason why the uniform value was specified. Results on horizontal hydraulic conductivities are presenting in Table 1.

Here are zones of horizontal hydraulic conductivities, for vertical hydraulic conductivities were assumed to be 10 % of the horizontal values. And these values were adjusted during the model calibration and optimization. For simulation time, the groundwater flow model was kept at steady-state and Cl transport model run with a constant transport step of 30 days for the future 50 years from 2017 to 2066.

Table 1. Horizontal hydraulic conductivities after calibration for different zones per layer and values for effective porosity and dispersivity

	Horizontal hydraulic conductivity (K_h) zones[m/day]					
Model layer	1	2	3	4	5	6
Unconfined aquifer	1	15	12	18	16	15
Aquitard (layer2)	0.5	1	1	1	0.1	1
Semi-confined aquifer	1	15	12	18	10	15
Aquitard (layer 4)	0.25	0.25	0.25	0.25	0.25	0.25

Effective porosity	Dispersivity Longitudinal [m]	Transversal Horizontal	Transversal Vertical
0.3	10	0.1	0.01
0.15	10	0.1	0.01
0.3	10	0.1	0.01
0.15	1	0.1	0.001

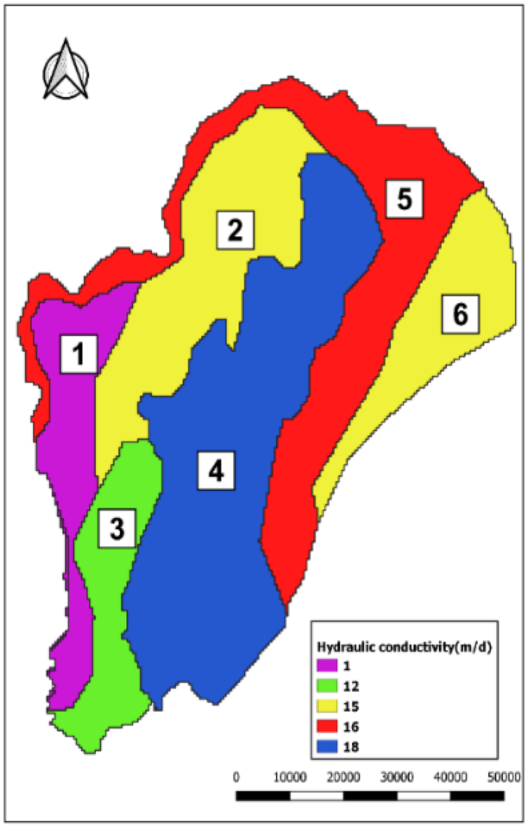


Fig. 5 zone of horizontal hydraulic conductivities

2.4.3 Hydrological stresses

The model includes four hydrological stresses, precipitation recharge, interactions with the Incomati River, discharge to streams, and groundwater abstraction. Using the spreadsheet, according to the groundwater recharge from precipitation infiltration was computed with a daily soil-water balance. Because the soil and water balance model include the interception and evapotranspiration, so the result of recharge can seem as net groundwater recharge.

(1）Precipitation recharge:

Groundwater recharge from precipitation infiltration was delineated into 12 recharge zones as shown in the graph based on the topography, soil types and land use (Fig.6).

The Incomati River flows from the north to the south across the model area. From the literature, it is indicated that the groundwater discharges to the river in this section.

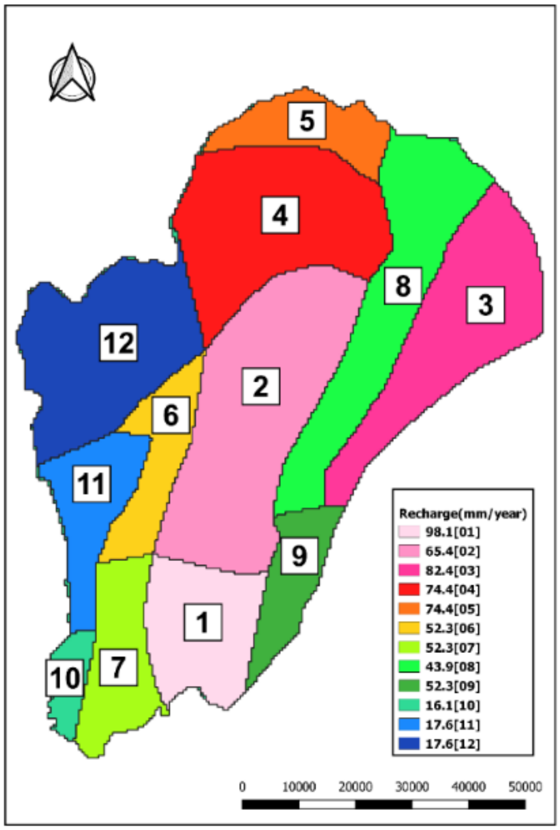


Fig.6 zone of recharge

(2) Interaction with the Incomati River:

Bounding the system of North to North-Western margins, which to simulate Incomati River. This behaviour can make Incomati River as a groundwater divide from which water can flow in/out of the system. The river elevation is digitized from the 30-meter DEM

(3) Discharge to stream:

So the river package was used to simulate groundwater discharge to and possible recharge from the river. Besides, many small streams receive groundwater discharge, therefore The Drain package was used to simulate them.

(4) Groundwater abstraction:

The drains are shown as the yellow line in the Fig.7. And the good package was used to simulate for 735 abstraction wells in the model. Also, the discharge values the model computed were used to compare with the measured values in the field during the model calibration.

2.4.4 Saltwater sources

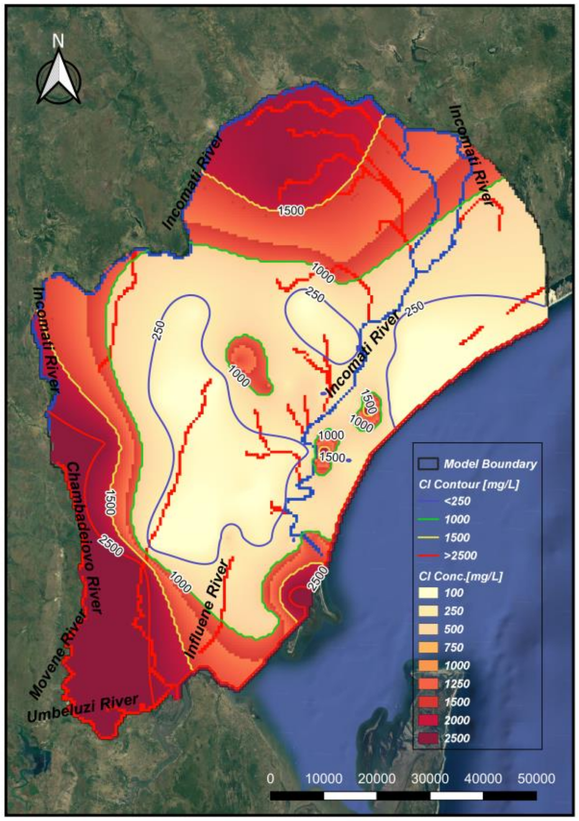


Fig.7 Initial concentration in the second aquitard (layer 4) in 1869

There are four saltwater resources have been considered, during the model simulation of the initial chloride concentration of natural saltwater, which hypothesis by Dr Nogueira(2017).

