Duna & Água

Inhambane, Mozambique

Jochem Caspers
Valerie Demetriades
Jacintha Tjia
Pim Versteeg

Technische Universiteit Delft

TU Delft

DUNA & ÁGUA

dunea

Duna & Água

Inhambane, Mozambique

by

Jochem Caspers
Valerie Demetriades
Jacintha Tjia
Pim Versteeg

Students	Jochem Caspers	4390202
	Valerie Demetriades	4290755
	Jacintha Tjia	4244990
	Pim Versteeg	4194438
Project duration:	November, 2018 – January, 2019	
Course:	CIE4061 - HP279	
Supervisors:	Prof.dr.ir. Luuk Rietveld	
	Dr. Boris van Breukelen	

TU Delft

Preface

This project was done in the context of course CIE4061 - Multidisciplinary project. This is part of the Civil Engineering master's program of the Delft University of Technology. Expertise of different master tracks are combined within this project to form an interdisciplinary and integrated approach.

This project is supervised by Prof.dr.ir. Luuk Rietveld and Dr. Boris van Breukelen. We would like to thank you for your guidance, support and feedback. We have started with the preparation from this project from May 2018 on. We have visited their offices numerous times to get together a good preparation for the measurements in the field as well as a strategy to gain the best results. Thanks to this we have visited Mozambique with more confidence.

We are honored to get this opportunity from Dunea to imply our knowledge in the field, supporting the IWAMAMBA project. Sebastiaan Schuemie has been very kind and helped us a lot with answering questions about Mozambique. The same goes out for Ruben Wentink. We wish Dunea a successful journey in Inhambane and we are convinced that the IWAMAMBA project will be of great benefit for the people and environment of Mozambique.

Great gratitude to our local partner ARA-Sul by supporting during our time in the field. Suzanna, Angelo, Daisy, Dias and Gildo have been a great help with their knowledge and kindness. Thank you for helping us to get in contact with the local people, assisting us with measurements during the hot summer days of Mozambique and giving us advice and feedback on our presentations.

We would also like to thank Manuel Martins Jije Jije. We have always felt save on the Mozambican roads with his guidance. Many thanks for introducing us to the beautiful culture of Inhambane and helping us communicate with the local people. We would never got all this information without his bilingual skills.

The collaboration with ESUDER - Univesidade Eduardo Mondlane has been very special to us. We would like to thank Timoteo Wiliamo and all the students who have joined our Duna & Agua case days. We experienced it as the most exciting days of the research by exchanging our knowledge.

This project could not have been done without the financial support of our sponsors. Our research could only be this extensive by the financial support of Dunea, Delft Global Initiative and Rinny Huizinga Stichting.

And at last we would like to thank our friends and family for the support. Experiencing a journey like this is one of a kind and it is great to share our stories with our loved ones.

Figure 2: Project Team Duna & Agua

Meet the team

This multidisciplinary project group consist of four master students from the Civil Engineering and Geosciences department of the TU Delft. An introduction of the group members is stated below.

Jochem Caspers

- Personal: 22 years - Living in Delft
- Bachelor Programme: Civil Engineering
- Master Programme: Hydraulic Engineering - Hydraulic Structures and Flood Risk
- Specializations: Flood risk - Probabilistic design - Hydraulic structures
- Skills: Matlab - Python - LaTeX - Sketchup - Excel - QGIS

Valerie Demetriades

- Personal: 25 years - Living in Delft
- Bachelor Programme: Civil Engineering
- Master Programme: Water management - Urban Water Management & Water Recourses Engineering
- Specializations: Groundwater modelling - (geo)Hydrology - River engineering - Drinking water engineering
- Skills: Excel - Python - Sketchup - BioWin - QGIS

Jacintha Tjia

- Personal: 25 years - Living in The Hague
- Bachelor Programme: Applied Earth Science
- Master Programme: Environmental Engineering - Environmental Science
- Specializations: Climatology - Atmospheric Sciences - Remote sensing
- Skills: Matlab - Python - C++ - LaTeX - Microsoft Office - QGIS

Pim Versteeg

- Personal: 25 years - Living in Delft
- Bachelor Programme: Civil Engineering
- Master Programme: Water Management - Urban Water Management & Environmental Technology
- Specializations: Waste Water Treatment - Biotechnology - Resource Recovery
- Skills: AutoCad - BioWin - LaTeX - Maple - QGIS

Abstract

The aim of this study is to identify the characteristics of the groundwater quality and -quantity of the peninsula of Inhambane, Mozambique. With increasing water demand an inventory on available water resources is essential to develop a climate resilient water system which water resources are not threatened by contamination and exhaustion, today as well as in the nearby future. During an eight week field survey an inventory on groundwater quality, a groundwater model and an area analysis with the concerning stakeholders were composed. The water quality is measured during three consecutive weeks indicated on pH, dissolved oxygen, electrical conductivity, temperature, nitrate, ammonium, phosphate, total iron, hardness and total coliform bacteria. A python model is build with water heights as boundary conditions and land heights, derived from SRTM 1-Arc-Second Global data and levelling with a theodolite, to gain insight on the groundwater flow at the peninsula. An area-stakeholder analysis, containing interviews with well-users, is developed to get a better understanding of whom has a contribution to the water system. The analysis shows how stakeholders are going to be involved when the water management is to be changed and which parties are able to make a change. None of the 12 monitored wells has significant toxic values in relation to drinking water purposes. Lower pH values and elevated bacteria count are present in two wells that are located along a river. Elevated electrical conductivity is detected in deeper water layers, that may indicate a beginning of salt intrusion at this location. No point source pollution, due to industries, latrines or waste sites is detected that could indicate leachate to the groundwater bodies. With high abstraction rates of drinking water company FIPAG and the boreholes of touristic lodges, the groundwater is affected drastically. Due to this over-abstraction, seawater may intrude in the fresh water aquifers at Salela and Barra and this already occurs at Tofo. When the touristic sector and the population in Inhambane continue to grow, the water resources are becoming more scarce in the future as water demand increases but less water is going to be available. Water abstraction by boreholes, mainly by the touristic sector in Tofo and Barra, is often not registered. Tourism is one of the rapidly growing sectors and has a major influence on the local water system. The exact values of water abstraction at the peninsula remains unclear as the touristic sector is rapidly growing and not all these associated boreholes are registered. For validation of the groundwater model and the extent of the aquifer overstress these numbers are key for a start of improvement. Development of a water buffer system by artificial infiltration, as in the IWAMAMBA project by Dunea and partners, can be a promising solution in relation to the future threat of water scarcity of Mozambique.

Contents

Preface i

Meet the Team iii

Abstract iv

List of Figures vii

1 Introduction 1
- 1.1 Problem statement 1
- 1.2 Project focus 2
- 1.3 Project division 2
- 1.4 Research questions 3
- 1.5 Methodology 4

2 Area Inventory 5
- 2.1 Geographics 5
  - 2.1.1 Mozambique 5
  - 2.1.2 Inhambane Province 5
  - 2.1.3 Cidade de Inhambane District 5
- 2.2 Demographics 6
  - 2.2.1 Mozambique 6
  - 2.2.2 Inhambane Province 7
  - 2.2.3 Cidade de Inhambane District 8
- 2.3 Climate 9
  - 2.3.1 Mozambique 9
  - 2.3.2 Inhambane Province & Cidade de Inhambane District 10
- 2.4 Research Area 11
  - 2.4.1 Stakeholder Analysis 11
  - 2.4.2 Field Analysis 13
- 2.5 Project Scope 14

3 Well & Borehole Inventory 15
- 3.1 Study area in QGIS 15
- 3.2 Salela 16
- 3.3 Barra Resorts 18
- 3.4 Tofo Resorts 18
- 3.5 Guiúa FIPAG 19
- 3.6 Tofo FIPAG 19

4 Social Aspects and Habits 21
- 4.1 Water consumption behaviour 21
  - 4.1.1 Local inhabitants about water from wells 21
  - 4.1.2 Local inhabitants about water from FIPAG 21
  - 4.1.3 Tourism and other industries about water from boreholes 22
- 4.2 Waste Disposal 22
  - 4.2.1 Behaviour on solid waste disposal by local inhabitants 22
  - 4.2.2 Behaviour on faecal waste disposal by local inhabitants 24
- 4.3 Water consumption charts 24

5 Water Quality **25**
5.1 Parameters – Theory . . . 25
5.1.1 Electrical Conductivity . . . 25
5.1.2 Total Dissolved Solids . . . 25
5.1.3 Dissolved Oxygen . . . 25
5.1.4 Potential of Hydrogen . . . 26
5.1.5 Ammonia . . . 26
5.1.6 Nitrate and Nitrite . . . 26
5.1.7 Phosphate . . . 26
5.1.8 Iron . . . 27
5.1.9 Hardness . . . 27
5.1.10 Coliform bacteria . . . 27
5.2 Methods and material . . . 27
5.2.1 EC-meter . . . 27
5.2.2 pH-meter . . . 27
5.2.3 DO-meter . . . 27
5.2.4 Test Strips . . . 27
5.2.5 Counting plates . . . 28
5.2.6 Protocol . . . 28
5.3 Results . . . 28
5.3.1 Salela . . . 28
5.3.2 Tofo . . . 31
5.3.3 Barra . . . 31
5.4 Discussion . . . 32
5.5 Conclusion . . . 32
5.5.1 Measurement errors and Accuracy . . . 32

6 Geohydrology **33**
6.1 The basics of geohydrology . . . 33
6.1.1 Confined and unconfined aquifers . . . 33
6.1.2 Flow in aquifers . . . 34
6.1.3 The discharge potential . . . 34
6.1.4 One well in steady flow . . . 35
6.1.5 Multiple wells in steady flow . . . 35
6.1.6 Wells near a river . . . 36
6.1.7 Wells near an impermeable layer . . . 36
6.1.8 Seawater intrusion and upconing . . . 37
6.2 Geohydrological Inventory . . . 38
6.3 The geohydrological model: step by step . . . 42
6.3.1 Step 1: Confined or unconfined aquifer? . . . 42
6.3.2 Step 2: The hydraulic conductivity . . . 42
6.3.3 Step 3: Start with a large scale model . . . 43
6.3.4 Step 4: Adding rainfall and evaporation . . . 44
6.3.5 Step 5: Adding points and lines with known heads . . . 45
6.4 Results geohydrological model . . . 47
6.4.1 Effects of discharge wells . . . 48
6.4.2 Influence of boreholes in Barra . . . 48
6.4.3 Influence of boreholes in Tofo . . . 49
6.4.4 Influence of extraction point Guiúia river FIPAG . . . 52
6.4.5 Overall influence of all extraction points . . . 53
6.5 Conclusion . . . 54

7 Conclusion **55**

8 Recommendations **56**

References **57**

Appendix **59**

List of Figures

2 Project Team Duna & Agua . . . ii

1.1 Overview rivers province Inhambane . . . 1
1.2 Project focus . . . 2
1.3 Visualization of the methodology . . . 4

2.1 Mozambique - Inhambane - Cidade de Inhambane . . . 6
2.2 Mozambican population in millions [11] . . . 6
2.3 Population by area of residence in percentage [11] . . . 7
2.4 Distribution of population by age and sex Mozambique [11] . . . 7
2.5 Distribution of population by sex and population density per province [11] . . . 8
2.6 Distribution of population by sex and population density per district [11] . . . 8
2.7 Distribution of population by age and sex Cidade de Inhambane [12] . . . 8
2.8 Mozambique map of Köppen climate classification [25] . . . 9
2.11 Field analysis Cidade de Inhambane . . . 13
2.12 Well inventory IWAMAMBA . . . 13
2.13 Project scope Cidade de Inhambane . . . 14

3.1 Research areas . . . 16
3.2 Well overview Salela . . . 16
3.3 ERT profile Salela-Tofo from WeConsult . . . 17
3.4 Borehole overview Barra . . . 18
3.5 Borehole overview Tofo . . . 18
3.6 Borehole overview Tofo . . . 19

4.1 Interview with a local inhabitant of Salela . . . 22
4.2 Water quality results by Minesterio da Saude . . . 23
4.3 Litter habits . . . 23
4.4 Water Supply Distribution 2007: Adapted from Estatísticas do Distrito Cidade de Inhambane [11] 24
4.5 Water function chart based on interviews . . . 24

5.1 Standards of pH [31] . . . 26
5.2 Electrical Conductivity measurements of the 12 wells . . . 28
5.3 TDS measurements of the 12 wells . . . 29
5.4 PH measurements of the 12 wells . . . 29
5.5 Nitrate measurements of the 12 wells . . . 29
5.6 Iron measurements of the 12 wells . . . 30
5.7 Phosphate measurements of the 12 wells . . . 30
5.8 Hardness measurements of the 12 wells . . . 30
5.9 Coliform measurements of the 12 wells . . . 31
5.10 Coliform plates . . . 31

6.1 Confined- versus unconfined aquifers . . . 33
6.2 Flow in aquifers for confined and unconfined aquifers . . . 34
6.3 The discharge potential for confined and unconfined aquifers . . . 34
6.4 The discharge potential for one well in confined and unconfined aquifers . . . 35
6.5 A well near a river, with its image well . . . 36
6.6 A well near an impermeable layer, with its image well . . . 36
6.7 The phenomena of seawater intrusion and upconing . . . 37
6.8 Cross-sections overview Salela . . . 38

6.9 Cross-section C1 . . . 38
6.10 Cross-section C2 . . . 39
6.11 Cross-section C3 . . . 39
6.12 Cross-section C4 . . . 39
6.13 Cross-section C5 . . . 39
6.14 New cross-section C1 . . . 40
6.15 New cross-section C2 . . . 40
6.16 New cross-section C3 . . . 40
6.17 New cross-section C4 . . . 41
6.18 New cross-section C5 . . . 41
6.19 Theodolite measurements . . . 41
6.20 An unconfined aquifer - Assuming a constant saturated thickness - Theory of confined aquifers can be used . . . 42
6.21 Start of the model with sea boundaries . . . 43
6.22 Overview model with sea boundaries . . . 43
6.23 Model with infiltration area . . . 44
6.24 Contour plot showing headlines . . . 44
6.25 Contour plot including boundary wells . . . 45
6.26 Model with point boundaries . . . 46
6.27 Model with point boundaries . . . 46
6.28 Overview Inhambane with large extraction locations . . . 47
6.29 Influence of discharge wells in the model . . . 48
6.30 Influence of extraction point in Barra 2019 . . . 48
6.31 Influence of extraction point in Barra 2025 and far future . . . 49
6.32 Influence of extraction point in Tofo resorts 2019 . . . 49
6.33 Influence of extraction point in Tofo resorts 2025 and far future . . . 50
6.34 Influence of extraction point in Tofo resorts 2019 . . . 50
6.35 Influence of extraction point in Tofo resorts 2025 and far future . . . 50
6.36 Influence of extraction points FIPAG & resorts in Tofo resorts 2019 . . . 51
6.37 Influence of extraction points FIPAG & resorts in Tofo resorts 2025 and in far future . . . 51
6.38 Influence of extraction point Guiúia river FIPAG 2019 . . . 52
6.39 Influence of extraction point Guiúia river FIPAG 2025 and in far future . . . 52
6.40 Influence of all extraction points 2019 . . . 53
6.41 Influence of all extraction points 2025 and in far future . . . 53

1

Introduction

1.1. Problem statement

At the moment, the province Inhambane located in Mozambique faces serious water scarcity. The population is dependent on water from rivers (fed by groundwater from the dunes) and groundwater itself. In this area there is still a lot unknown about the quantity and quality of these groundwater resources. Therefore, proper management of the large groundwater reservoir is needed to maintain access to clean drinking- and irrigation water. The concerning groundwater reservoir is known as the Mutamba Basin and the IWAMAMBA project contains the management of this groundwater reservoir, including stakeholder participation. The IWAMAMBA project contains of five different implementing partners: ARA-Sul, Mozambique Organicos, Kukula, Weconsult, Wetterskip Fryslân and Dunea.

The main part of the population of the district Cidade de Inhambane, is getting their water from the distribution system organized by the local drinking water company FIPAG. FIPAG's main water source is the Guiúa River, shown in Figure 1.1, which in turn is fed by water from the dunes in the eastern part of Inhambane. While the feeding of water from the dunes to the river is not always constant, the abstraction for drinking and irrigation purposes from the river is however mostly constant. This leads to a lowering of the water table of the river and will result in a source which can not be used in the future anymore. Therefore, new sources need to be found for FIPAG. The Mutamba River can not be used directly for drinking- and irrigation water purposes due to contamination of industry. A possible solution for this problem is to infiltrate the water from this river into the dunes for natural cleaning. Hence, the river will be fed by natural cleaned water from the dunes.

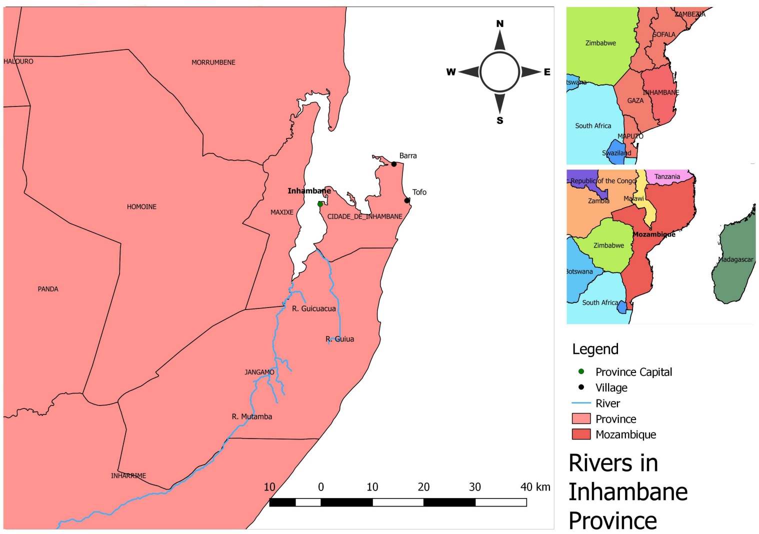


Figure 1.1: Overview rivers province Inhambane

Another part of the population is not connected to the distribution system of FIPAG and is getting their water from groundwater wells. Important for the population is to have sufficient groundwater and to also have clean enough water. A great part of the IWAMAMBA project is to examine the quality and quantity of the used water by groundwater wells, since there is still a lot unknown. The quality of the water could be affected through subsurface flow from litter leakage or seawater intrusion. Therefore, it is of great concern for the IWAMAMBA project to examine the quality of the groundwater in the wells. Moreover, in addition to the quality of the groundwater, a lot is unknown about the quantity of the groundwater available in the Mutamba Basin. For future purposes, it is of utmost importance to examine the geohydrology of the Mutamba Basin to get more insight in terms of the quantity of the groundwater reservoir.