1. General-Head boundary and constant head cell with a constant chloride concentration, which can represent the sea.

2. The previous water sampling analysis can get the chloride concentration of the Incomati River, which did by Okello et al. (2012).

3. Since the precipitation will distribute on the defined recharge zone, so we can use the previous data and the distance from the sea to estimate the chloride concentration.

The method is showing below.

$Cp+D$ (mg/l), can be done from Hutton (1976) using:

$$C_{p+D} = 35.45 * (\frac{0.99}{d^{0.25}} - 0.23)$$

d is the distance from the sea (km).

4. According to the sampling activity finished by Dr Nogueira(2017), find out that chloride concentration is related to EC.

$$For\ EC \ \leq 1500; Cl^{-} = 0.1569EC - 1.6$$

$$For\ EC\ \geq 2500; Cl^{-} = 0.3887EC - 561.3$$

Then using VES and piezometer locations to obtain the formation resistivity, and using EC to estimate the chloride concentration, which might not be accurate, but it can show other information, such as the distribution of chloride.

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Our model did not obtain the observed chloride concentrations in 2017 to simulate the future situation. So based on the hypotheses presented by Dr Nogueira regarding potential entrapped fossil saline water of aquitard formations into aquifers, we used the specified chloride concentration by a chloride evolution model in 1869 as the initial condition of chloride concentrations to run over 150 years from 1869 to 2017 from the assumed saltwater sources to obtain the simulated chloride concentration in 2017, and then we used this simulation result to simulate the future situation of this area in transport model from 2017 to 2066. Here is the 2017 chloride concentrations distribution in the unconfined aquifer and the semi-confined aquifer. From the chloride distribution map, we can know that chloride mainly distributes in the western area of Matola River and the northeast area. And the General-head boundary and constant-head cells with a constant chloride concentration of 19,000 mg/L representing the sea. The concentration of precipitation recharge value is set up as Alberto master thesis. (Alberto,2018)

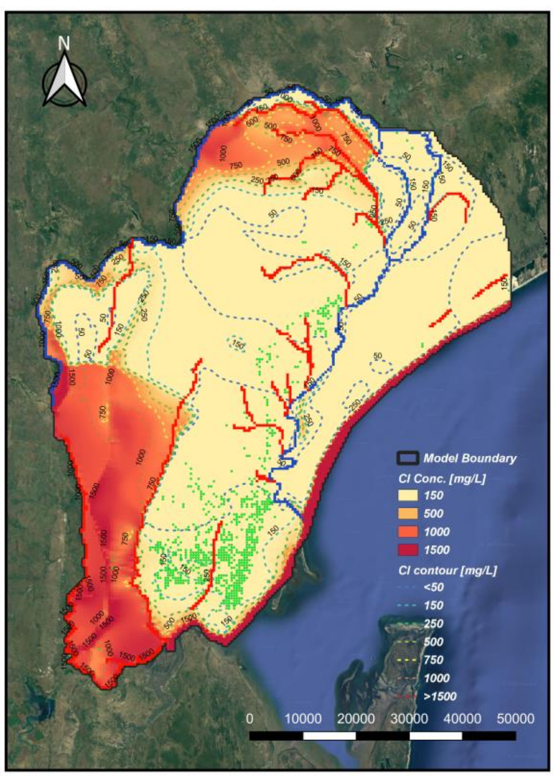

Fig.8 Semi confined concentration in 2017(initial concentration for transport modelling)

2.4.5 Model calibration

The purpose of calibration is the adjustment of parameters until the comparison between the model outputs and the observed values on the field can match (Moore and Doherty 2006). In this part, we calibrated the groundwater model manually, only calibrated the head values of the submerged layer and semi-confined aquifer, and compared the simulated values with the observed values, and finally carried out statistical analysis.

2.5 Formulation of scenarios

Three scenarios were used to compare with the benchmark model, and these scenarios took into account that the saltwater transportation has been simulated for 50 years to reach equilibrium (2017-2066). The groundwater flow model has remained stable, and at the same time, the Cl transmission model has remained stable with a step of 30 days. In addition, compare the calculated Cl concentration at the end of each year.

(1) Benchmark situation

In the simulation model, normal hydrological conditions and current abstractions were used. Cl model transportation simulates saltwater groundwater level and salinity distribution in 2017 to 2066. Compare the results of these models with the results of the comparison scenarios model.

(2) Scenario 1: planned new abstractions

We have newly constructed 23 abstraction wells to meet water supply needs, these wells are mainly along the Infulene River. The total abstraction rate of these new wells is 11.83Mm3/year, so the total abstraction rate will be increased to 33.8Mm3/year.

(3) Scenario 2: sea-level rise

According to the predictions of Serdeczny et al (2017)., the average sea level rise in the Maputo region by 0.75m at the end of this century may bring the risk of seawater intrusion in coastal areas. In order to simulate any possible effects, the cases where the sea level rises to 1 meter and 1.5 meters are used.

(4) Scenario 3: precipitation recharge decreasing

Climate change can not only cause seal level rising, but also may lead to extreme climate possibility increasing. In Great Maputo aquifer area, the main source of recharge is from precipitation, which is also one of most important stress in our groundwater modelling. So, under climate changing conditions, the increasing possibility of extreme drought in Africa gives much heavier pressure on available groundwater resources. In this scenario, our group simulates the situation with higher chance of drought by decreasing precipitation recharge.

3. Results and discussion

3.1 Model calibration

In the model calibration part, the steady state groundwater flow model was calibrated by hand. The calculated groundwater heads data and the observed water heads were used to draw scatter plot of them. The result is shown in Figure 9 and the calibration statistics of the model is shown in the Table 2. From the graph, it is clear that the trend line of the calculated groundwater heads against the observed values in the phreatic and semi-confined aquifer is almost parallel to the 1:1 line, indicating that there was a good fit between the calculated values and observed values. In addition, from the statistics table, it is also known that the calculated water heads and observed heads show a pretty high correlation coefficient of 0.91 for both phreatic aquifer and semi-confined aquifer.