1.2. Project focus

Within this research project, a selection of groundwater wells in a small area of the district Cidade de Inhambane will be located and investigated. By performing water quality tests on the water from the groundwater wells, it can be said if the water has a sufficient quality according to water health guidelines. Moreover, the usage of water and waste in this area will be investigated by conducting interviews with local inhabitants. The next step of the project is to build a geohydrological model to examine the geohydrology of this area with the located groundwater wells. The geohydrological model will give insight in the stream flow pattern. Also, by abstracting a large quantity of water from wells or boreholes in the surrounding area, the influence on the local stream flow pattern in the study area can be compared with the current situation. As an output of this project, a recommendation will be given about the quantity and quality of the water from the groundwater wells for future purposes. Note that the availability of water for the FIPAG distribution network will not be investigated within this project, however the extraction which potentially influences the surrounding stream flow pattern will be investigated. To summarize, the project focus is illustrated in Figure 1.2.

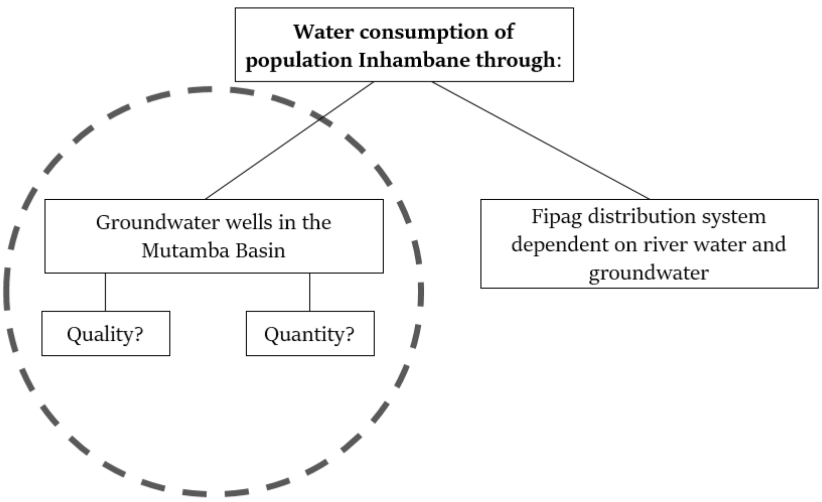


Figure 1.2: Project focus

1.3. Project division

Since this research report is an integrated project covering different subtopics, a project division is made to emphasize all these topics. The project is divided into 4 subtopics: social aspects, water quality, geohydrology and GIS.

Social Aspects

This subtopic deals with the behaviour of the users and owners of the groundwater wells regarding water usage & waste consumption. Social aspects can influence both the quality and quantity of the groundwater from the wells.

Water Quality
This subtopic is about examining the water quality of the groundwater from the wells and boreholes. Multiple important parameters of the water quality are monitored to conclude if the water is clean enough or contaminated.

Geohydrology
In contrast to the water quality, also the water quantity must be investigated by performing a geohydrological model. The water quantity can be expressed in terms of a head profile and a stream flow pattern.

GIS
The last subtopic is GIS: Geographical Information System. GIS is a software that provides data for the project about for example land heights, which are needed for geohydrological modelling. Moreover, with the software GIS maps can be made to illustrate results.

1.4. Research questions

The research questions focus on the one hand on the water wells and the subsurface flow, and on the other hand on the participation of the stakeholders within their water- and waste usage. First of all an appropriate study area must be found to apply the project focus to. Therefore, an area and well inventory is needed which deals with the local drinking water company ARA-Sul, and with the local distribution company FIPAG. To summarize, all research questions are stated below, and will all be answered in this research project.

1. **Area inventory**
   - 1.1 What different areas can be distinguished?
   - 1.2 Where runs the FIPAG distribution system?
   - 1.3 Where are drinking water wells being used?
   - 1.4 Which stakeholders are involved?
2. **Well & Borehole inventory**
   - 2.1 What are the locations of the wells to be monitored?
   - 2.2 What are the locations of the FIPAG extraction points?
   - 2.3 What are the locations of the private boreholes to be monitored?
3. **Social aspects**
   - 4.1 What is the water usage of the consumers of the wells?
   - 4.2 What are the main water usage needs?
   - 4.3 What is the waste usage of the consumers of the wells and what are the locations?
   - 4.4 What are the main waste types?
4. **Water quality**
   - 4.1 What are the wells being used for?
   - 4.2 What are the drinking water quality parameters of the wells? Are they contaminated?
5. **Geohydrology**
   - 5.1 What is the direction of the subsurface flow between the wells?
   - 5.2 Do private boreholes have any influence on the groundwater reservoir in the study area?
   - 5.3 Is there salt intrusion in the study area?

1.5. Methodology

The first step of this research is to perform an area inventory of the Cidade de Inhambane District to find an appropriate study area for the project, where the project focus can be applied on. An appropriate area would be an area where a lot of groundwater wells are located, such that both the quality and quantity of the water can be examined. Secondly, the project does not focus on an area where houses are connected to the local FIPAG distribution system. Finally, areas with relatively high extraction rates are of interest to the flow patterns and water quantity of the surrounding area.

Once the appropriate study area is chosen, a well & borehole inventory can be performed. For this inventory, a map is made of all the wells and boreholes to be measured in the chosen areas. Moreover, boundaries of the area are chosen such that they can easily be used as head boundaries for the geohydrological model.

After the inventories, on all the wells the water quality and quantity tests can be performed to collect data. This data will be discussed in the sanitary and geohydrology chapters. In addition to these tests, surveys are performed to get more insight in the social aspects and habits of the users and owners of the groundwater wells. The above mentioned steps are visualized in figure 1.3. Note that, after the collection of data, the geohydrological model is build with the use of the software Python. After all steps are performed, a recommendation and conclusion about the water quality and quantity in the area can be given.

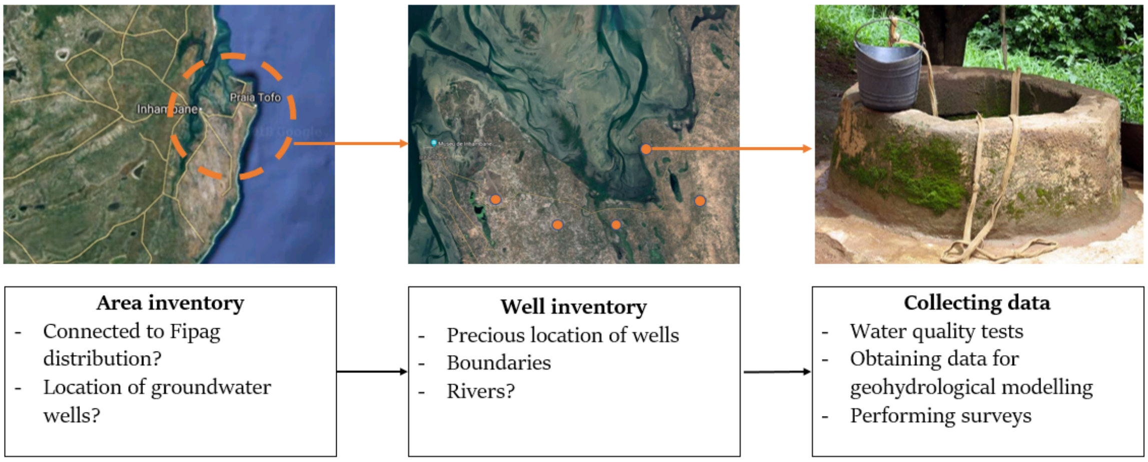


Figure 1.3: Visualization of the methodology

2

Area Inventory

In this area inventory geographic, demographic and climate information will be discussed from large to small scale. Geographically and demographically this will be done starting with Mozambique as a country, and zooming into Inhambane Province and Cidade de Inhambane District. Climate wise this will furthermore be divided from yearly averages to the period of research specifically. As a result of the district analysis, the stakeholder and field inventory will define the scope area.

2.1. Geographics

2.1.1. Mozambique

The country of Mozambique is located in southwestern Africa, between parallels 10°27' and 26°52' south latitude and between 30°12' and 40°51' east longitude. It is bordered to the north by Tanzania, to the east by the Mozambique Channel, to the west by Malawi, Zambia, Zimbabwe and Swaziland, and to the south by the Republic of South Africa. The entire coastal range is bordered by the Mozambique Channel, a channel of the western Indian Ocean over a length of 2.470 km. This extended coastline results in very different views; with cliffs in the north, increasing mangroves going southward and with dunes and lagoons all the way in the south. Mozambique has eleven provinces, as shown in Figure 2.1 with a total surface of 799.380 km^2. The largest province is Niassa and the smallest province is Maputo City, which is also the capital of Mozambique. Of the total surface only 2.2% is a water surface, which includes the Zambezi and Limpopo river flowing from the western border to the Mozambique Channel. Mozambique consists of 44% lowland (0-200m), 43% tableland (200-1000m) and 13% highland (1000-1500m). [11]

2.1.2. Inhambane Province

Inhambane is a province situated in southwestern Mozambique, which can also be seen in Figure 2.1. With a surface of 68.615 km^2, the Inhambane province is still larger than the Netherlands. In the north the province is bordered by Sofala and Manica, to the east and south by the Indian Ocean and to the west by Gaza. The coastal range is bathed by the Mozambique Channel for a total length of approximately 620 km. This coastline is characterized by shoals, dunes, mangrove swamps and a number of bays opened to the north. [11]

2.1.3. Cidade de Inhambane District

Cidade de Inhambane is situated in the southwest of the Inhambane Province which can also be seen in Figure 2.1. It is bordered to the north and east by the Mozambique Channel, to the west by Cidade de Maxixe, and to the south by Jangamo. The coastline consists of mainly shoals, dunes and mangrove swamps. Cidade de Inhambane is one of the fourteen districts of Inhambane Province. With a surface of 195 km^2 the Cidade de Inhambane district is one of the smallest districts in the Province containing the capital of the province named as the Province itself, Inhambane. [12]

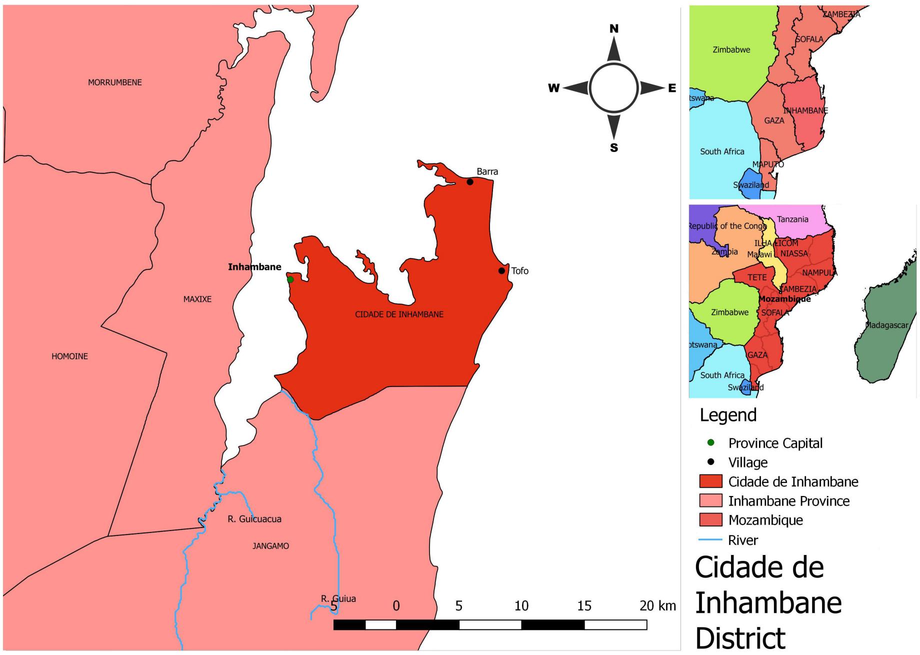


Figure 2.1: Mozambique - Inhambane - Cidade de Inhambane

2.2. Demographics

2.2.1. Mozambique

Historical data on censuses and demographic projections shows a growing trend in the population evolution of Mozambique. According to Figure 2.2, when the population was estimated at more than 6 million in 1950, it doubled over a 30-year period to reach 12 million in 1980. Population projections pointed to more than 25 million inhabitants by 2014, showing that the pace of growth is still high.

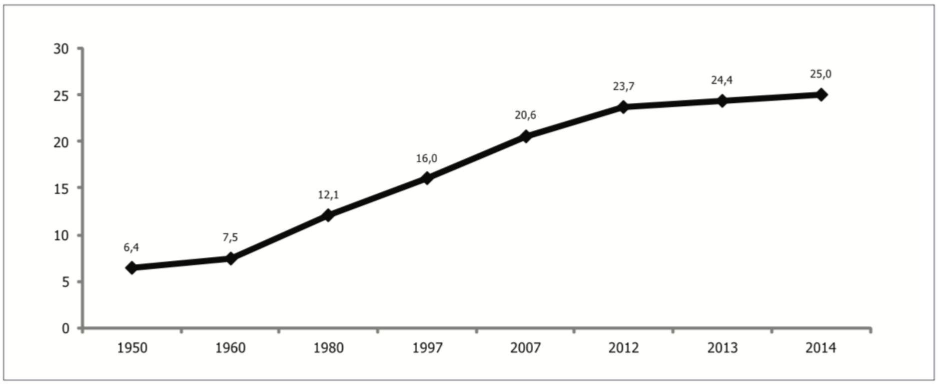


Figure 2.2: Mozambican population in millions [11]

Figure 2.3 shows that the majority of the Mozambican population lives in rural areas. This trend is not different from other African countries. Urban population growth has been very slow, data from 1997 pointed out that 28.6% of the population living in urban areas during 10 years only grew to 30.1% in 2007. An urban population in Mozambique was projected to be at approximately 32% in 2014, showing the pace of urbanization is still low.

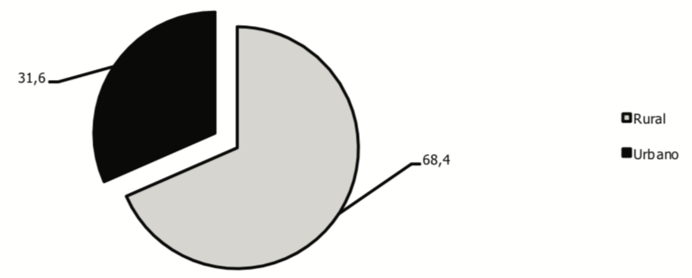


Figure 2.3: Population by area of residence in percentage [11]

Figure 2.4 shows the age structure of the Mozambican population in 2007 and 2014. There is an increase in population regarding all age groups for both sexes. This increase may have been influenced by the high fertility rates, the gradual reduction of mortality and the increase of safety after the ending civil war.

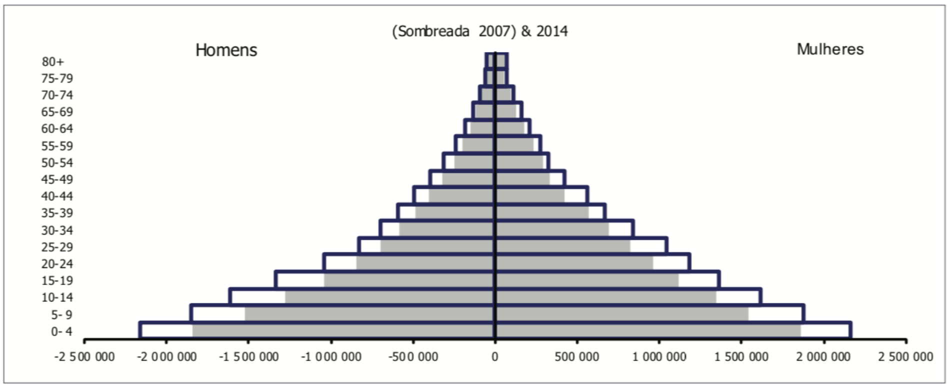


Figure 2.4: Distribution of population by age and sex Mozambique [11]

The Pyramid of Mozambican population has a broad base and a narrow top, a typical distribution format for the population of developing countries, where the overall age structure is very young. The highest concentration of the population is in the age group of 0-14 years, representing more than 45% of the total population in 2014. Finally, the distribution of the population can be summarized in three broad age groups; young people (0-14 years old) with 45%, adults (15-64 years old) with 52% and elderly (65+ years old) with only 3.1%. [11]

2.2.2. Inhambane Province

Figure 2.5 shows the total population by sex and population density according to the provinces in 2014, stating a population of 1.475.318 for the province of Inhambane. The province represents one of the smallest population densities, with only 21.5 inhabitants per square kilometer. This fact can be associated to the quite large surface that the province presents, and that no relatively large cities exist in the province. Only the capital of the province, Inhambane, can be seen as a worth mentioning city with 63.837 inhabitants in 2007. [11]

Província	Total	Homens	Mulheres	Pop/km2
País	**25 041 922**	**12 082 782**	**12 959 140**	**31,3**
Niassa	1 593 483	782 879	810 604	12,3
Cabo Delgado	1 862 085	901 617	960 468	22,5
Nampula	4 887 839	2 413 164	2 474 675	59,9
Zambézia	4 682 435	2 261 254	2 421 181	44,6
Tete	2 418 581	1 182 933	1 235 648	24,0
Manica	1 866 301	899 425	966 876	30,3
Sofala	1 999 309	971 089	1 028 220	29,4
Inhambane	1 475 318	661 775	813 543	21,5
Gaza	1 392 072	633 279	758 793	18,4
Maputo Província	1 638 631	785 143	853 488	62,9
Maputo Cidade	1 225 868	590 224	635 644	4 086,2

Figure 2.5: Distribution of population by sex and population density per province [11]

2.2.3. Cidade de Inhambane District

Figure 2.6 shows the total population and population density according to the district in 2013, stating a population of 68.775. Cidade de Inhambane, continues to be on of the cities that represents the largest density of the population, with 379 inhabitants per square kilometer. This fact can be associated to the quite small surface that the district represents, which contains the relatively large city of Inhambane.