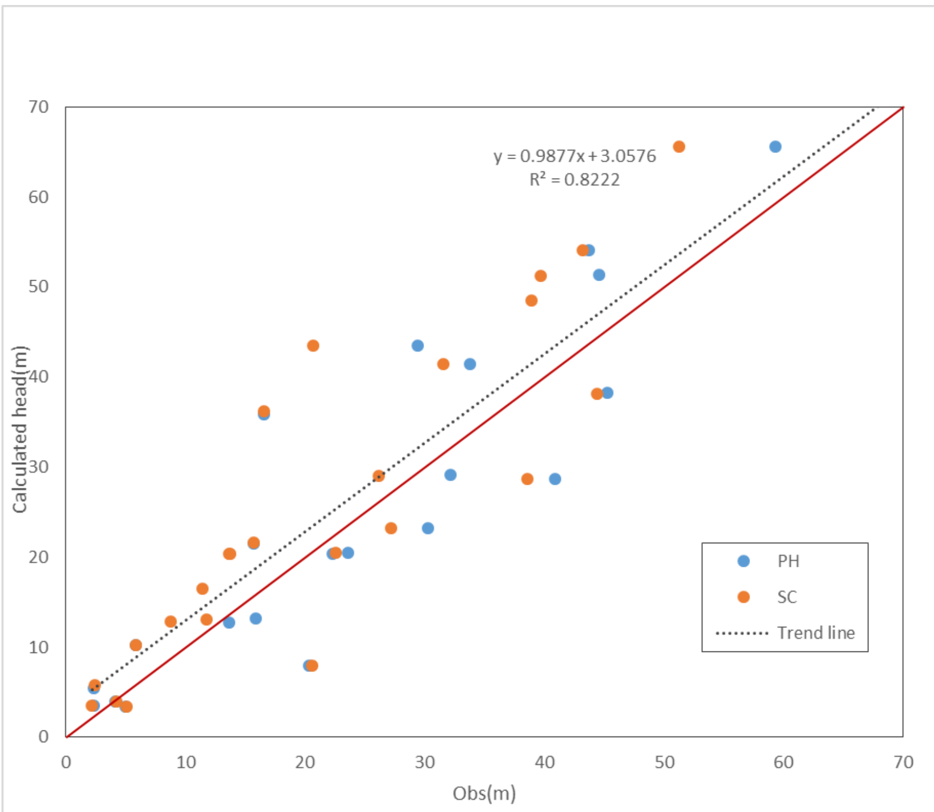

Fig.9 The calculated head against the observed head in the phreatic and semi-confined aquifer

Table 2 The statistics of the groundwater flow model calibration

	overall	Phreatic	Semi-confined
ME	-2.75077	-0.69948	-4.55591
RMSE	8.784494	8.063442	9.373248
MAE	7.008887	6.43806	7.511214

CORRELATIO N	0.906769	0.919509	0.910519
SRMSE	0.10509		

Even though the root mean squared error RMSE is a little bit large, but the value of 10% indicates that it is only a small proportion of the total variation of groundwater heads in the area. Thus, the calibrated groundwater flow model is feasible and acceptable for the analysis of the groundwater flow model and water budget and build the chloride transport model.

3.2 Benchmark model results

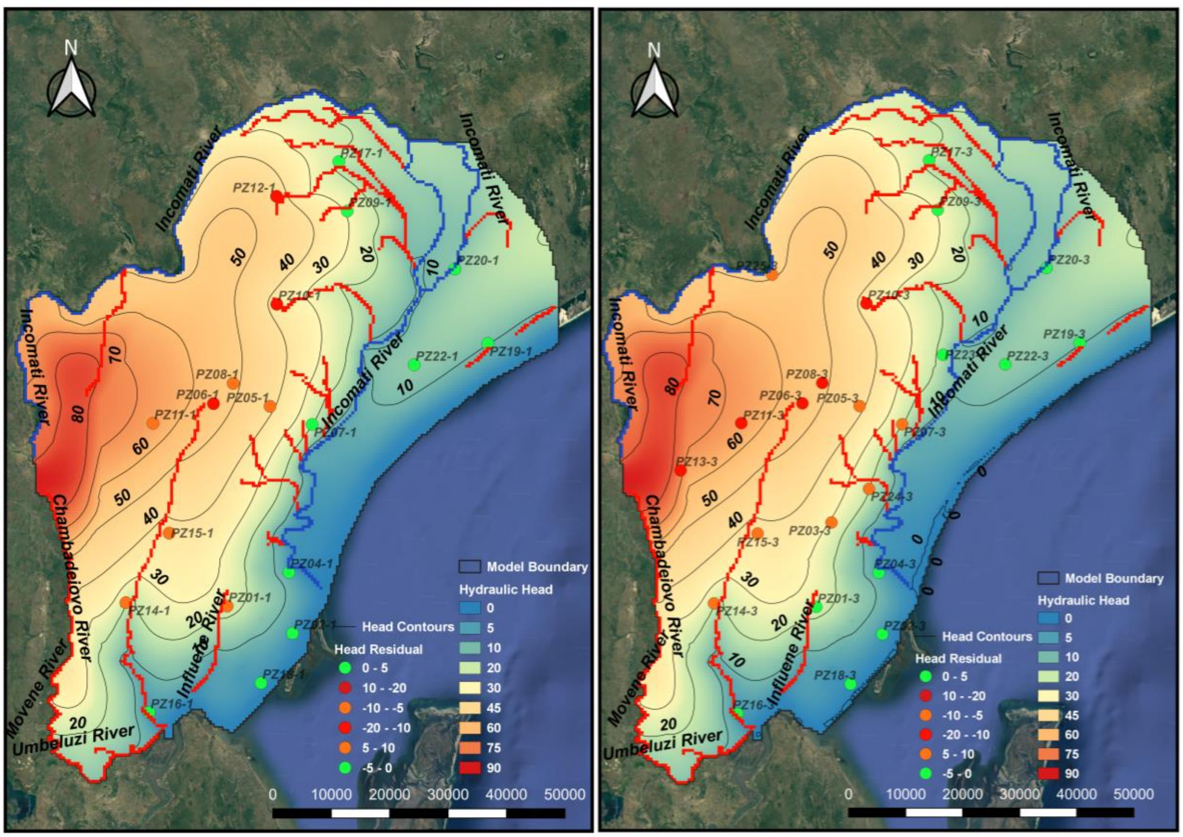

Fig.10 Contour lines of hydraulic head in unconfined and semi-confined aquifer

Figure 10 presents the contour lines of hydraulic head of Maputo benchmark steady state flow model. The contour maps show that the hydraulic head of groundwater is higher in west and lower in southeast, which is consistent with the trend of topography. From Figure, we also can identify the interaction between surface water and groundwater. Same as previous analysis and model setting, red drains in Figure are obviously determined discharge area for both unconfined and semi-confined aquifer and Incomati River mainly is recharge area and only some parts of downstream of Incomati River are discharge.

Table 3 Mass budget in benchmark model

Hydrologic Terms	Benchmark model	
	In	Out
Discharge to sea	3.3	69.6
Abstraction	0	22
Discharge to stream	0	162
Discharge to River	3.3	109.5
Recharge from precipitation	356.5	0
Sum	363.1	363.1

The groundwater budget of total aquifers is listed in Table 3. Precipitation occupies for over 98% of recharge, which is the main source of groundwater in this area. Except rainfall recharge, there are few recharge from Incomati River (1%) and seawater intrusion (1%). Oppositely, the discharges are more distributed, to streams (44.6%), to Incomati River (30.2%), to sea (19.2%), and abstracted for human activities (6%). Obviously, groundwater abstraction is relativity low and the preliminary conclusion is that some capacity of groundwater abstraction is left under current conditions. We will assess whether the abstraction rate can increase with no saltwater intrusion in Scenario 1and if increasing is allowed how much capacity can be added.

Chloride contribution in different three years in semi-confined aquifer is presented in Fig.11 below, which is from chloride transport modelling results. No obvious difference can be identified in Fig.11. This means that the chloride transport keep steady state in the 50-years period of simulating. There are almost no seawater intrusion and saltwater intrusion from the second aquitard (layer 4).

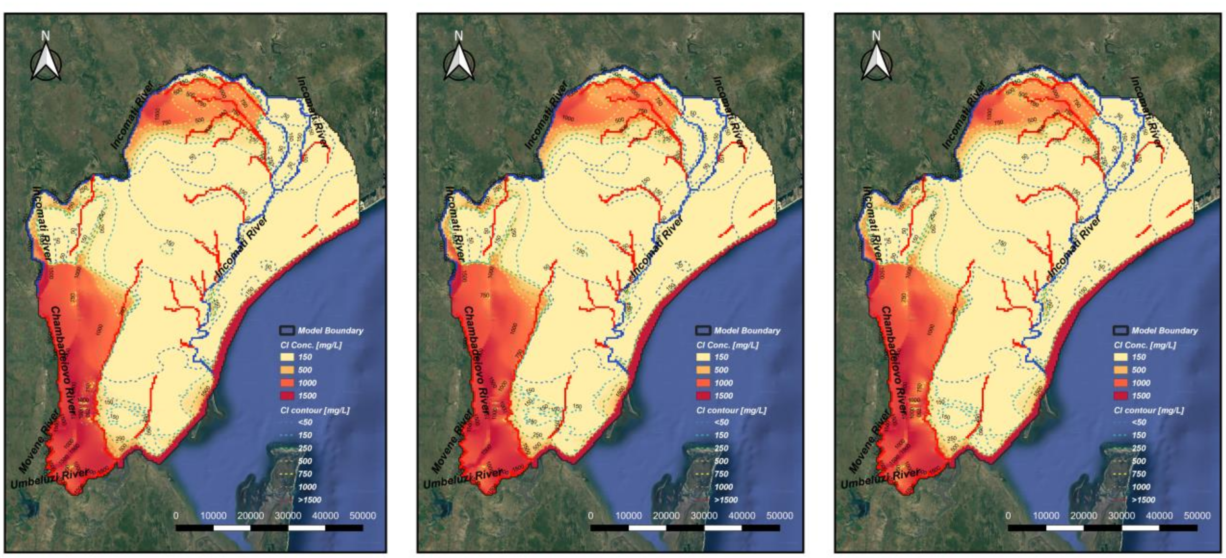

Fig. 11 Chloride distributions in semi-confined aquifers in 2018, 2041 and 2066

3.3 Simulation of Scenarios

3.3.1 Scenario 1: abstraction increase

As mentioned above, , there is a plan to increase total capacity of the abstraction by constructing 23 new abstraction wells so as to meet the demand of water supply in the urban and suburban area of Maputo. The model was built to inspect the impacts of installing these new abstraction wells in the semi-confined aquifer with the estimated pumping rates on the groundwater level, water budget and salinization processes in the period of 50 years from 2017 to 2066. Setting up the new abstraction model was on the basis of the Benchmark model by creating new pumping wells in the MODFLOW cells being set the pumping rates by using the WELL package. The majority of the newly installed extraction wells are distributed averagely in the urban area along with the Infulene River. The locations of these 23 new wells are shown in Fig.12.

The planned capacity of these new abstraction wells are to be 11. 83 Mm^3/year. Hence, the Total abstraction ability will reach to 33.8Mm^3/year. Each of the coordinates and the pumping rates of these new wells are listed in Table 4.

Table 4 The coordinates and pumping rate of the new abstraction wells

Name	X	Y	Pumping Rate(m^3/d)
NW1	458737.2	7156160	400
NW2	456654.9	7146833	800
NW3	457923.7	7146833	2000
NW4	456194	7146301	2400
NW5	4562781.1	7144786	4500
NW6	465029	7144801	400
NW7	455352.7	7144365	1800
NW8	461073.5	7144534	600
NW9	466289.6	7144281	1800
NW10	456698.8	7143860	2000
NW11	456147.3	7143276	1000
NW12	456362.3	7142682	3500
NW13	456316.5	7141413	3500
NW14	456194	7139147	1200
NW15	455301.5	7137348	600
NW16	459138.5	7137295	600
NW17	455857.5	7136706	500
NW18	459700	7135316	400
NW19	455727	7134745	1600