	Distrito	Província	Distrito/Província (em %)
Superfície	195	68,775	**0.3**
População	73,948	1,426,684	5.2
Densidade Populacional	379.0	20.7	1827.3

Figure 2.6: Distribution of population by sex and population density per district [11]

Figure 2.7 shows the age structure of the district's population in 2013. The Pyramid of Cidade de Inhambane's population has again a broad base and a narrow top, a typical distribution format of the population of developing countries. The distribution of the population in the district can be summarized in three broad age groups; young people (0-14 years old) with 37.2%, adults (15-64 years old) with 57.4% and elderly (65+ years old) with only 3.4%. This follows the pattern of Mozambique. [12]

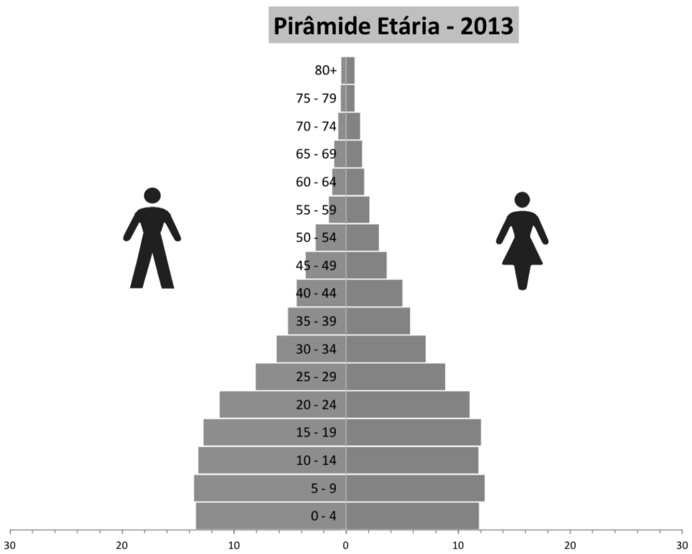


Figure 2.7: Distribution of population by age and sex Cidade de Inhambane [12]

2.3. Climate

2.3.1. Mozambique

Weather patterns across Africa are becoming more and more unpredictable, which might be due to global warming. Mozambique stretches roughly 2000km along the coast, the country covers latitudes from about 11°to 27°south. As the coastline is completely bordered by the Mozambique Channel, it drives a tropical ocean current running north to south along the country's length throughout the whole year. Although the stretched shape of the country covers a wide range of latitudes, the whole country broadly follows the southern African weather pattern. This includes the monsoon season, which is approximately from November until April. However, this monsoon season slightly differs between the north and south of the country, with rainfall lasting a few weeks longer in the north than in the south. Furthermore, during the monsoon season the humidity increases compared to the rest of the year. When the rain season has ended, the humidity will drop again. June to October is the dry season in Mozambique, which is characterized by tropical weather including clear skies, a lot of sun and almost no rain. June to August are the coolest months in Mozambique.

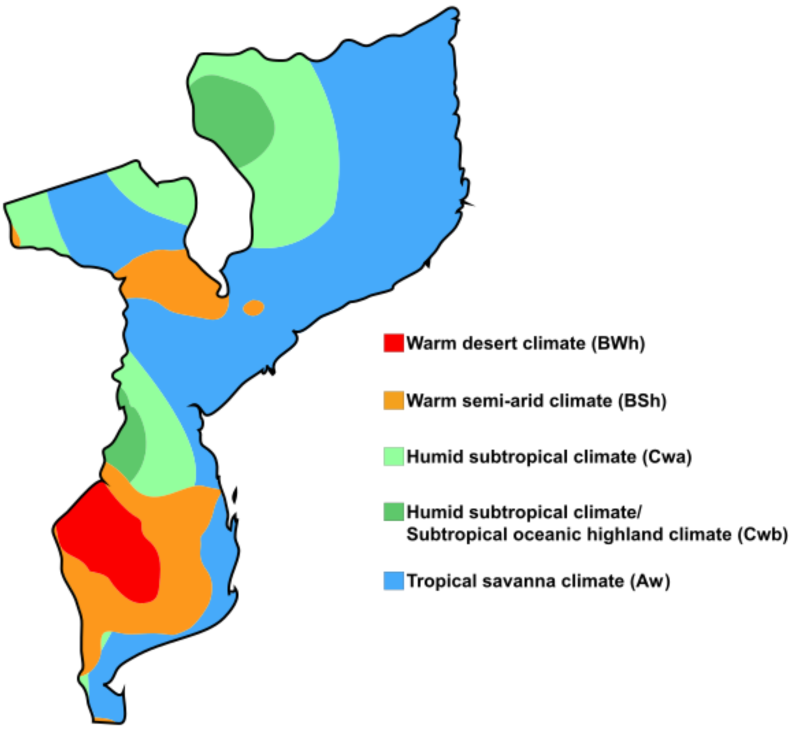
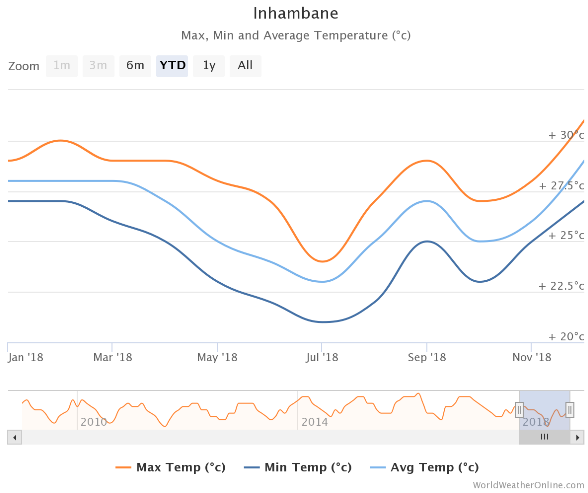


Figure 2.8: Mozambique map of Köppen climate classification [25]

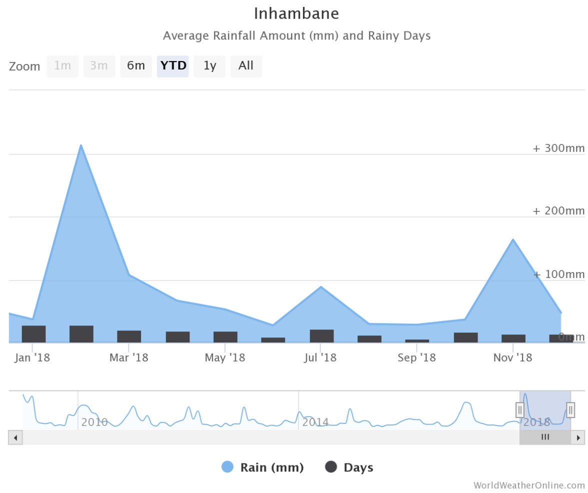
In Figure 2.8 it can be seen that the country is divided into five different climatic zones according to the Köppen classification. The most dominant climate is the tropical savanna climate A. This climate is characterized by: monthly temperatures greater than 18° Celsius throughout the year and an annual precipitation greater than 1500 mm. The specific Aw classification has an extended dry season during winter. Precipitation during the wet season is usually less than 1000 mm and only during the summer season. Furthermore, more inland and towards the south the warm desert- and warm semi-arid climate exists. These climates are characterized by the fact that the potential evaporation and transpiration exceed precipitation. More inland and to the north, the humid subtropical climates are present. These are characterized by the warm and humid summers and mild winters. During the winter, mid-latitude cyclones can occur. Convective thunderstorms dominate during the summer months. [25]

2.3.2. Inhambane Province & Cidade de Inhambane District

As the climate is the same for both the province of Inhambane and the district, only small variety in the local weather across the province is present. These sections will therefore be discussed together, as the climate is representative for both scales. The Inhambane Province has a tropical savanna climate. For the Cidade de Inhambane District, temperature and rainfall data can be seen in figures 2.9a and 2.9b respectively for the year 2018. Figure 2.9a shows minimum temperatures throughout the year do not drop below 21°C, with the lowest temperature in July. The maximum temperature is approximately 32°C, which is reached in December. This is similar to the characterizations of the tropical savanna climate. Furthermore, Figure 2.9b shows that in 2018, February seems to be the wettest month, with over 300mm rainfall.



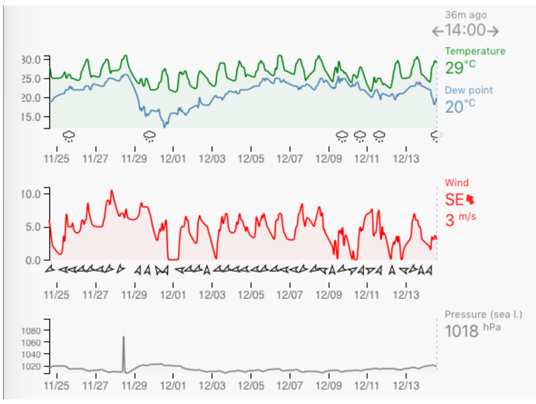
(a) Temperature Inhambane 2018



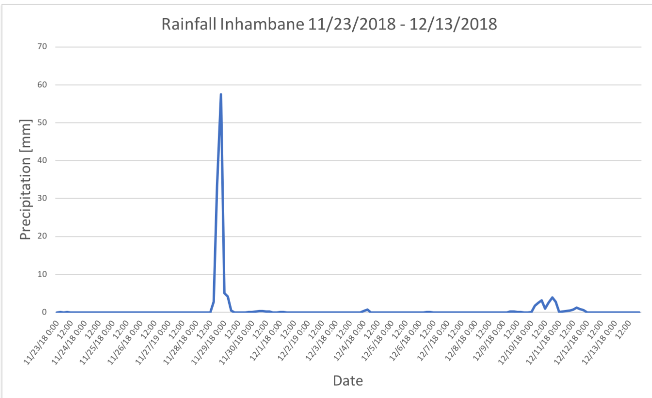
(b) Precipitation Inhambane 2018

Weather during project 11/23/2019 - 12/13/2019

The weather at the time of fieldwork was representative for November/December according to historical averages from measured data [1]. Looking at Figure 2.10a it can be seen that the temperature was always approximately between 25-30°C. Furthermore, the study period was not characterized by a lot of rain, with only a few days of rainfall. In Figure 2.10b it can be seen there was a peak on the 29th of November with almost 60 mm of rainfall.



(a) Weather Inhambane time of study



(b) Precipitation Inhambane time of study

2.4. Research Area

In order to find a suitable research area within the Cidade de Inhambane District, an analysis will be performed by looking at all stakeholders involved concerning water quality and quantity in the area. Furthermore, a field analysis will be performed by defining all different areas within the district. All information will finally be combined in order to mark the areas with the most interest, concerning water quality and quantity.

2.4.1. Stakeholder Analysis

In the Cidade de Inhambane District a lot of different stakeholders are involved concerning water quality and quantity. Not only acting on district level, but sometimes also on province level. These stakeholders can be distinguished in directors, consumers and producers. All individual stakeholders have different goals and interests, which makes their relation to each other interesting to observe. These different aspects will be discussed to represent the concerning stakeholders in the district Cidade de Inhambane.

Directors

ARA-Sul is the local waterboard involved in the southern area of Mozambique and thus responsible for the river basins in southern Mozambique such as the Mutamba Basin in the Inhambane Province. In this specific area, ARA-Sul deals with hydrological modelling including water quality, water availability, dam operation and flood forecasting. One of their main tasks is to monitor the water quality in the districts of Inhambane Province. In Cidade de Inhambane two boreholes are located which are monitored every now and then. This monitoring does not happen regularly, whenever someone has time, the water quality of these wells are measured. However, their main concern is guarding the water quality standard in the districts where they operate. Furthermore, if somebody wants to place a well, they need a legal permit from ARA-Sul to do so. All extracted water from the registered borehole is then monitored and charged with a monthly fee per extracted cubic meter.

Land chiefs are involved in small parts of Cidade de Inhambane. These are men/women who are chosen by the local inhabitants of the villages and who serve as 'land chief'. Nothing goes unnoticed in a village, thus land chiefs have to be informed when entering their area. Approximately every five years a new land chief will be elected by the local inhabitants. Their main task is to protect their land and make sure all inhabitants are safe and in peace.

Ministério da Saúde or the ministry of health, is a governmental organization located in Cidade de Inhambane dealing with public health. This organization demands that operational lodges, resorts and restaurants test their water at the ministry of health on a two to three months basis. Common practice of lodge and resort owners is the payment to a local inhabitant to arrange all associated paperwork to fulfill the laws.

Producers

FIPAG is a local water company with a distribution network of 148.081km of piping in the district Cidade de Inhambane. They provide water in and around Inhambane and Tofo with this distribution network. To provide enough water in this area, there are two extraction points in the area. One extraction point is at the Guiúa river, where they an artificial side-river is used to extract water from a natural river. Since the levels of this river are low during dry seasons, four additional ground water pumps are connected to the system to fulfill the demands. The second extraction point is in Tofo, where five pumps are used to extract water from the aquifer in order to fulfill the demands.

Aqua para Amigos is a drinking water company located six kilometer out of Barra and Praia de Tofo at Babelaza. It produces and distributes drinking water PET bottles in Cidade de Inhambane, Tofo and Barra. Agua para Amigos refills self brought bottles of consumers, to stimulate re-use and they distribute bottles for shops, lodges and markets. They have one borehole where water is abstracted at a depth from 50 metres. A yearly abstraction of 425.000 litres was registered for 2018, with a peak abstraction in the month of December of 80.000 litres. The water which is abstracted is treated with ozonation, paper filter, sand filter and UV disinfection for purification. Water is regularly tested at a laboratory in Maputo.

Resorts can also be considered as producers as almost all construct a private borehole to meet their water demands. In this way they contribute to the abstraction of groundwater of the peninsula. A considerable amount of resorts have their own private borehole as the distributed water in the area has a brownish color due to the iron concentration in Tofo. Another reason would be that there is no distribution system, which is the case in Barra. These private boreholes are not monitored or not shared with the public, thus their extraction remains unknown. However, it can be assumed that this extraction can be considered to be a serious amount, as salt water intrusion is a problem along this coast. These places depend on tourism, thus the water quality in the area needs to be of high standard.

Community wells and private boreholes are constructed by local constructors without any registered/legal firm. These small firms can place wells and boreholes on a location by request. The open wells to a depth of approximately seven meters are constructed with eight bags of cement, two layers of gravel and 0.125 kilogram of bunches. Adding all costs together results in a total amount of 14.150 meticais (205 euro). The borehole is constructed with a filter, tube, pump and casing. The casing is of importance in order to prevent any robbery of equipment. Adding all costs together results in a total amount of 25.000 meticais (362 euro).

Consumers

Inhabitants of rural areas use open wells in order to provide themselves with water. Each well has at least one owner. This owner is responsible for the placement and maintenance of a well. The well owners have interest in the provision of good water quality on short and long term. Some wells are shared between different households, all involved households collectively fund the placement and maintenance of the well. Depending on the well and the owner, maintenance takes place varying from every four months to every two years. Not every well has the function for drinking, thus these wells are often less maintained. The owners of the well seem to know about the water quality of the well, as mentioned that not all wells are used for drinking purposes. Some owners even put chlorine drops (sodium hypochlorite certeza) in the water every now and then when they find the money for it. Others deliberately don't do this as they are sure that their water quality is good. Most wells are placed close to the owner's household. However, a lot of households still have to walk approximately 100-200m to the closest water source. As this is a heavy task, a lot of people store their water in big ceramic pots at home. This water often is stored so they can use it for approximately 2 weeks. Sometimes, microbes develop in this water, some people put chlorine drops in the stored water. The local people in our area are dependent on the water quality of their well. If for instance the water in the ground layer of the well is not of good quality, they are limited to other alternatives.

Inhabitants of domestic areas are using a water distribution network of the local water company FIPAG in order to provide themselves with water. For every household that is connected to the FIPAG distribution network, a measuring device is installed to their water tap. This device monitors how much water is used per month, in order for FIPAG to know their monthly usage. Users are obligated to visit FIPAG monthly in order to pay their water usage. If this bill is not paid on time, somebody from FIPAG will come to the concerned household to collect the money. If for any reason this bill cannot be paid, the household will be cut from the distribution network until they have paid their bill. As some people find the distributed water expensive, they dismantle this device so it looks like their usage is less than it actually was. However, they risk that they will need to pay a higher amount per liter water used.

Tourists in large numbers visit the coast of Barra and Tofo in the district of Cidade de Inhambane where lot of resorts and lodges are located. During the peak seasons, mainly South-Africans return yearly for their summer holiday. They will mainly use the water provided from the private boreholes that are owned by the resorts and lodges. Tourism has grown over the last couple of years, with a growth of 4.6% in 2017[8].

The agricultural sector in the Cidade de Inhambane district is not dominated by certain companies but consists mainly of local inhabitants owning small pieces of land to grow agricultural products, called 'machamba'. Water from nearby community wells is used for irrigation.

2.4.2. Field Analysis

The information gathered during the field analysis performed in Cidade de Inhambane during the first week of the project will be used to distinguish several areas in the district. These different areas are visualized in Figure 2.11 below. All the different areas will be discussed one by one. Note that all the relevant pictures taken can be found in the Appendix 1.

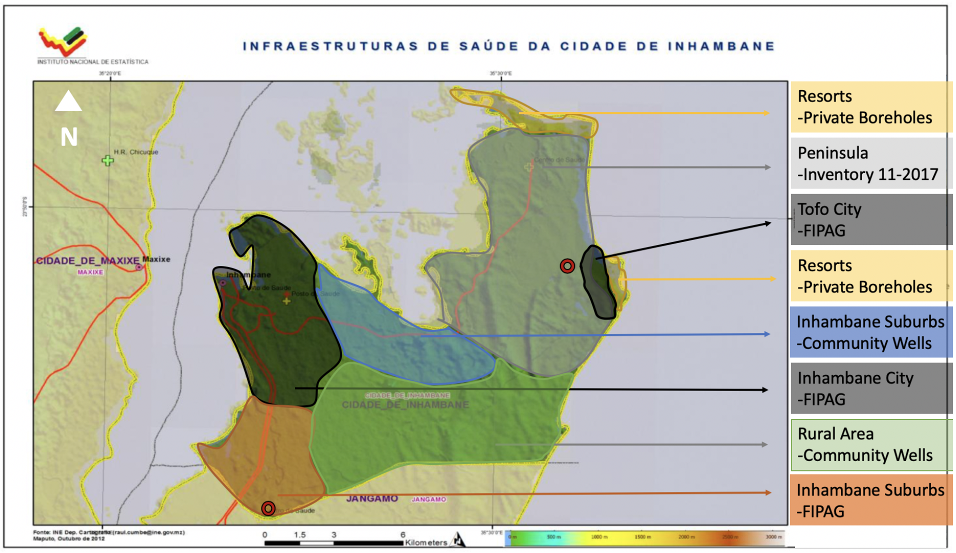


Figure 2.11: Field analysis Cidade de Inhambane

Barra and Tofo Resorts

The resorts located in the north and east of the Inhambane peninsula have each their own private boreholes. However, the owners of the resorts (mainly South-Africans) are still worried about the quality of this drinking water and the quantity available. At all extraction points the extraction rates were unknown.