NW20	454195.3	7133233	1000
NW21	453670.1	7132666	600
NW22	457754.5	7130912	800
NW23	458381.4	7129804	1500

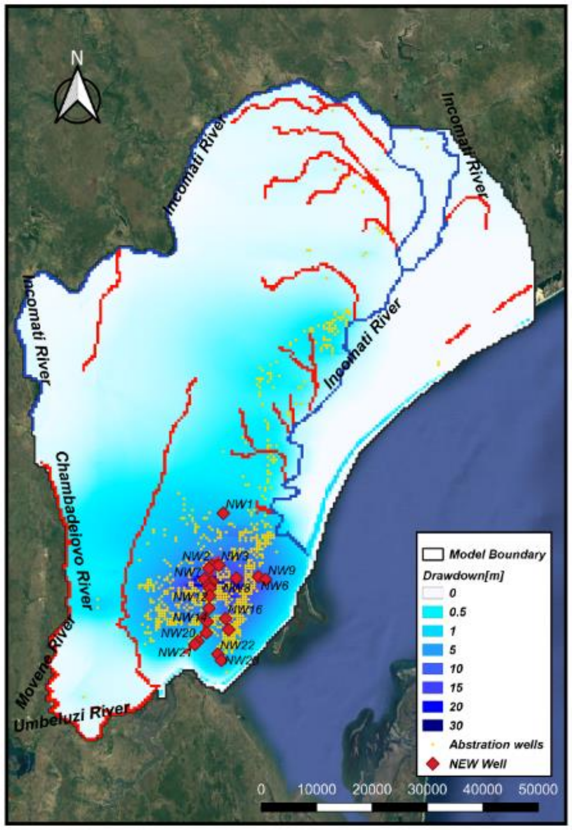

Fig.12 The locations of new abstraction wells and the cone of depression in semi-confined aquifer in 2066

(1) Water Budget

Increasing the total abstraction capacity directly affects the groundwater discharge to streams and rivers. From the water budget shown in the Table 5, it is obvious that the reduction of total groundwater discharge to drains decreases by 5% from 162 Mm^3/year to 154.5Mm^3/year. At the meanwhile, the discharge to river also reduce by 1% from 109.5 Mm^3 to 107.9Mm^3, this is primarily because only very small part of rivers were situated at within the radius of influence of the abstraction wells. Additionally, it is also indicated that the amount of sea water flowing into aquifer increases from 3.3 Mm^3/year to 4.1 Mm^3/year, nearly rises by 33.3% comparing to Benchmark model, which means that increasing the abstraction in Maputo can give rise to more saline intrusion. Furthermore, in the water budget, the quantity of the abstraction are increased by 31% from 22Mm^3/year to 32Mm^3/year, however, it is found that the result of simulated total abstraction in water budget is different from the initially setting value of 33.83Mm3/year. It is mainly because highly productive abstraction leads to not enough water to be abstracted in the aquifer, causing the phreatic aquifer to be dry in the part of urban area.

Table 5 The water budget of Scenarios 1 and Benchmark model after 50 years

Flow Term	Scenario 1		Benchmark Model	
	In(Mm^3/year)	Out(Mm^3/year)	In(Mm3/year)	Out(Mm^3/year)
Discharge to sea	4.1	66.2	3.3	69.6
Abstraction	0	32	0	22
Discharge to stream	0	154.5	0	162
Discharge to River	3.3	107.9	3.3	109.5
Recharge	353.1	0	356.5	0
Sum	360.5	360.5	363.5	363.1

From the Figure 13, it can be seen that the precipitation account for 98% of the total recharge to groundwater in the study area while the sea water entered into groundwater is 1% and the recharge from river is only 1%. For outflows, it is known that the most of groundwater discharge is to the streams and rivers with the proportion of 43% and 30% respectively. Besides, discharge to the sea is about 18% under the naturally hydraulic gradient from west to east and from north to south. While the abstraction accounts for 9%.

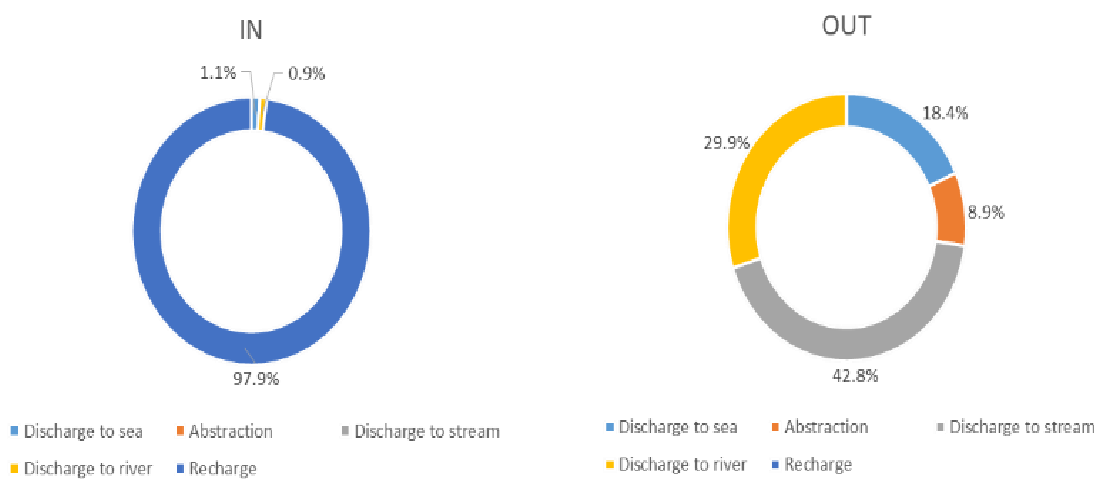

Fig.13 Water budget for inflow and outflow

(2) Drawdown

From the Figure 12, it can be known that there is a cone of depression located in the well field in the semi-confined aquifer and it has a wide range of influence. The drawdown varies from 0.5m to 34m, where the maximum drawdown generated by these pumping wells in the high dense of abstraction well locations approached to 34 meters more or less. It is definitely indicated that the large exploitation of groundwater abstraction will cause very large cone of depression and make the phreatic aquifer become dry and finally will lead to the large amount of groundwater loss in the semi-confined aquifer, which can give rise to not possibly recover completely and seawater intrusion along the coastline. Furthermore, based on the Figure 14 which describes the groundwater heads in the phreatic aquifer in 2066, there will be a small empty area which reflects no available water for abstracting anymore in that area. It is consistent with the result of water budget mentioned above.

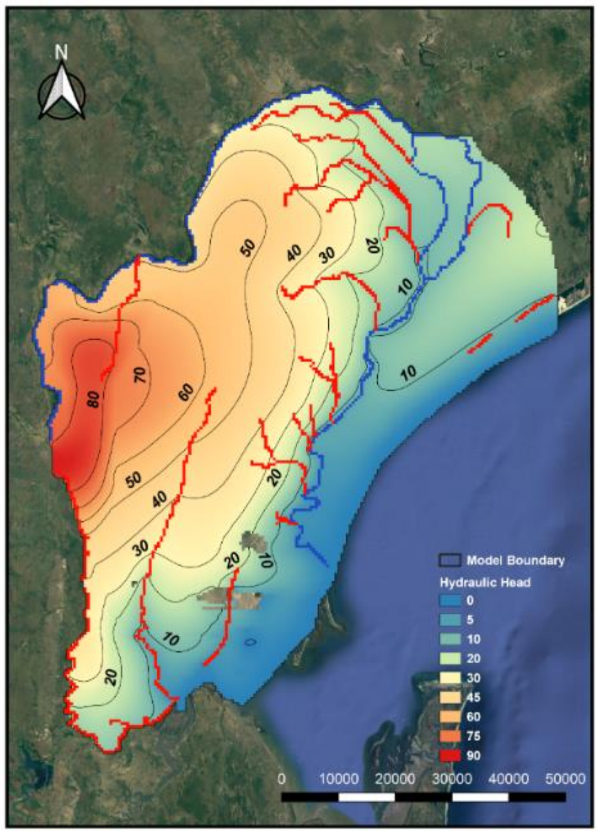

Fig.14 Groundwater heads in the phreatic aquifer in 2066

(3) Cl breakthrough curve

Some of added new wells were chosen as the chloride concentration observation wells which were marked in the Figure 15. After running 50 years from 2017 to 2066, the chloride concentration against time breakthrough curves of these selected observation wells were produced and shown in Figure 16. The table 6 presents the chloride concentration in the observation wells at the last transport step.

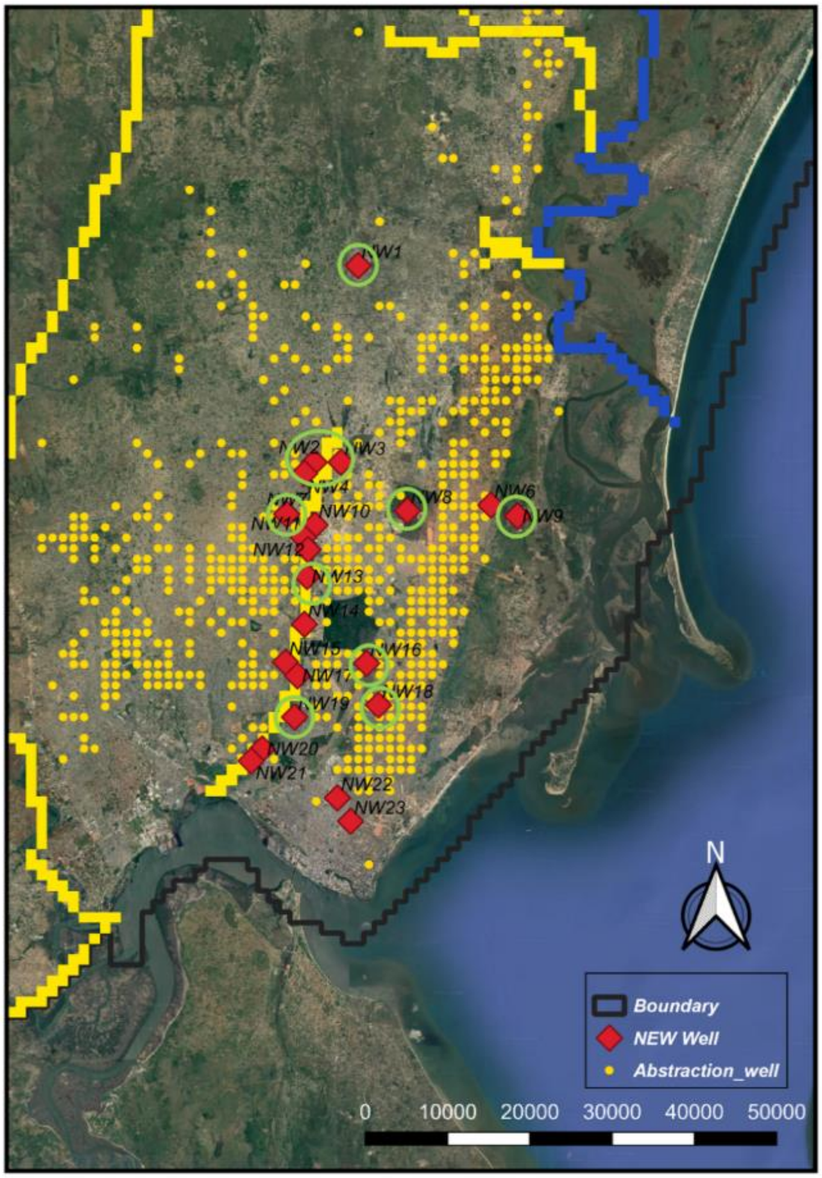

Fig.15 The locations of the selected Cl concentration observation wells

Table 6 the simulated results of the Cl concentration in observation wells in 2066

Name	Observed Cl concentration in (mg/l)
NW1	56.55
NW2	78.44
NW3	89.47
NW4	96.55
NW7	101.91
NW8	88.30