Peninsula

The whole peninsula area is part of the IWAMAMBA initiative. On Figure 2.12 below the water extraction points visited during the well inventory of the IWAMAMBA project are given. At some of these water points the following parameters are measured; location, date, type of source, owner, well depth from ground level, groundwater level below ground level, temperature, EC, pH, height, groundwater level above sea level.

Figure 2.12: Well inventory IWAMAMBA

Inhambane and Tofo City

Inhambane and Tofo City are in general connected to the FIPAG network. The reason for this connection is the dense population in these areas. Local inhabitants are still using some of the traditional water wells to obtain water for washing and agriculture. The water points given in Appendix 1 were visited during the area inventory.

Inhambane Suburbs - Community Wells

The Inhambane suburbs east of Inhambane city are in general not connected to the FIPAG network. The reason for this disconnection is the sparse population in this area. Local inhabitants are using the traditional water wells, called 'fonte de agua', to obtain drinking water. The wells given in Appendix 1 were visited during the area inventory.

Inhambane Suburbs - FIPAG

The Inhambane suburbs south of Inhambane city are in general connected to the FIPAG network. The reason for this connection is the relatively wealthy population. Local inhabitants have enough money to afford the water distribution from FIPAG instead of using the traditional water wells to obtain drinking water. The water points given in Appendix 1 were visited during the area inventory.

2.5. Project Scope

After performing the area inventory, the suburban area of Inhambane with community wells, called Salela, is the most interesting. Since the inhabitants of this area are not connected to the FIPAG distribution network a lot of people are using the numerous present drinking water wells. In terms of water quantity, the touristic areas, Barra and Tofo, are of interest next to the two FIPAG extraction points in Guiúa and Tofo. This is due to the fact that all of these locations extraction rates are relatively high compared to the extraction rates within the peninsula. Below an overview is given in Figure 2.13 of the research areas defining the project scope. In the next chapter a broad overview will be given of this research area Salela together with the four influencing extraction points/areas in the Cidade de Inhambane district.

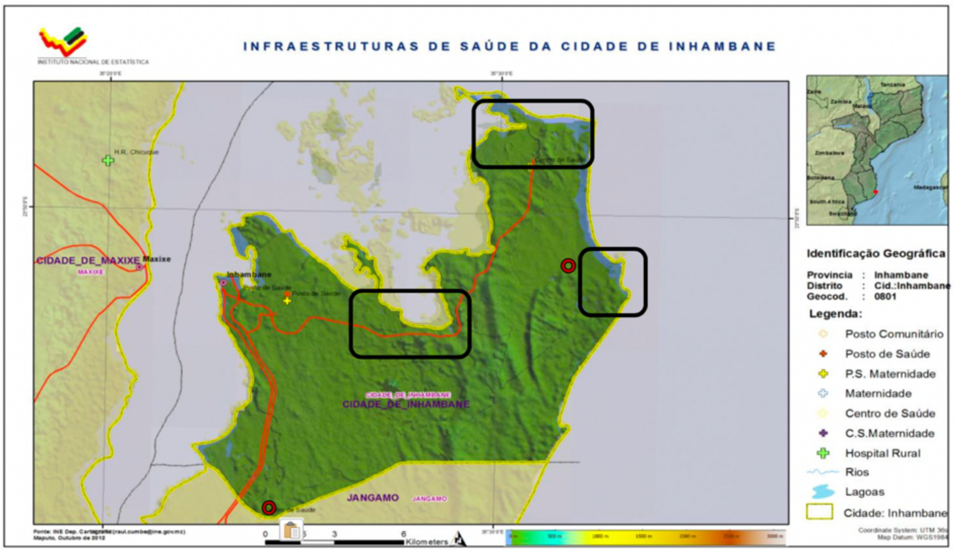


Figure 2.13: Project scope Cidade de Inhambane

3

Well & Borehole Inventory

In this inventory five areas defined in the project scope will be discussed. In order to inventorize these areas, the application QGIS was used. First, the method and information derived in QGIS will be explained. Secondly, all areas will be discussed. The Salela area which will be the primary research area needs to be considered first. Within this area, research on water quality and -quantity will be performed. Next, the Barra and Tofo beach areas will be considered as influence points on the water quality and -quantity in the Salela area. Finally, the Tofo and Guiúa FIPAG extraction points will also be considered as influence points on the water quality and -quantity in the Salela area. An overview of these five locations is already illustrated in Figure 2.13 and will now be discussed in detail.

3.1. Study area in QGIS

After studying the Inhambane peninsula area by land thoroughly, an inventory was made in QGIS. With this application, different maps can be produced and crucial information could be derived from satellite data. An important parameter for this research is elevation. This can be derived from a Digital Elevation Model (DEM) in QGIS. A DEM is a 3D representation of a terrain's surface created from terrain elevation data. In this case ASTER GLOBAL DEM and SRTM 1 Arc-Second Global data are used. ASTER GLOBAL DEM's has a 30-90m spatial resolution. This proved to be of insufficient quality, comparing the elevation extracted with field observations. However, SRTM 1 Arc-Second Global data provides a 1 arc second or 30 m spatial resolution, which proves to be more accurate compared to field observations. The elevation data extracted form both DEM's can be found in the Appendix 4. [16]

Elevation map

From SRTM 1 Arc-Second Global data downloaded from USGS, an elevation map can be made in QGIS. In this elevation map, all coordinates of points of interest can be loaded. Now, it is possible to derive the elevation at all points of interest. These will serve as input parameter for the cross sections and hydrological model. In Figure 3.1 the elevation map of the Inhambane peninsula can be seen with the three areas of interest. In these three areas information will be extracted from the elevation map.

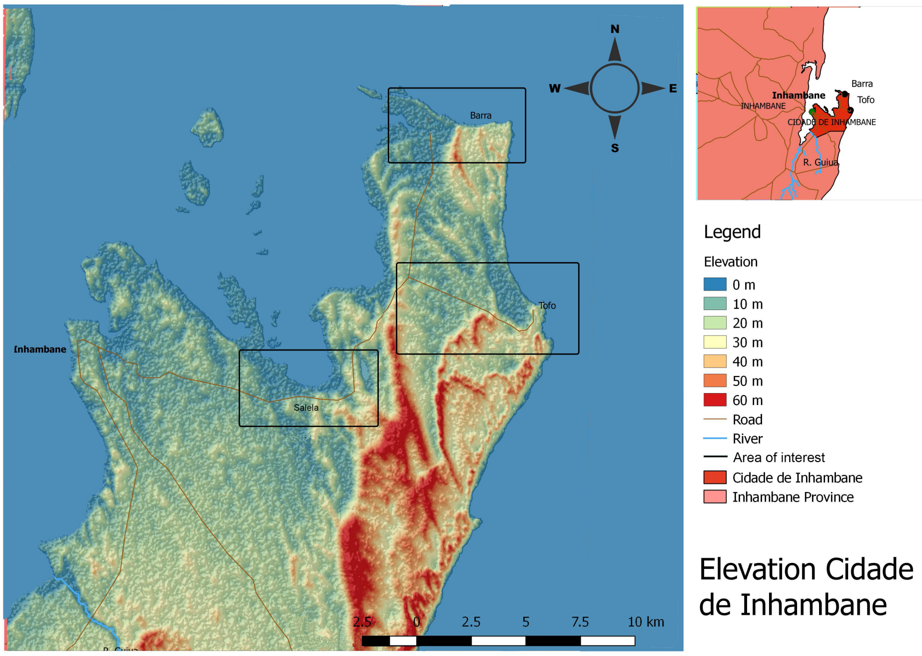


Figure 3.1: Research areas

3.2. Salela

In the area of Salela, which lies east of Inhambane city, twelve wells were visited during a three-week period in November-December 2018. The wells are identified with the numbers F1-F12. At these wells the water quality and -level were monitored in this three-week period. Some additional boundary points are identified with the numbers B1-B8. At these boundary points, the water level in the wells was only monitored. All these locations are visualised in Figure 3.2. Note that the relevant pictures taken during this inventory are added to Appendix 2.

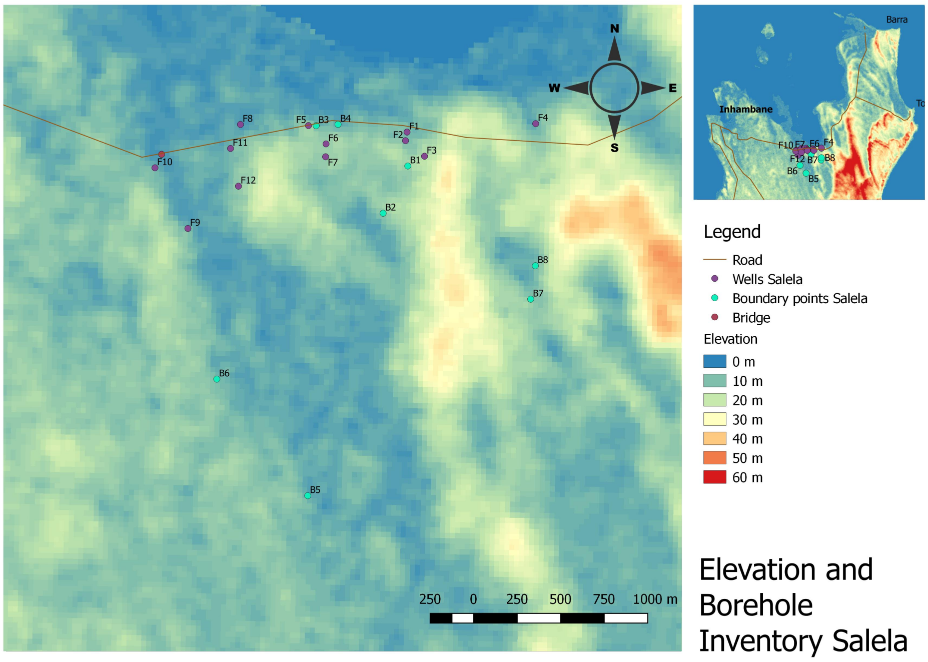


Figure 3.2: Well overview Salela

Parameters primary research area

For the water quality the following parameters were measured; Electric Conductivity, Temperature, pH, Dissolved Oxygen, Nitrate-nitrite, ammonium, phosphate, total iron, hardness and coliform bacteria. The results of each well are given in the Appendix 4 and will be discussed in Chapter 5, Water Quality.

For the water quantity the following parameters were measured; Height, Diameter, Bottom level, Top level, Water level and Extraction rate. The results are given in the Appendix 4 and 5 and will be discussed in Chapter 6, Geohydrology.

Some parameters were not possible to measure and are derived from data sets and/or reference projects. First, the geographical height was initially obtained by using satellite data in QGIS and later in our research improved by levelling measurements.

Next, the lithology of the Salela area was predicted using previous studies on the peninsula performed by WeConsult. This research was performed with electrodes, placed every five meters, to create an ERT profile of the subsoil. In the ERT profile types of subsoil can be derived from resistance values. Salt water of clayish subsoil have low resistance values and sand has high resistance values.

The ERT profile, given in Figure 3.3, runs from west (Salela) to east (Tofo). From ERT 83 we can derive the following subsoil profile. First, 8 meters of sand (unsaturated zone), then 50 meters of medium to coarse sand (aquifer) and finally 20 meters of fine sand. This lithology information is assumed to be representative for the district area of Cidade de Inhambane.

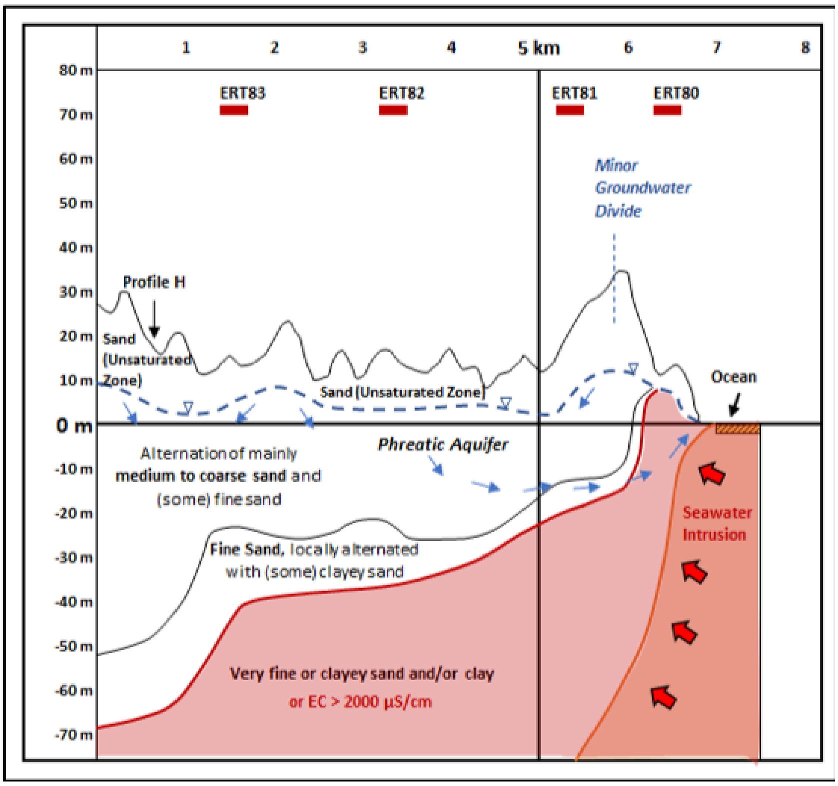


Figure 3.3: ERT profile Salela-Tofo from WeConsult

At last, as Salela is located along the coast, it experiences two low tides and two high tides every lunar day, which is exactly 24 hours and 50 minutes. Because this is longer than a 24 hour solar day, the low- and high tides shift every day [28]. However, sometimes only one low- or high tide occurs. For example, on Saturday the first of December the first there were two low tides at 05:38 AM and 19:00 PM, and at 11:53 AM there was only one high tide. The heights were respectively 1.8m, 1.7m and 2.3m. The tides in Inhmambane vary from almost 0m at fullmoon to 2m for lowtide, and 1.5m to 4.5m at fullmoon for high tide. [29] From field observations, it was noticed that the tides affect the areas a lot, submerging mangroves and walking areas from time to time. This tide information is assumed to be representative for the district area of Cidade de Inhambane.

3.3. Barra Resorts

In the area of Barra beach, the northern part of the Cidade de Inhambane District, approximately 25-35 resorts are located. Based on the inventory of Bibo Sands lodge, Sia Sente resort, Sunset lodge, Barra Reef Diver school, Casa do Mangal and Chill bar, average extraction rates based on the capacity of the resort or lodge can be made. For a small resort based on an average of 3 units, an average extraction of 5 m3/day/small-resort is derived. For a large resort based on an average of 16 units, an average extraction of 25 m3/day/large-resort is derived. The locations of the specific boreholes visited during the inventory, are visualized in Figure 3.4 below.

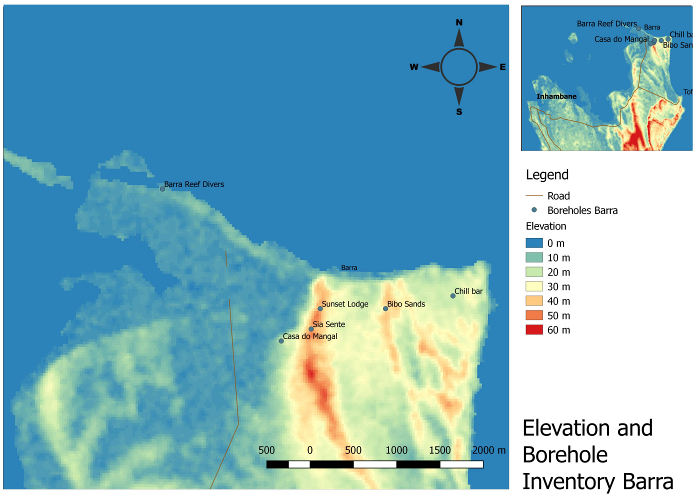


Figure 3.4: Borehole overview Barra

3.4. Tofo Resorts

In the area of Tofo beach, the eastern part of the district, the highest density of lodges and resorts are located, which counts a total of approximately 35-45 resorts. Based on the inventory at the Surf Shack shop, Aqua para Amigos company and Tofo Mar resort, the same extraction rates can be derived for small and large resorts as in the area of Barra beach. In the area of Tofo beach, the extraction rates from the groundwater via boreholes could however be slightly lower since there is also a FIPAG distribution network available. However, this distribution network is not often used due to the poor quality. The locations of the boreholes, visited during the inventory, are visualized in Figure 3.5 below.

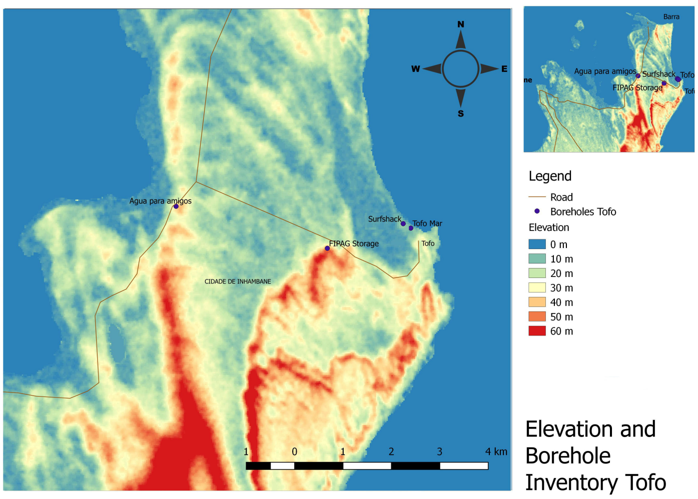


Figure 3.5: Borehole overview Tofo

3.5. Guiúa FIPAG

The first extraction point of FIPAG is at the Guiúa river, located in the southern part of the Cidade de Inhambane District. At this location an artificial side-river is used in order to extract water from the natural river. This Guiúa river is the main water resource for water distribution in Inhambane. Next to the river, four additional ground water pumps are connected to the system to fulfill the demands when the river level is becoming too low. To create more resilience in the water availability in the future, there are plans to use the water of the Jangamo river.

The following treatment procedure is being performed at this specific extraction point; extraction, aeration, filtration and sedimentation, chlorine disinfection, storage and distribution. This is visualized with pictures in the Appendix 2. The yearly extraction rate at the Guiúa location is not known exactly, only an extraction rate from the artificial river and total boreholes at both locations is known. This is visualized in Figure 3.6 below.

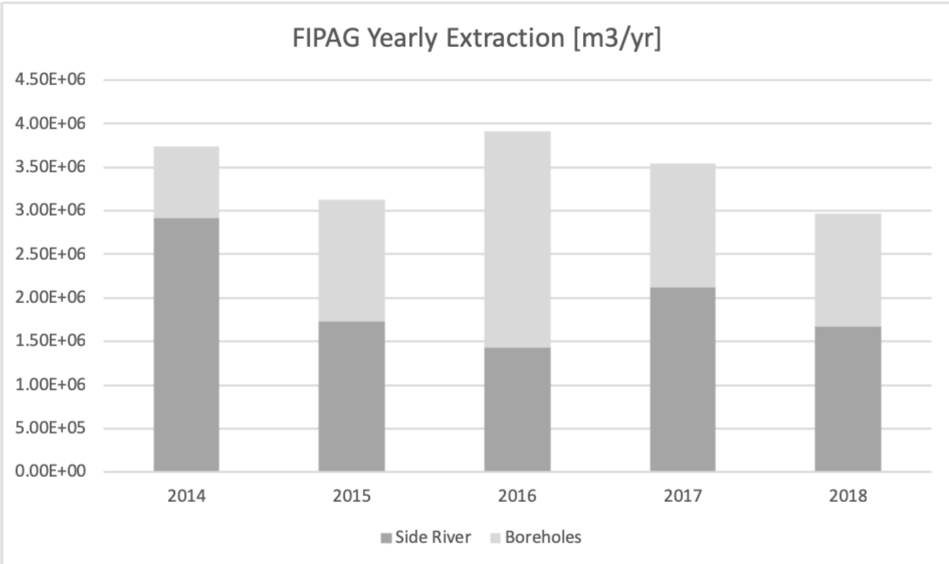


Figure 3.6: Borehole overview Tofo

3.6. Tofo FIPAG

The second extraction point of FIPAS is in Tofo, located in the eastern part of the District. Five pumps are used to extract water from the aquifer in order to fulfill the demands. The natural presence of iron in the ground is a well-known issue in this region.

The following treatment procedure is being performed: extraction, aeration, storage and distribution. This is visualized with pictures in the Appendix 2. Water is aerated by a cascade, however as there is lack of financial support, a follow up filtration step is missing. This results in inefficient removal of iron, which is still present at the consumers end, having a brownish color. This problem will later be addressed in chapter 5. The yearly extraction rate at the Tofo location is not known exactly, only an extraction rate from the artificial river at Guiúa and total boreholes at both locations is known. This is visualized in Figure 3.6 above.

Parameters secondary research areas

For the areas/locations with a relative high extraction rate, an overview is given of the estimated total extractions. First, an overview of Barra and Tofo are given in table 3.1. The direct tourism growth was estimated exponential with the water extraction. Second, an overview of Tofo and Guiúa FIPAG are given in table 3.2. The water extraction increase was estimated proportional to the direct population growth.

Table 3.1: Estimated total extraction 2019 and 2025 for Barra and Tofo

	Barra	Tofo
Extraction [m^3/day/small lodge]	5	5
Extraction [m^3/day/big lodge]	25	25
Small lodges [#]	20	10
Big lodges [#]	20	30
Direct Tourism growth [%/year]	4,6	
Total extraction 2019 [m^3/day]	600	800
Predicted extraction 2025 [m^3/day]	785	1047

Table 3.2: Estimated total extraction 2019 and 2025 for Tofo and Guiúa FIPAG

	Tofo	Guiúa
Extraction [m^3/day/river]	0	5000
Extraction [m^3/day/boreholes]	3000	1000
Direct Population growth [%/year]	2,9	
Total extraction 2019 [m^3/day]	3000	6000
Predicted extraction 2025 [m^3/day]	3929	7858

4

Social Aspects and Habits

In this chapter the social aspects on water consumption and waste disposal are discussed. In the research area water is supplied by three different systems: FIPAGs distribution system, groundwater drinking wells and self-constructed boreholes. For every system the users have shared their positive and negative experiences. Furthermore, the behaviour on waste disposal of local inhabitants of the research area was investigated to create an image on possible (point source) pollution of the groundwater.

4.1. Water consumption behaviour

4.1.1. Local inhabitants about water from wells

Water of wells is used for multiple functions throughout Mozambican households. Water is often collected with big buckets and jerrycans carrying 20L in once. As it is quite a heavy task, water is collected at the beginning and end of a day, when it is cooler than midday. When bigger distances (more than 50 metres) have to be overcome, water is often stored in bigger vessels. Drinking water wells are placed throughout the area and maximum walking distances were not observed to be more than approximately 250 metres. The storage vessels which are big clay pots, are often placed inside small cabins. This water is used for cooking, washing, cleaning and other household activities. Only if the water is of good quality, which is often only based on the appearance and odour, it will be used for drinking. Water is heated to inactivate microbes and when the consumers do not trust the quality of the water they will add a few drops of 'certeza' (sodium hypochlorite solution) as a disinfectant [7]. This is available at local hospitals for approximately 200-300 meticais. The frequency of cleaning the wells depends on the owners interest. The frequency ranges from once a year to four times per year among those questioned. The costs of cleaning are spread over the users of the well and are approximately 600 meticais.

The heavy task of water collection, is mostly a women's job. Women were most often encountered at home during working hours, whereas the men have jobs in the city or at 'machamba' (farm). Children sometimes helped collecting water, as they were off from school during December period. People do not have to pay for utilisation of community wells and are happy with this fact. They prefer water for free over the water from FIPAG, which is considered expensive. Besides, the people are aware of some problems FIPAG has to deal with and are satisfied with the quality of the community wells. An interview with Hilaria Neves, one of locals in Salela and also one of the well-users, was added to Appendix 3.

4.1.2. Local inhabitants about water from FIPAG

Cidade de Inhambane Most of the households in the district are connected to the infrastructure of FIPAG. A gauge meter, as seen in Appendix 1, registers the consumption for each household. Every month, households need to pay for their water consumption at FIPAGs headquarter or if a FIPAG employee visits their house. When no payment is fulfilled, households will be disconnected from the distribution network. An estimation for one household of five people has a monthly bill of 1500 meticais. As mentioned, the availability of FIPAG water is not always reliable. Sometimes the water from the tap is not available for a few days. To overcome periods of no water distribution, people store water in tanks to overcome periods when no water is available. If there is no water left, people will take water from a nearby lake or well and/or buy it at stores [15].

Figure 4.1: Interview with a local inhabitant of Salela

Praia de Tofo Due to discoloration of the water by the presence of iron, consumers in Tofo are skeptical on utilisation of FIPAG water. Lodge owners and other enterprises with sufficient financial resources are starting their own agenda. Hotel Tofo Mar has added an additional sand filter on its FIPAG water prior to distribution in the hotel. Peri-Peri divers, Surf Shack and other local enterprises in Tofo are making use of their private boreholes. However, most locals do not have these financial resources and are dependent on the water of FIPAG. Complaints are mostly about the brownish colour, whereas some people mentioned to have irritated skin. Stains in clothes by washing were never mentioned, unless it was asked. No health issues have been directly related to the presence of iron in water.

4.1.3. Tourism and other industries about water from boreholes

The tourism in Inhambane is mostly located along the eastern coastline of the peninsula and has been increasing for the last decades. Lodges abstract water by boreholes to provide their guests clean and drinkable water. Or water is used for the irrigation of plants and trees. Barra and Praia de Tofo/Tofinho are the main touristic places at the Inhambane peninsula. Most private boreholes are therefore at this location. Construction of a borehole approximately costs 25,000 meticais [24]. Treatment of borehole groundwater is not consistent throughout the area. Whereas some lodge owners have treatment steps like reverse osmosis or disinfect the water with chlorine, others do not treat their water at all. One of the owners had a borehole relatively close to the sea, but after some years they experienced a salty taste. The owner reacted by placing a new borehole one kilometre inland. Owners of lodges have to test the water every two months at Minesterio da Saude to guarantee the safety of water consumption. Water is tested on nitrate, nitrite, turbidity, pH, coliform, ammonium and total hardness. Conductivity and iron is not measured. After some days the results are available as a form, see Figure 4.2.

Licenses for boreholes are obliged to rightfully abstract ground water and need to be registered by ARA-Sul. The amount of water is registered by a gauge meter and owners have to pay per m^3 of water abstraction to ARA-Sul. However, some of the owners are not aware of this registration and do not pay. This remains a large problem for ARA-Sul, as they are not aware of the total extraction of the boreholes. Furthermore, there is no such thing as a penalty for this procedure so illegal boreholes remain untouched.

4.2. Waste Disposal

4.2.1. Behaviour on solid waste disposal by local inhabitants

One of the first things noticed in the area, is the barely present municipal waste collecting system throughout Inhambane. The solid waste of households mainly consists of plastic bottles and packages, cans and food remains. There is not a lot of electronic waste. Organic food remains are not collected and often thrown on land, assuming this organic material will degrade and enriches the soil. Plastic and other material is collected is self-dug holes in the ground, but also a lot of plastic is littered in open areas. Self-dug holes are filled up when full, followed by a new hole dug just few metres next to the old one, see Figure 4.3. Some people collect waste on stacks and incinerate.

REPÚBLICA DE MOÇAMBIQUE
MINISTÉRIO DA SAÚDE
GOVERNO DA PROVINCIA DE INHAMBANE
LABORATÓRIO PROVINCIAL DE ALIMENTOS E ÁGUAS DE INHAMBANE
BOLETIM DE ANÁLISE DE ÁGUA

No da Ficha:	**Código:**	**Subcódigo:** FO	**Nº do Reg: 1147/2018**
Proveniência da amostra: Cidade de Inhambane – Bairro Conguiana, Praia de Barra (Farol de Barra)			
Data e Hora da Colheita: 07/11/2018			ás 09 : 00 Horas
Data e Hora de Chegada no laboratório: 07/11/2018			ás 10 : 39 Horas
Motivo de Analise:C.Q.			
Proprietário da amostra: Farol de Barra			

PARÂMETROS FÍSICOS E ORGANOLÉPTICOS

Cor: Incolor	Sabor: Insipido	Cheiro: Inodoro
Turvação: 0.24 NTU	Depósito: Ausente	Ph: 6.88
Condutividade:	Cloro residual total:	

PARÂMETROS QUÍMICOS

Parâmetros	Resultados Obtidos	Resultados mg/L	
		Limite Mínimo	Limite Máximo
Nitritos	<0.02 mg/l		3 mg/L
Nitratos	4.4 mg/l		50 mg/L
Cloretos	113.4 mg/l		250 mg/L
Amoníaco	0 mg/l		1.5 mg/L
Dureza Total	208 mg/l		500 mg/L
Cálcio	48.0 mg/l		50 mg/L
Magnésio	39.0 mg/l		50 mg/L

PARÂMETROS MICROBIOLÓGICAS

Coliformes	NMP/100 ml
Coliformes Totais: 37°C;24/48h	
Coliformes Fecais: 44°C; 24h	Ausentes

JUÍZO

A amostra de água analisada **corresponde** aos requisitos de potabilidade, de acordo com o regulamento de água para o consumo humano, diploma ministerial nº 180/2004 de 15 de stembro.

OBS: O Controlo de qualidade de água para o consumo humano, **é feito de 2 em 2 meses**

O Chefe do Laboratório

08/11/2018

Figure 4.2: Water quality results by Minesterio da Saude

Associacao de Limpeza e Meio Ambiente (Association of Cleaning and Environment), in short ALMA, is an association which is working on a cleaner environment in Inhambane. Beach cleaning and other activities are carried out by their members. Recently a recycling centre in Tofo was opened and more awareness on pollution and the negative consequences is created by ALMA. This organisation depends on donations and contributions and on its volunteers.[18]

During the fieldwork some bigger landfill sites were encountered. For example, a site of approximately 30 by 30 metres of solid waste was located at an sparsely populated area just south of the research area. Some people were looking around for anything of value or use. Salient detail is that the location is nearby a water stream, see Figure 4.3a. Without proper equipment, it is difficult to detect the pollution of the ground by solid waste. Leachate contamination to surface- and ground waters could occur, resulting in a major environmental health hazard.

(a) Big landfill site | -23.910037,35.462219 (b) Lichera: a hole filled with litter

Figure 4.3: Litter habits

4.2.2. Behaviour on faecal waste disposal by local inhabitants

The most common way for faecal disposal in the research area is by utilisation of a private latrine. On the property of local inhabitants, or just outside their property, are latrines which consist of holes that are dug 2-3 m deep. Fences are build around for privacy reasons, however no roofs are build on top. Sometimes after some years, these latrines are filled up and moved to a new spot. However, latrines often are kept at the same location for longer periods of about 3-5 years. At the lodges and resorts the common way for faecal disposal as septic tank waste water treatment. Waste water is treated by sedimentation of sludge under gravity and flotation of scum. The outputs are effluent and settled solids which are anaerobically digested. Numerous cases of groundwater contamination by septic tanks have been reported, especially in regions with high septic tank density. No problems with septic tanks were noticed, but it is advisable to guard the possibility of high septic tank densities with increasing tourism and welfare.

4.3. Water consumption charts

About 13% of the people in the district of Inhambane depends on public wells as their water resource, whereas 42% is connected to a distribution system, see Figure 4.4[11]. Water from wells is used for multiple purposes within Mozambican households. Local inhabitants use their water different from Dutch people or the well represented South-African tourists. During the fieldwork a survey was carried out to indicate the water usage amounts for drinking, irrigation and household functions, which can be seen in Figure 4.5. Please note that this applies to the people who are using water from wells, which may differ when water is supplied by other resources.

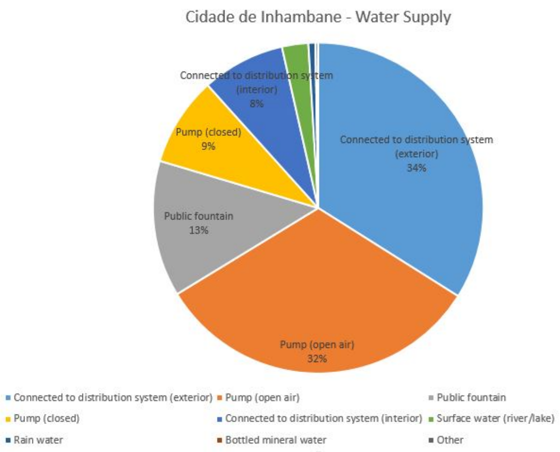


Figure 4.4: Water Supply Distribution 2007: Adapted from Estatísticas do Distrito Cidade de Inhambane [11]

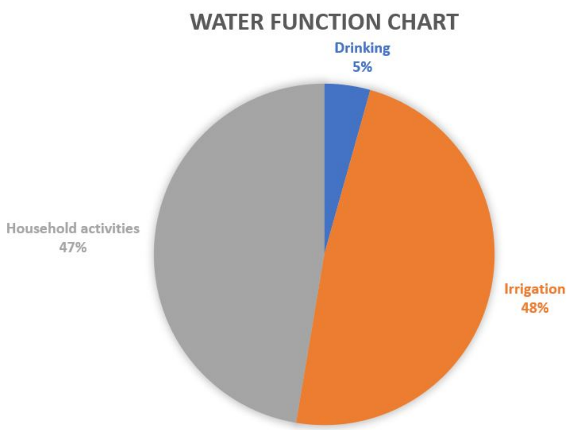


Figure 4.5: Water function chart based on interviews

5

Water Quality

Water of wells has been tested on multiple quality parameters. These parameters are used to indicate the water quality of the wells in the rural area Salela. The parameters tested are: electrical conductivity, dissolved oxygen, pH, temperature, nitrate, nitrite, phosphate, iron, ammonium, hardness and coliform bacteria.

5.1. Parameters – Theory

5.1.1. Electrical Conductivity

The electrical conductivity (EC) is the ability to allow transport of electric charge, measured in siemens per centimeter [26]. A high EC is measured in waters with a high availability of charged particles or ions. Distilled water contains (almost) no ions and is therefore an insulator, resulting in low EC values. Seawater on the other hand contains many ions, being a reasonable electrical conductor[14]. EC can be used as a measure of the total dissolved solids (TDS) and salinity. It should be noted that the EC varies with temperature, most commonly measured at 25 °C. Potable water has a range of 50-1000 µS cm^{-1}. For agricultural usage, the recommended maximum EC is limited to 3000 µS cm^{-1} [2]. Too high salt concentration can accumulate in the shallow water table or upper root zone and may result in a lowered crop yield [9].

5.1.2. Total Dissolved Solids

The concentration of total dissolved solids (TDS) is the solid residue when all water is evaporated. This includes salts and organic solutes which originate from natural sources, sewage, urban and agricultural run-off. TDS can be estimated from the EC measurement with an empirical conversion factor K, ranging from 0.5 -0.8 [6].

$$TDS[mgL^{-1}] = EC[\mu Scm^{-1}] * K \tag{5.1}$$

For K the value of 0.7 is often used, however this depends on the ionic composition of water [30]. Guidelines for TDS are based on quality/taste, but are dependent on personal preference. Below 300 mg L^{-1} the water is usually experienced as excellent, between 300-600 mg L^{-1} as good, 600-900 mg L^{-1} as fair, 900-1200 mg L^{-1} as poor and greater than 1200 mg L^{-1} as unacceptable for Australian standards [32]. WHO has slightly different guidelines with acceptable water quality below 1000 mg L^{-1} [23].