NW9	156.76
NW13	121.77
NW16	109.95
NW18	109.99
NW19	153.73

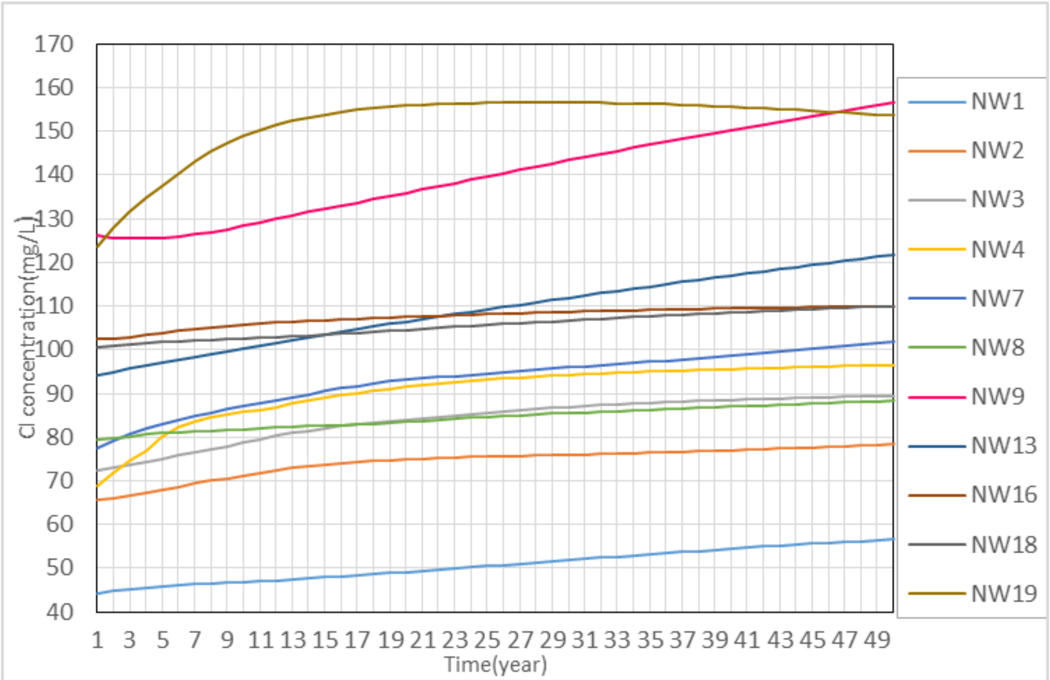

Fig.16 Concentration-time breakthrough curves of the observation wells

From the Figure 16 and Table 6, it can be known that there is an increase of Cl concentration in all observation wells after 50 years, where the variation range of NW4, NW7, NW9, NW13, NW19 are more than 24 mg/l while that of NW1, NW2, NW3, NW8, NW16 and NW18 is between 7.4 mg/l and 17 mg/l. Besides, for those wells located along the Infulene River including the NW2, NW3, NW4, NW7, NW13 and NW19, there is an increase of Cl concentration for these wells from north to south. The initial Cl concentration distribution map of 4th semi-permeable layer can explain this situation, it is because there is a higher Cl concentration distribution under the southern Infulene River than that of the north in semi-permeable aquitard, when abstracting groundwater from the semi-confined aquifer, it will lead to the quantity of salt water in the 4th layer flowing into the aquifer because of the change of the hydraulic gradient between these two layers. Thus, comparing to northern river area, more saltwater are extracted, resulting in larger chloride concentration in southern abstraction wells. Besides, it also because the wells located in southern area is closer to the ocean, the increase of the Cl concentration also is caused by the seawater intrusion. In terms of NW9, there is a high chloride concentration with the value of 156 mg/l, this well is close to the sea comparing to other wells, thus the saline intrusion has more influence on it when abstracting groundwater from the aquifer, as a result of much higher Cl concentration and larger variation of concentration than the rest wells. However, the NW8 near it has relatively low Cl concentration, it is due to that NW8 is situated in the area with lower density of installing abstraction wells and also has a lower abstraction capacity of 600m3/d. For NW19 with the Cl concentration of 153mg/l and bigger variation, it is because of the more saltwater entering into aquifer in that area as mentioned above together with seawater intrusion effect. Regarding the NW13 with the value of 121mg/l, it is larger than those of wells near it, except salt water in 4th layer, it is also because NW13 and NW12 which is very close to it have much larger abstraction capacity of 3500m3/d, thus it has a large impact on the Cl concentration. NW1, NW2, NW3 and NW4 have a lower Cl concentration due to relatively small distance to the sea and saltwater area in the south.NW1 has a lowest value of chloride concentration, because it is the farthest well to the sea.

3.3.2 Scenario 2: mean sea level increase

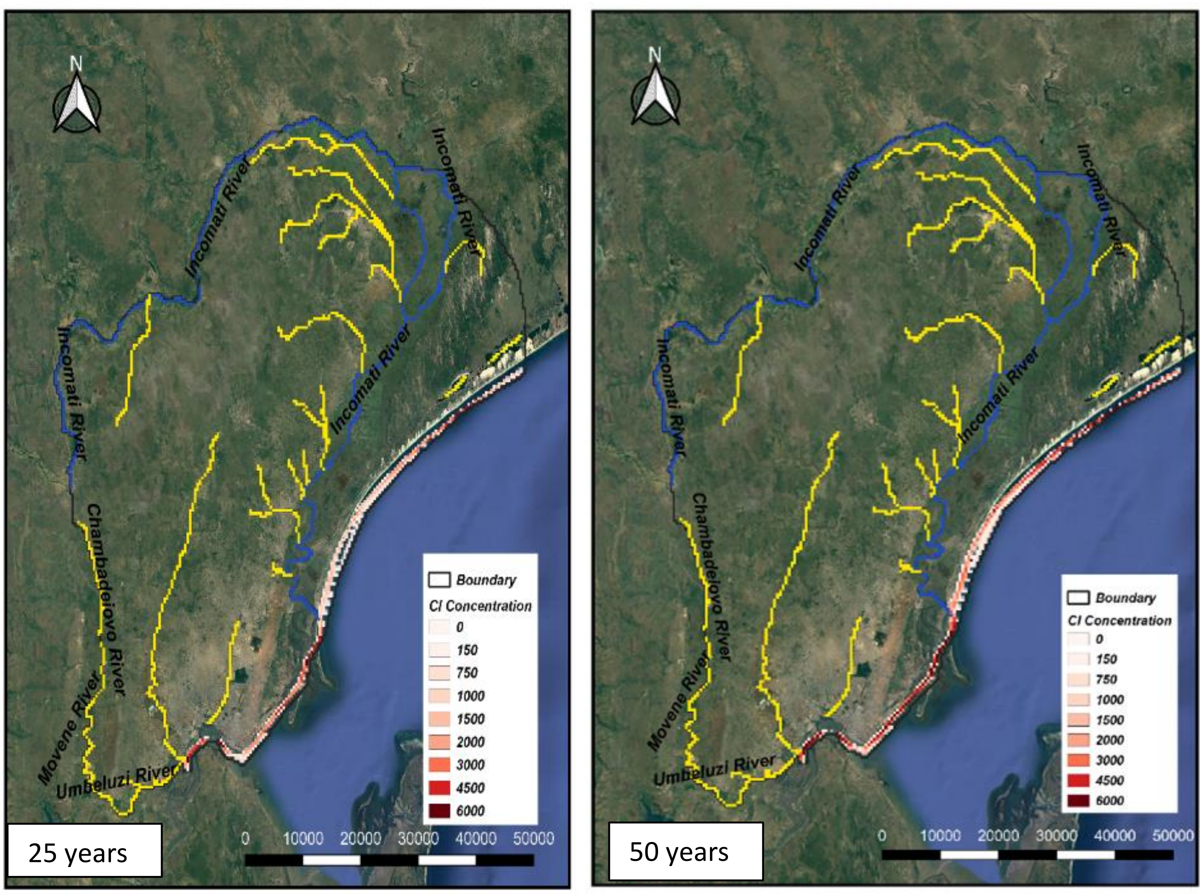

Fig.17 The difference of chloride concentration in semi-confined aquifer between basic model and sea level rise model at 25 years and 50 years