5.1.3. Dissolved Oxygen

Dissolved oxygen (DO) is the amount of gaseous oxygen present in water, important for aquatic life. DO is expressed in mass of oxygen per volume of water. A deficiency of oxygen can lead to loss of aquatic species [27]. The temperature of water influences the maximum DO concentration, as cold water can have higher concentrations than warm water. Furthermore, another parameter that is of importance in particular is salinity, as it affects the dissolved oxygen content. Salt water holds less oxygen than fresh water. To decompose organic materials oxygen is required. Chemical oxygen demand (COD) is this demand. Part of the COD is decomposed biochemically by bacteria, which is known as biochemical oxygen demand (BOD). Deep groundwater is usually low in DO values, thus often anaerobic. Minerals in deeper layers consume the oxygen, i.e. reduction of iron Fe(III) and sulphate SO_4^-, methanogenesis. Shallow groundwaters will contain higher DO values. Surface waters have naturally higher DO values than groundwaters, caused by re-aeration from air or by photosynthesis of aquatic plants.

5.1.4. Potential of Hydrogen

Potential of hydrogen (pH) indicates how acid or alkaline water is, and is an important water quality parameter of natural water resources. pH expresses the negative logarithm of the concentration of hydrogen ions. It has influence on the presence on different type of organisms and affects the solubility of compounds. With too high and too low pH most organisms will die, as most organisms survive in neutral waters of pH around 7, see figure 5.1. pH can increase by carbonate-rich soils or decrease by sewage outflow and aerobic respiration. Rain events can either increase or decrease the pH, depending on the normal pH of a watershed. The mean value for the pH of rain is about 5.6, whereas ocean water has a mean value of 8. Acidic water can be unsafe to drink as it is more likely to be contaminated [10].

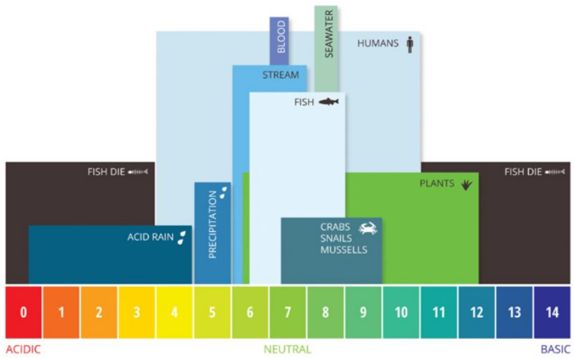


Figure 5.1: Standards of pH [31]

5.1.5. Ammonia

Dissociation of ammonium (NH_4^+) may result in ammonia (NH_3), which is highly poisonous. The equilibrium is

$$\frac{[NH_3][H^+]}{NH_4^+} = 6.2 * 10^{-10} | [T = 20°\text{C}], \tag{5.2}$$

which means that in a basic environment the ammonia concentration can be high. Ammonium can enter water bodies by the breakdown of urea, this is when ammonia reacts with water to form ammonium. Urea is a nitrogenous fertiliser and is excreted by humans and animals. Ammonium is converted to nitrite (NO_2^-) by Nitrosomonas bacteria, which in turn, nitrite is converted to nitrate (NO_3^+) by Nitrobacter bacteria, both within aerobic environments [17]. Ammonium might also contribute to acidification, as nitrification produces H^+.

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O \tag{5.3}$$

5.1.6. Nitrate and Nitrite

Nitrate and nitrite, respectively stable and unstable, are parts of the nitrogen (N) cycle. Presence of the compounds in groundwater can give an indication of the land-use. Effluent of agricultural, domestic and some industrial land-uses can result in higher concentrations in receiving water bodies. A hiher concentration of nitrate in groundwater can indicate any leaching of nitrogenous fertilisers or domestic/industrial waste. Rainfall events can add a surplus to groundwater flow, resulting in an increase of nitrate. A high level of nitrate can lead to cyanosis/methaemoglobina, due to excessive concentration of deoxyhemoglobin in the blood [13]. The total nitrate consist of total Kjeldahl nitrogen plus nitrate-nitrogen and nitrite-nitrogen. Total Kjeldahl nitrogen consists of the sum of ammonium, ammonia and organic nitrogen. Nitrate levels in drinking water should be controlled below 50 mg L^{-1} and for nitrite below 3 mg L^{-1}, according to WHO guidelines [22].

5.1.7. Phosphate

Phosphate is another nutrient which could be present in water and together with an increase of nitrogen may result in algae and aquatic plant growth. Higher concentrations can occur by organic fertilisers used in agriculture [19]. However, (ortho)phosphate concentrations are often lower than nitrate concentrations, as it is often the most limiting nutrient for plant growth. There is no WHO guideline for phosphate/phosphorus in drinking water.

5.1.8. Iron

Iron can be naturally present in groundwater and gives the water a brownish colour. Anaerobic groundwater may contain iron (II) of several milligrams per litre. It can cause stains in clothing for concentrations above 0.3 mg L^{-1}. Taste of iron is noticeable for concentrations above 0.3 mg L^{-1}, but discoloration of water can occur already at lower values. Furthermore, it might indicate the presence of other particles as well. Iron is essential in human nutrition and a minimum daily required amount is in range of 10-50 mg per day. The presence of iron is not of health concern if values of 0.8 mg kg^{-1} body weight is not exceeded, so low concentrations in water is not a health hazard. Allocation of 10% of the provisional maximum tolerable daily intake for drinking water gives 2 mg L^{-1} iron [21]. A range of 0.3-3 mg L^{-1} can be acceptable for anaerobic drinking water, however no health-based guideline is proposed for iron as it does not form a direct hazard for human health.

5.1.9. Hardness

Hardness is the sum of the concentration of calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}). Hardness is considered an important water quality parameter especially for household equipment. The hardness of groundwater depends on the aquifer soil layer. Natural or human processes, like weathering of limestones or mining industry activities may increase the hardness of groundwaters. Hardness is often expressed in calciumcarbonate $CaCO_3$ equivalents. Low concentrations might result in dissolution of minerals into the water, whereas high concentrations can cause scaling effects. Hardness values above 200 mg $CaCO_3$ L^{-1} indicate a poor quality and above 500 mg $CaCO_3$ L^{-1} is harmful for humans, like exacerbate exzema or laxative effects (diarrhoea) [20]. Surface water tends to have lower hardness than groundwater [32].

5.1.10. Coliform bacteria

Coliform bacteria originate commonly from faecal contamination of warm-blooded animals. Coliform ferment lactose when incubated at 35-37 °C can give an indication of the quality of water or food. Coliform bacterium itself are not a cause of serious illness, but it gives a good indication of other pathogenic bacteria originated from faecal contamination is present. Pathogenic organisms may be excreted by human beings or animals and can cause diseases of gastrointestinal tract and may be cause of death. Faecal coliforms in soils have survival times of <120 days, but usually it is less than <50 days [17].

5.2. Methods and material

The 12 water wells in Salela were measured triplicate in duration of three weeks in November and December. EC, DO and pH were measured with designated devices, concentrations of nitrate-nitrite, phosphate, iron, ammonium and hardness with test strips and coliform bacteria with counting plates. The water quality in Tofo and Barra were both only a single measurement at multiple locations and taps in January.

5.2.1. EC-meter

To measure the electrical conductivity an EC-meter(Greisinger-GMH3431) is used. An EC-meter has to be calibrated at least once per week, but this is carried out every day before measuring. An extensive protocol on calibration and measuring is added in Appendix 4. The EC-meter also measures the temperature of water.

5.2.2. pH-meter

To measure the pH a pH-meter (Greisinger-G1500) is used. This has to be calibrated as well and is more sensitive than an EC-meter. Therefore a pH-meter has to be calibrated every day and is regularly checked with the calibration buffer solutions. An extensive protocol on calibration and measuring is added in Appendix 4.

5.2.3. DO-meter

To measure the dissolved oxygen a DO-meter (Greisinger-1610) is used. The DO-meter is calibrated every day and an extensive protocol on calibration and measuring is added in Appendix 4.

5.2.4. Test Strips

Nitrate, nitrite, phosphate, iron and ammonium are measured by colorimetric test strips. In combination with the AKVO app (if possible), which objectively reads the colour of the strips after calibration, the concentrations are determined. The strips have a reagent which will react with the measured parameter. The more a parameter is present in the water, the more a strip will discolour. An overview is given in table 5.1.

Table 5.1: Overview of test strips and product information

	Brand	Serie	Range (ppm)	AKVO
Nitrate-Nitrite	HACH	27454-25	0 - 50	yes
Total Iron	HACH	2745348	0 - 5	yes
Phosphate	Quantofix	91320	0 - 100	yes
Hardness	HACH	2745250	0 - 425	no
Ammonium	Machery-Nagel	90714	0 - 6	no
	Quantofix	91315	0 - 400	yes

5.2.5. Counting plates

To give an indication of the bacteriological water quality on site, 3M™Petrifilm™total coliform counting plates are used. Coliform bacteria will grow onto the medium and produce fermentive gas bubbles. Counting the colonies with gas bubbles will give the most probable number and indicates microbial safety of water.

5.2.6. Protocol

The measuring protocol is added to Appendix 4 and describes every measuring step in more detail.

5.3. Results

All described parameters were measured during three consecutive weeks from 12/23/2019 until 1/13/2019. Together they give an indication of (future) water quality problems in the area of Salela, Tofo and Barra.

5.3.1. Salela

Electrical Conductivity and Total Dissolved Solids

Well 6 showed a higher EC value of 1121-1167 µS cm^{-1}, which is derived to a TDS of 785-817 mg L^{-1}. Values are still acceptable, but a salty taste was already noticed by the users. The range of EC at well 8 was spread from 257-920 µS cm^{-1}. During week 3 the highest value was measured, which was significantly higher than the first two measurements and might be considered as an outlier.

TDS was derived by multiplication of K = 0.7 with the EC measurements. No TDS standards for drinking water were exceeded, as the highest value was around 810 mg L^{-1} for well 8. This is fair quality, but almost classified as poor. The other wells showed lower values and are classified, excellent or good.

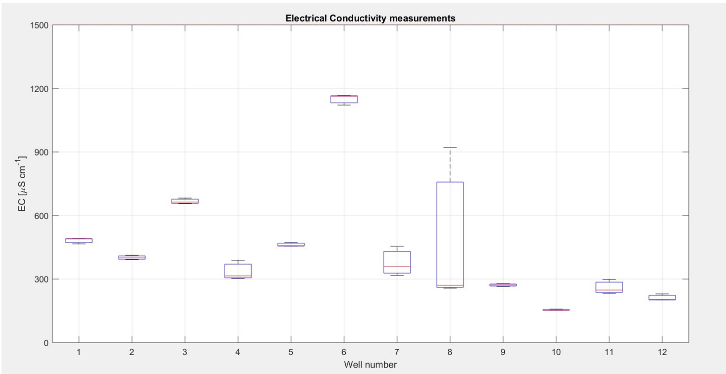


Figure 5.2: Electrical Conductivity measurements of the 12 wells

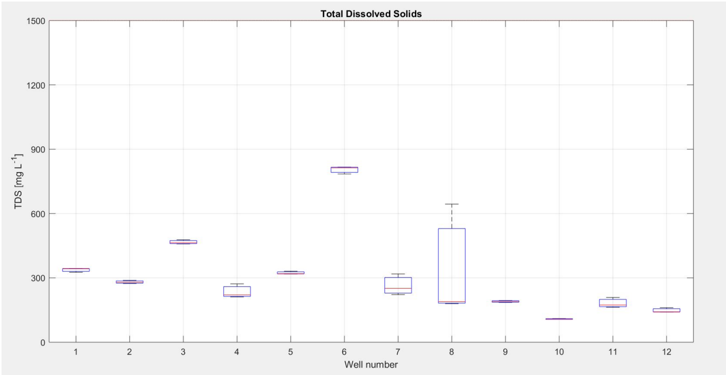


Figure 5.3: TDS measurements of the 12 wells

Potential of Hydrogen

The pH measurements show that most is in the range of 6.5 and 8.5. At well 9 and 10 the values are significantly lower, around a value of 5 to 6. These shallow wells are located next to a river, making it possible that lower values are due to upstream activities. No extreme acidic or basic values are detected.

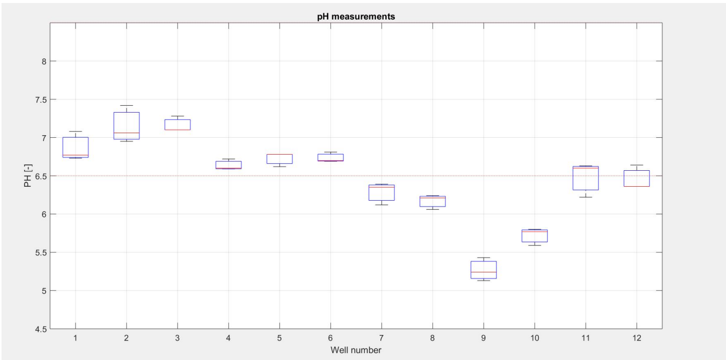


Figure 5.4: PH measurements of the 12 wells

Nitrate-nitrite

No values of possible threat were indicated during the surveying period considering nitrate and nitrite. Some elevated values were indicated in well 3, which is located on a hill next to an agricultural field. However no higher value than 9.5 mg L^{-1} was measured, never exceeding the WHO guideline of 50 mg L^{-1}.

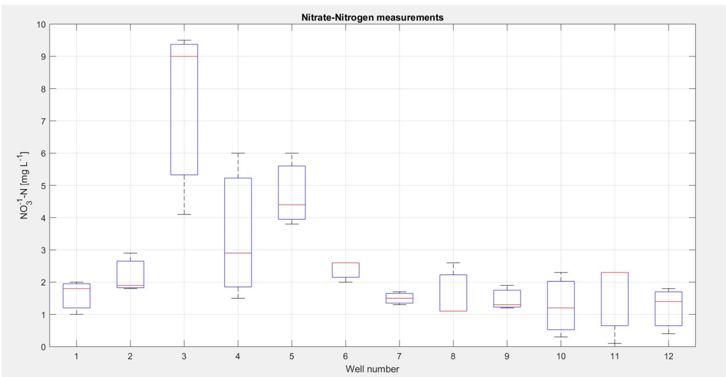


Figure 5.5: Nitrate measurements of the 12 wells

Iron

Iron has been detected unnoticeable for 6 wells and acceptable for 6 other wells. Well 7 has the highest iron values ranging from 1-2.25 during the observation period. No health issues are concerned, but the concentrations above 0.3 mg L^{-1} are troublesome for the use of washing and resulted in discoloration of the water.

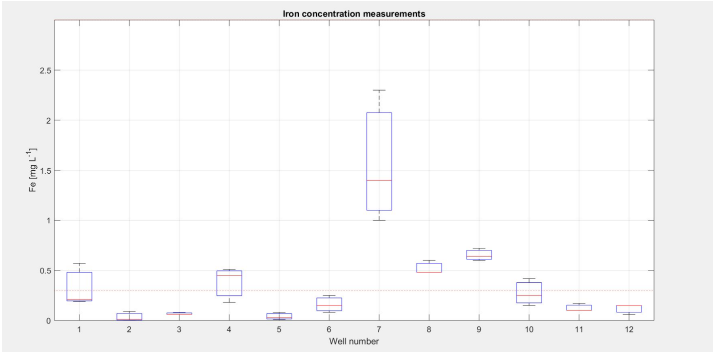


Figure 5.6: Iron measurements of the 12 wells

Phosphate

Phosphate is only toxic for high concentrations, but this was not detected during measurements. The highest concentrations were detected at wells which were located next to agricultural fields, but the elevated values could also be due to the geology. No concentration above 17.8 mg L^{-1} was observed.

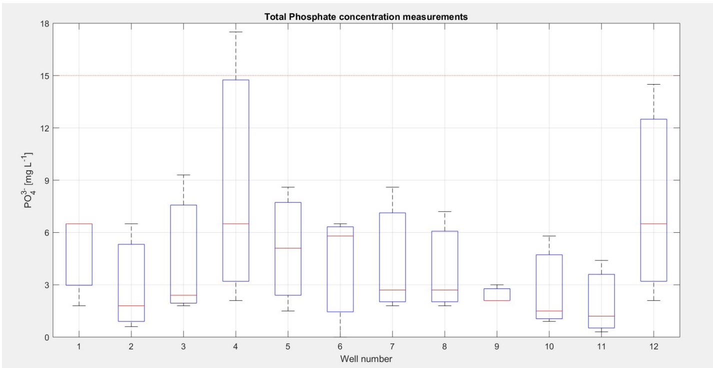


Figure 5.7: Phosphate measurements of the 12 wells

Hardness

Hardness measurements were not carried out correctly during the first weeks. Therefore collection of data on hardness consists of single measurements, Figure 5.8. The highest value of 338 ppm $CaCO_3$ L^{-1} was detected at well 1 and is relatively high, but not harmful. Lower values of 50 ppm $CaCO_3$ L^{-1} were detected at well 9/10, near the river. Surface water tends to have lower hardness than groundwater, which explains the above.

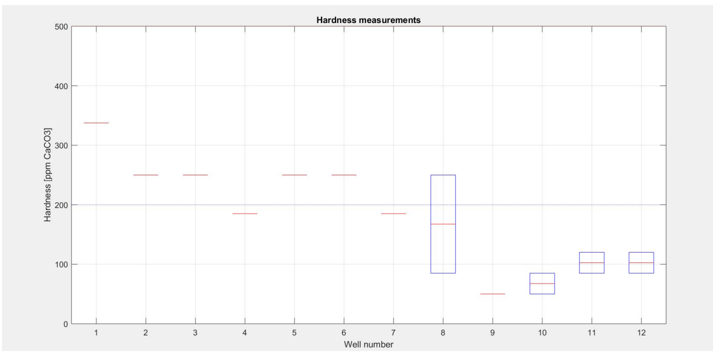


Figure 5.8: Hardness measurements of the 12 wells

Coliform Bacteria

Regarding coliform bacteria, no values higher than 38 were detected for the first 7 wells and well 12. Relative to these values, well 8 showed similar results, however a high value was detected during the last week. It should be noted that well 8 is only used for irrigation purposes. At well 9 values rose to 91 at the last measurement, but during other weeks did not exceed a value of 19. Well 11 showed one high value of 61 during the second week, but did not exceed 9 MPN for the other two measurements. Figure 5.10a and Figure 5.10b show a low MPN of well 2 and an elevated MPN of well 9, other photos of coliform plates are added in Appendix 4.

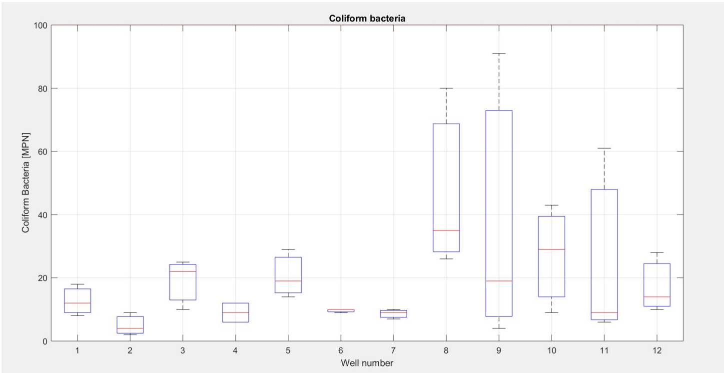
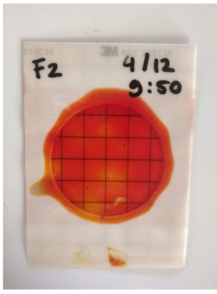
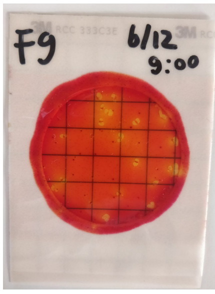


Figure 5.9: Coliform measurements of the 12 wells



(a) Coliform plate F2: 4-12-18



(b) Coliform plate F9: 6-12-18

Figure 5.10: Coliform plates

5.3.2. Tofo

The water quality of a community well, FIPAG water in the storage tank and at the tap after distribution and Agua para Amigos before and after treatment was measured. An overview of all measurements is given in Appendix 4.

A well-known concern in the area of Tofo is the presence of iron. This can be traced back in the concentrations at the FIPAG storage tank and at the consumers end. The concentrations at the consumers end are even higher than concentrations in the storage tank. This might be caused by the accumulation of iron(-hydroxide) in the pipeline system. The water from a shallow well in Tofo showed a lower iron concentration than water from FIPAG.

Agua para Amigos has a slightly lower pH, 6.0 for the untreated water. After treatment the water has a pH of 6.5, which is just in range of drinking water standards.

5.3.3. Barra

The water quality of 6 boreholes of lodges and one shallow well was measured in Barra. An overview of these measurements is given in Appendix 4. Notable is the high EC value of the shallow at Barra Reef Divers, which is located just along the beach. This water is only used for recreational purposes.

5.4. Discussion

Elevated electrical conductivity was measured for especially deeper wells. Well 6 is the deepest well in this survey, which could indicate that the lowest water layers are more saline. This could be caused by the intrusion of salt water from the sea or coning effects. Fresh water from precipitation remains on top of salt water and will not mix. During the weeks of fieldwork some precipitation occurred. During drier periods, no recharge of fresh water, but more evaporation occurs. This might also result in an elevation of EC values, but is less plausible. A geological presence of minerals at this locations seems a more probable explanation.

Elevated iron concentrations were detected at FIPAG near Tofo, before this research and also during this survey. The highest values were measured at the consumers end, not at the storage tank. This may indicate that some accumulation iron in the pipelines is present. Moreover, at some wells near Salela elevated values of iron were detected. Presence of iron is therefore a broader concern for groundwater at the peninsula.

Low pH values were measured for wells 9 and 10 along the river. These lower values could have a natural cause, i.e. rain water is slightly acidic. But it could also be by man-made influence, i.e. by agricultural activities which was present along this river. It is worth mentioning that 2 kilometres inland a solid waste landfill is present, as mentioned in Chapter 4 and Figure 4.3a. At the borehole of Agua para Amigos slightly lower pH values were measured, probably by natural cause. This might have had a corrosive effect on the equipment at the factory, which was a concern of the owner.

Higher coliform counts were detected for some measurements. For well 8 this could be due to the fact that ducks are swimming in this open well. Well 9 and 10 are both open wells and higher values could be for this same reason. Moreover, well 9 and 10 are located next to small stream at which water body stagnation might occur, a better indicator for bacteria. Furthermore, higher values were often measured in the last week. This could also be related to the higher temperatures during the whole week.

Some elevated total hardness concentrations were detected at well 1, resulting in poor quality, but not harmful. Low total hardness concentrations were measured at the wells along the river. Nitrate, phosphate and ammonium were never detected as unacceptable concentrations and are not a contemporary problem.

5.5. Conclusion

Contamination by point source pollution, i.e. private latrines or landfill sites, could not be concluded by this research. No parameters have shown a significant deviation that could be directly harmful to consumption. However, some measurements have shown presence of coliform bacteria. Open wells are more vulnerable to pollution by faecal matter of animals or other pollution sources. Well 9 and well 10, which are located next to a river and at the most western boundary of our research area, are more vulnerable for this microbial water quality deterioration. Additionally, during the last measuring week algae growth was observed at well 9. In this area, groundwater wells are only available at approx. one kilometer, but it would be desirable to have an alternative.

The elevated EC values of well 6 could be due to geology in deeper layers, but the phenomenon of salt water intrusion can not be neglected in this area. High abstraction rates in Tofo, Inhambane and Barra have influence on the groundwater flow in this area. A measurement campaign of 2 months could not show any effects on water quality of this increase of groundwater abstraction. However, a geohydrological model could help with more understanding.

5.5.1. Measurement errors and Accuracy

Coliform counting plates are laboratory equipment and would be placed in an oven or other secluded environment to maintain a steady temperature whilst the coliforms grow onto the growth medium. However, no laboratory was available and the outdoor temperatures in Mozambique were about 30 °C, but clearly not as steady as a laboratory oven could be. The measurements of coliform bacteria are therefore less accurate.

Hardness measurements were carried out with the AKVO Flow app, assuming the settings of the app corresponded to the HACH strips. However, this was not correctly carried out and resulted in missing measurements during the first two measuring weeks.

6
Geohydrology

This chapter focuses on the geohydrology of the study area by performing a geohydrological inventory and model. This should give insight into the subsurface flow directions within the aquifer, the capture zones of the wells, the influence of private boreholes in Barra and Tofo, and lastly into the phenomena salt intrusion.

6.1. The basics of geohydrology

6.1.1. Confined and unconfined aquifers

In geohydrology, an important distinction must be made between confined and unconfined aquifers. In a confined aquifer, the head of the aquifer is above the top of the aquifer. In this case, the soil is fully saturated. For example, when placing a hollow tube in the ground, the water level will rise till a certain point above the top of the soil. The groundwater is in this case under pressure, which is only possible by the presence of an impermeable layer such as rock. On the other hand, in unconfined aquifers the groundwater is not under pressure and an impermeable layer is not present in the aquifer. The groundwater in an unconfined aquifer is in direct contact with the atmosphere, depending on streamwater recharge and infiltration. When placing a hollow tube in an unconfined aquifer, the water level (h) is somewhere in the aquifer itself. The difference of a confined and unconfined aquifer is also visualised in Figure 6.1 [3].

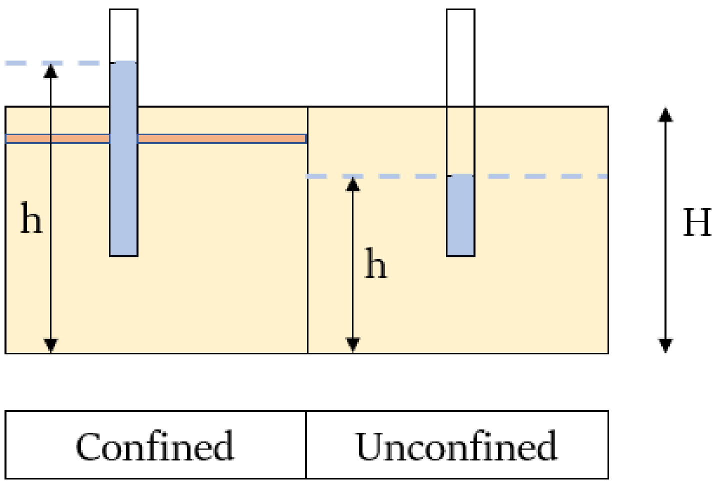


Figure 6.1: Confined- versus unconfined aquifers

6.1.2. Flow in aquifers

The specific discharge in an aquifer can be written as the discharge [m3/d] divided by the surface [m2] [3]:

$$q_x = \frac{Q_x}{A}\ [m/d] \tag{6.1}$$

By applying Darcy's law, the specific discharge can be rewritten as [3]:

Darcy' s law:

$$Q = \frac{dh}{dx}\ [m3/d] \tag{6.2}$$

Specific discharge:

$$q_x = -k \cdot \frac{dh}{dx}\ [m/d] \tag{6.3}$$

Now a distinction must be made between confined and unconfined aquifers, whereas in confined aquifers the transmissivity T is the hydraulic conductivity times the thickness of the aquifer H (since the soil is fully saturated). However, for unconfined aquifers, the soil does not have to be fully saturated, such that the transmissivity T is the hydraulic conductivity times the water table h of the aquifer [3].

Since the water table varies over distance in unconfined aquifers, the transmissivity (T) is not a constant value, but depends on the distance (x) as well. On the other hand, the transmissivity (T) in confined aquifers is a constant value due to a fully saturated soil thickness (H) [3].

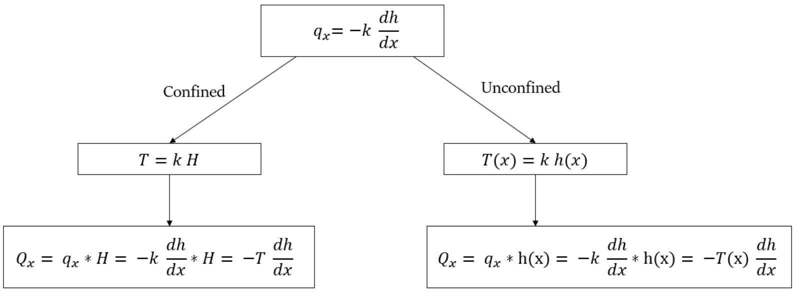


Figure 6.2: Flow in aquifers for confined and unconfined aquifers

6.1.3. The discharge potential

The minus gradient of the discharge potential is equal to the flow discharge [3]:

$$Q_x = -\frac{d\phi}{dx}\ [m3/d] \tag{6.4}$$

The discharge potential does differ in confined and unconfined aquifers [3]:

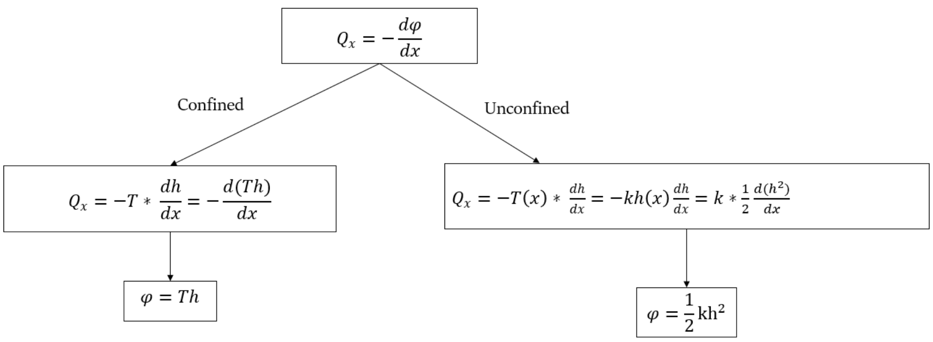


Figure 6.3: The discharge potential for confined and unconfined aquifers

6.1.4. One well in steady flow

For a well in steady flow in a certain area, a water balance can be used to derive an equation for the head in that area [4]. Note that the discharge of a well is positive when taking water out.

$$Out - In = 0 \tag{6.5}$$

$$Q + Q_r * 2\pi * r = 0 \tag{6.6}$$

$$Q_r = -\frac{d\phi}{dr} \tag{6.7}$$

$$Q = -\frac{d\phi}{dr} * 2\pi * r = 0 \tag{6.8}$$

$$\frac{d\phi}{dr} = \frac{Q}{2\pi} * \frac{1}{r} \tag{6.9}$$

$$\phi(r) = \frac{Q}{2\pi} * \ln r + constant \tag{6.10}$$

Equation 6.10 is a general equation for a well in steady flow and needs at least one boundary condition to solve the constant. The r in the formula is the distance from the well to a certain (x,y) point in the area solving for the head. Furthermore, it depends if the well is located in a confined or unconfined aquifer, as is visualized in Figure 6.4 [4].

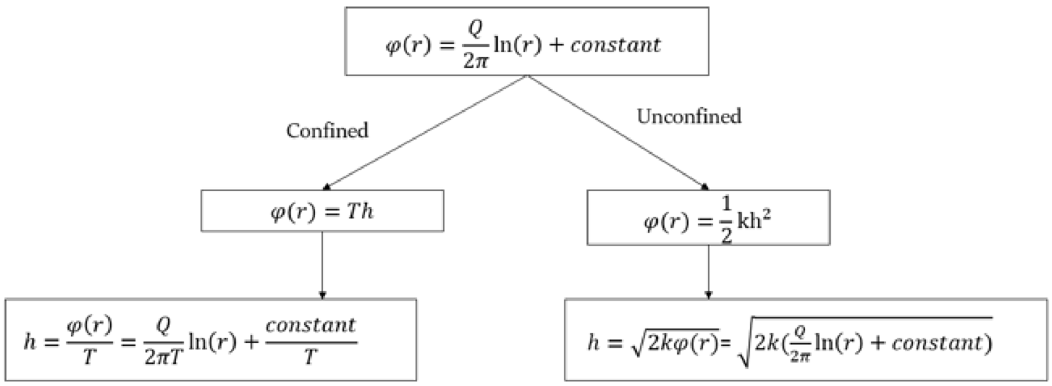


Figure 6.4: The discharge potential for one well in confined and unconfined aquifers

6.1.5. Multiple wells in steady flow

When multiple wells are present in a certain area, the principle of superposition can be applied to calculate the head in the area around the wells [4]:

One well:

$$\phi(r) = \frac{Q1}{2\pi} * \ln r1 + constant \tag{6.11}$$

Two wells:

$$\phi(r) = \frac{Q1}{2\pi} * \ln r1 + \frac{Q2}{2\pi} * \ln r2 + constant \tag{6.12}$$

Three wells and so on:

$$\phi(r) = \frac{Q1}{2\pi} * \ln r1 + \frac{Q2}{2\pi} * \ln r2 + \frac{Q3}{2\pi} * \ln r3 + ... + constant \tag{6.13}$$

Note that when there are multiple wells located in the area, at least one boundary is needed to solve for the constant in the equation.

6.1.6. Wells near a river

When a well is located in the surroundings of a river with a fixed head, an image well must be implemented in the area. The image well has the same pumping rate as the real well, but oppositely [4]. And hence, the river between the well and image well will still have the same fixed head as without the wells, see Figure 6.5.

$$\phi(r) = \frac{Q1}{2\pi} * \ln r1 - \frac{Q2}{2\pi} * \ln r2 + \phi_0 \tag{6.14}$$

$$Q1 = Q2 \tag{6.15}$$

$$\phi(r) = \frac{Q}{2\pi} * \ln \frac{r1}{r2} + \phi_0 \tag{6.16}$$

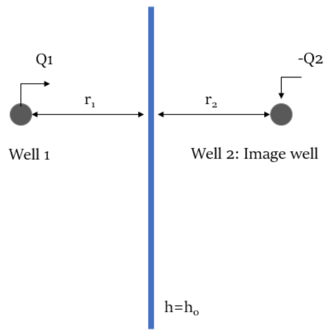


Figure 6.5: A well near a river, with its image well

6.1.7. Wells near an impermeable layer

When a well is located in the surrounding of an impermeable layer, such as rock, again an image well must be implemented in the area. The image well has the same pumping rate as the real well, and not the opposite as in the case for wells near a river [4]. This is visualised in Figure 6.6.

$$\phi(r) = \frac{Q1}{2\pi} * \ln r1 + \frac{Q2}{2\pi} * \ln r2 + \phi_0 \tag{6.17}$$

$$Q1 = Q2 \tag{6.18}$$

$$\phi(r) = \frac{Q}{2\pi} * \ln r1\dot{r}2 + \phi_0 \tag{6.19}$$

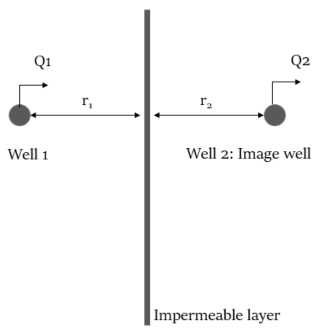


Figure 6.6: A well near an impermeable layer, with its image well

6.1.8. Seawater intrusion and upconing

Wells in the surroundings of the sea often have to deal with a high salinity in the abstracted water. There are two different phenomena that can occur with this high saline level: seawater intrusion and upconing. Both phenomena are explained below and visualised in Figure 6.7 [5].

Upconing

When wells are located in groundwater, where seawater is also present beneath, upconing can occur. During pumping, a lot of groundwater is abstracted and this results in a lower freshwater table. Sometimes this water table is so low, that seawater is also pumped up. This phenomena of upconing is found locally around wells.

Seawater intrusion

Seawater intrusion usually occurs where pumping wells are firstly located above freshwater, where no salt water is beneath. However, due to pumping the interface between fresh and salt water shifts towards the inland area. Sometimes,it shifts that much, that pumping wells are in direct contact with seawater.