Many studies have shown that due to climate change, the temperature gradually rise and the sea level will rise. In the last one hundred years, Gornitz et al (1982) estimated that sea level has risen about 12mm per year. Barnett (1983) said sea level has risen 15mm/year probably. IPCC also mentioned that by 2099, the maximum sea level rise might be 60 cm.
For scenario of sea level rise, our group has increased the sea level to 1m and 1.5m respectively, the concentration of chloride hardly changed in inland area after 25 and 50 years. This also shows that the seawater intrusion caused by sea level rise has little impact on the inland areas. By observing the color change in Fig.17, it can be concluded that the chloride ion concentration changes greatly along the coast. After 25 years, the chloride ion concentration increased compared with before. After 50 years, the chloride ion concentration is higher than that after 25 years. This shows that the impact of seawater intrusion is significant on the coast and in the estuary. Nevertheless, this kind of influence also only exists in the place very close to the sea, so we do not need worry too much about its influence in inland.

Table 7 groundwater budget at different sea level

Hydrologic terms	**Benchmark model**		**Sea level rise 1 m**		**sea level rise 1.5m**	
	In	Out	In	Out	In	Out
Discharge to the sea	3.3	69.6	20.9	85.9	32.2	96.5
Abstractions	0	22	0	22	0	22
Discharge to stream	0	162	0	162.6	0	163
River leakage	3.3	109.5	3.3	110.1	3.3	110.5
Recharge	356.5	0	356.5	0	356.5	0
Sum	363.5	363.1	380.7	380.6	392	392

At the same time, we see the inflow of discharge to the sea increased from table 7 and other components have not changed much, which also confirms sea water intrusion and means that seawater intrusion has increased compared to before. In addition, we also see that there is still a lot of outflow from discharge to the sea. The seawater intrusion did not go further to affect the inland areas.
In short, sea level intrusion will not have a significant impact in the whole area when the sea level is predicted to increase by 60 cm in the future.

3.3.3 Scenario 3: recharge condition change

In scenario 3, we decrease precipitation recharge by 20% to simulate drought increasing under climate change condition. Some blank area in unconfined aquifer is shown in Figure. These blank area represent no water in the unconfined aquifer. And the hydraulic head in this scenario declines compared with benchmark model. These indicates that the groundwater storage of aquifer also declines and depression is obviously formed. These results indicates the 20% decreasing of recharge has a large impact on groundwater available. The defectiveness of this scenario simulating is that flow modeling is steady state, so the process of groundwater storage and hydraulic head change cannot be described. So far, we haven't had the data of specific storage and specific yield parameters, so we didn't simulate translate flow modelling.

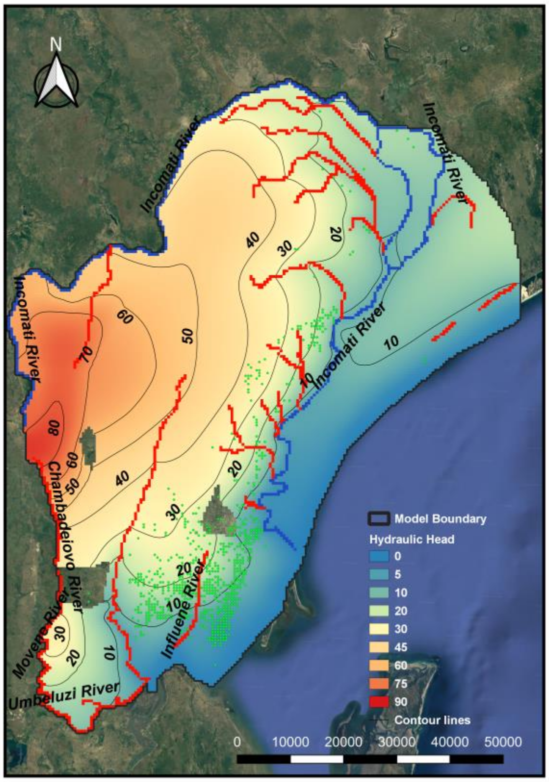

Fig.18 Contour lines in unconfined aquifer with scenario 3 decreasing precipitation recharge

Table 8 Water budget of scenario 3 and Benchmark model

Flow Term	Scenario 3		Benchmark Model	
	In(Mm^3/year)	Out(Mm^3/year)	In(Mm3/year)	Out(Mm^3/year)
Discharge to sea	5.2	60.3	3.3	69.6
Abstraction	0	22	0	22
Discharge to stream	0	120.8	0	162
Discharge to River	3.9	87.5	3.3	109.5
Recharge	281.5	0	356.5	0
Sum	290.6	290.5	363.5	363.1

4. Conclusion and recommendation

1. In our study area, the groundwater has already provided a good addition to the insufficient domestic water shortage to achieve the centralized public water supply, now it can provide water for most of the family in the city. In the future, the domestic water shortage will appear more seriously with the increase of population, which the groundwater can be a stable resource to solve this problem.
2. Then using the limited hydrogeological data and preliminary calibrations which were performed in this study we can establish the model. This model can investigate the potential impacts of sea-level rise, precipitation recharge decreasing and groundwater abstraction increase. Results indicate that groundwater stress at current time is not very high, but rational use of groundwater, which is essential resources in the Maputo area, is very essential, especially under high human activity influence conditions or extreme climate change conditions.
3. The results of the scenarios analysis suggest that the aquifer management must set up to prevent the influence of stream discharge reduction and saltwater coming. The reason of this situation appears is because the groundwater abstraction only occupied 6% of the total discharge, 22 million cubic meters per year and this we have mentioned before, is a huge potential of groundwater resources development, which can be used on the domestic water supplement, and the production wells along the influence river can be used for water supply. However, reasonable increasing capacity of abstraction is important to prevent that overpumping causes depression of groundwater and intrusion of saltwater especially from the second aquitard.
4. The Recommendation given for this management is combining managed aquifer recharge with optimization of pumping practices in which a larger number of scattered production wells are operated with small yields.Last but not the least, because of the environment situation of our study area, dry and hot climate with a high density of vegetation, the groundwater only occupied a small part of the annual precipitation and the evapotranspiration occupied the largest fraction.So, for the future study, to optimal groundwater resources development and management of this area, which the land-use can be changed to reducing the evapotranspiration, and can also use the groundwater upstream discharge to supply while maintaining groundwater-dependent ecosystems.

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