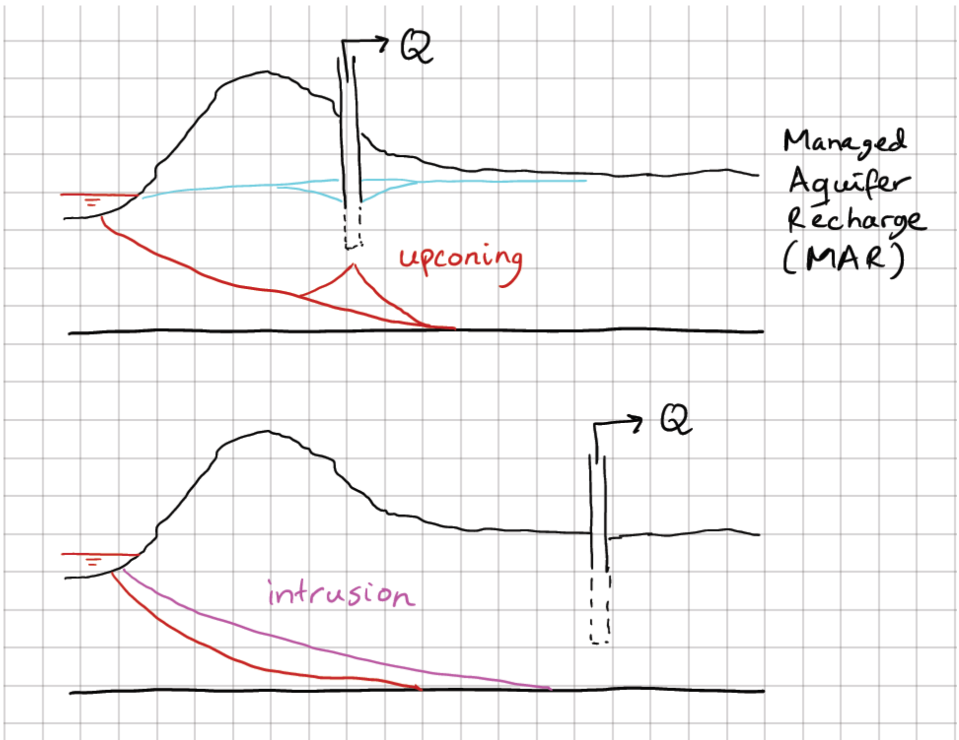


Figure 6.7: The phenomena of seawater intrusion and upconing

6.2. Geohydrological Inventory

For the primary research area Salela a 'geohydrological inventory' was performed in order to get some first insights into the groundwater tables. This has been done by creating imaginary cross-section throughout the research area, as visualized in Figure 6.8. In total five cross-section were created, identified by C1-C5, each starting from the sea and running approximately through three or four wells over a maximum distance of 2.2km.

Figure 6.8: Cross-sections overview Salela

These longitudinal cross-sections were created by heights from Google Earth (black) and SRTM-satellite data (orange) in reference to sea level (grey) and calculated heads from measurements performed on the wells over a three-week period, resulting in a water table (blue). The results of each of the cross-sections are visualized below with on both axis meters as units.

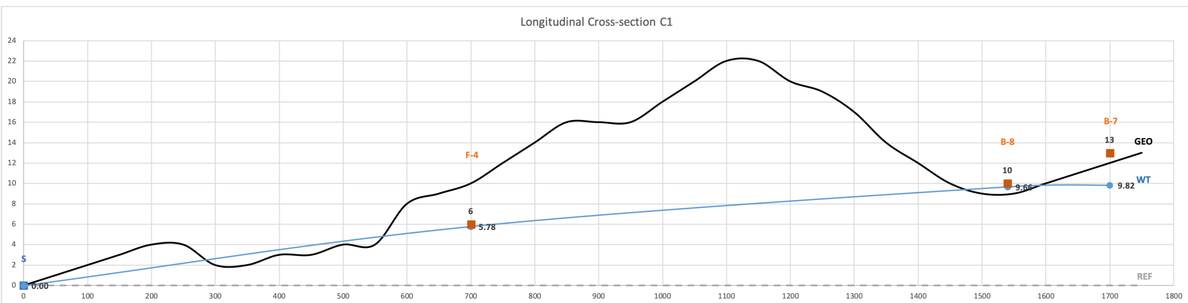


Figure 6.9: Cross-section C1

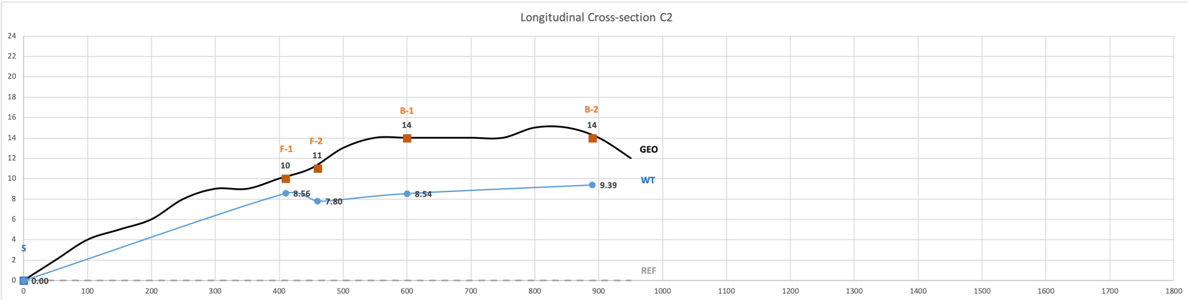


Figure 6.10: Cross-section C2

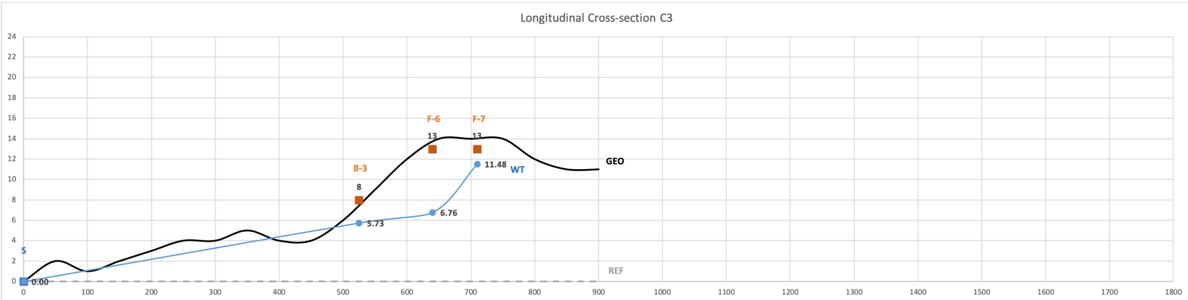


Figure 6.11: Cross-section C3

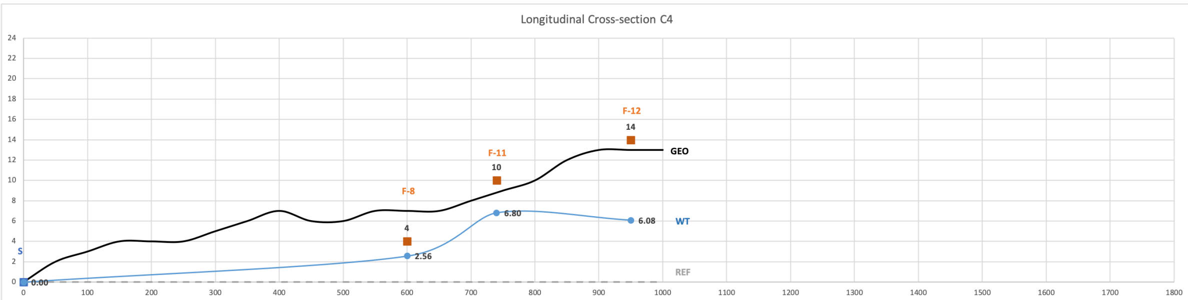


Figure 6.12: Cross-section C4

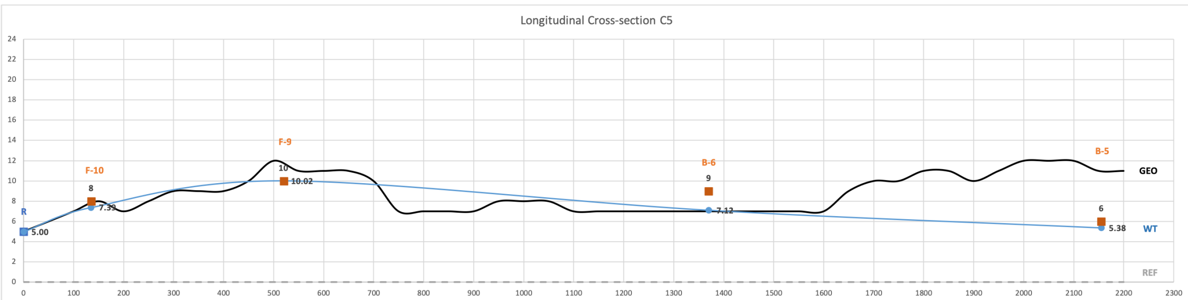


Figure 6.13: Cross-section C5

First of all, it is clear that the heights from Google Earth (black) and SRTM-satellite data (orange) in reference to sea level are at most locations quite matching but on some locations, like F-4 and B-5, they are quite different from each other. In order to work with consistent data, it was decided that the SRTM-satellite database should be used in order to compute the water tables.

From these resulting cross-sections it can be concluded that some water tables are a bit odd compared to what is expected, which is a gradual curve going seaward as rainwater should be flowing from the inland to the sea. Sections C1 and C2 show such a theoretical gradual curve quite well in practice. However, sections C3 and C4 show a deviation from this gradual curve. Note that section C5 along the river shows a gradual curve in inland direction instead of directing to the sea.

These deviations have been the main reason to perform extra levelling measurements between the wells that are part of the longitudinal cross section. With the use of a theodolite the height difference between two wells could be computed and checked to the satellite data. By performing these measurements, locations with deviations in the cross-sections could be checked and when necessary be adjusted in order to create a more gradual water table. This resulted in the following longitudinal cross-sections where F-1, B-3, F-6, F-7, F-8, F-11, F-10 and F-9 are modified based on levelling measurements. Note that the levelling calculations are added in Appendix 5.

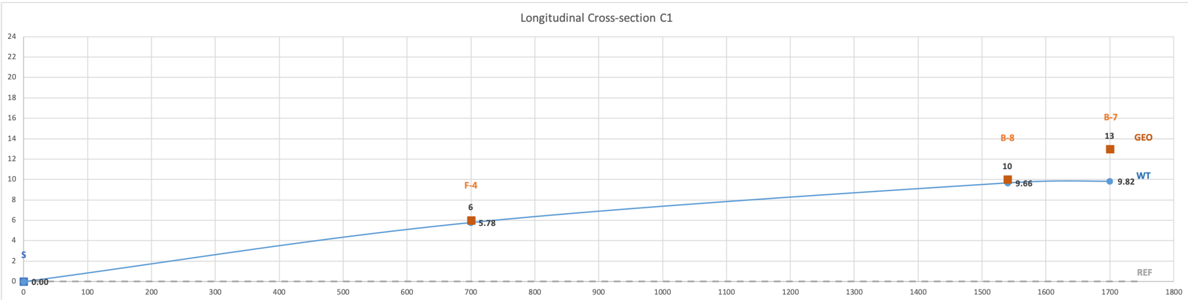


Figure 6.14: New cross-section C1

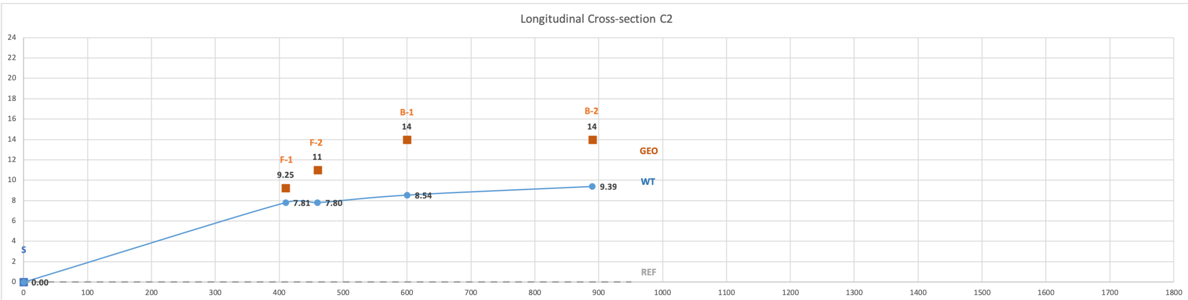


Figure 6.15: New cross-section C2

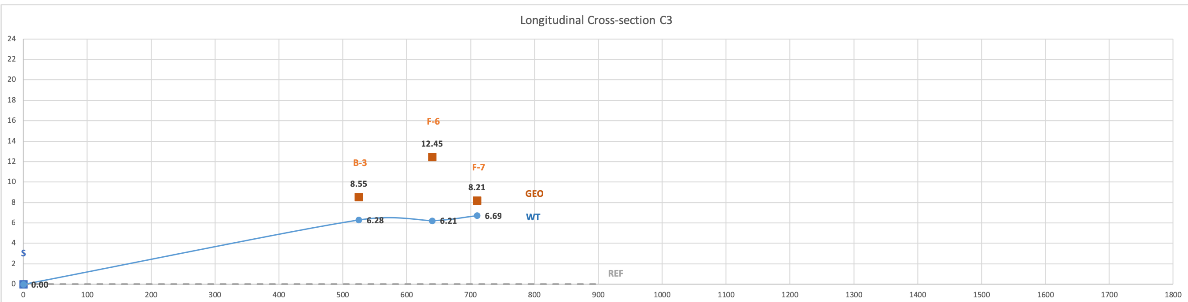


Figure 6.16: New cross-section C3

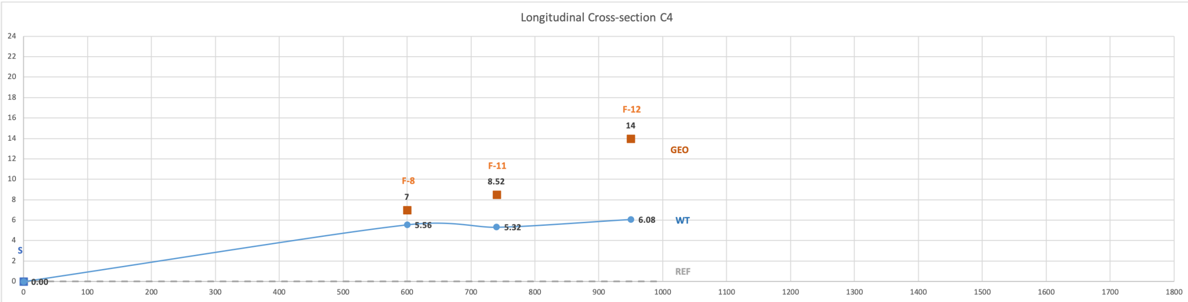


Figure 6.17: New cross-section C4

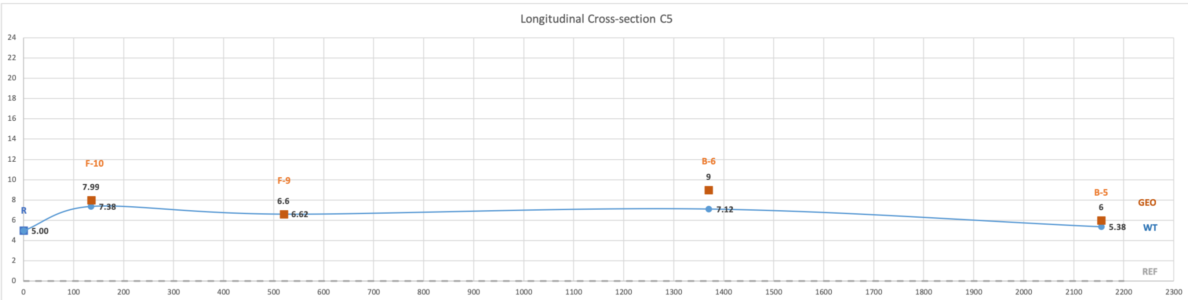


Figure 6.18: New cross-section C5

From these resulting cross-sections it can be concluded that the water tables overall show a gradual curve going seaward, what was expected as rainwater should be flowing from the inland to the sea. Sections C3 and C4 had most deviation from this theoretical curve but now, after implementing the levelling data, show a theoretical gradual curve quite well in practice. However, section C5 along the river still shows a gradual curve in inland direction instead of to sea. This can however be possible due to the dry season, such that seawater could be flowing in instead of rainwater flowing out.

Figure 6.19: Theodolite measurements

6.3. The geohydrological model: step by step

The geohydrological model is performed in the software Python by using the TimML package, which is a computer model using the theory described in Chapter 6.1. A few important assumptions are made to make use of this package for the study area [5]:

- Steady state flow: meaning flow rates are constant over time
- Dupuit assumption: resistance to vertical flow is neglected

In the next sections all the steps taken to compute the geohydrological model are elaborated. Note that for such a model it is of utmost important to start at large scale, followed by implementing more detailed information into small scale. Furthermore, the python script involving all these steps is included in Appendix 5.

6.3.1. Step 1: Confined or unconfined aquifer?

When looking at the lithology of the study area, no impermeable layer such as rock or clay is found, but a sandy aquifer with a thickness of around 50 meters as can be seen from Figure 3.3. Due to the absence of an impermeable layer, the aquifer is said to be unconfined. Another way to immediately see the aquifer is unconfined, is the fact that there are open wells located in the study area with a water level that does not rise above the top of the aquifer.

However, since the wells all show a water level that does not differ that much from each other, a constant saturated thickness (H) is assumed, resulting in a constant transmissivity (T). And hence, the theory for confined aquifers can be used. This is visualised in Figure 6.20.

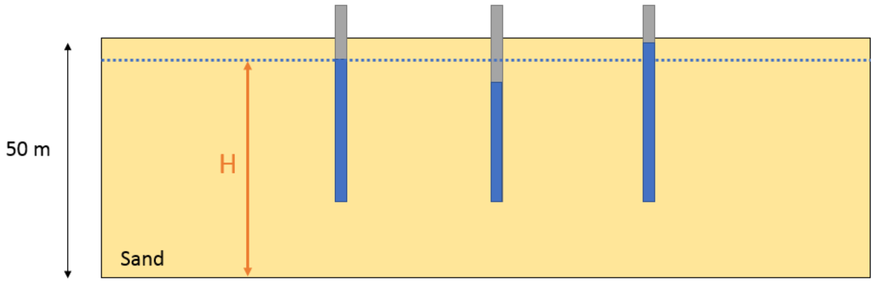


Figure 6.20: An unconfined aquifer - Assuming a constant saturated thickness - Theory of confined aquifers can be used

6.3.2. Step 2: The hydraulic conductivity

The hydraulic conductivity of an aquifer describes how easily water can flow through the layer in latitudinal direction. This depends on the type of soil in the aquifer. For sandy soils, the hydraulic conductivity is in a range of 0.1 (silty sand) to 100 m/day (course clean sand). In the study area the sandy aquifer contains fine clean sand, such that the hydraulic conductivity is around 1 m/day. In the model, a hydraulic conductivity of 1 m/day is used, and a saturated thickness of 50 meters. This results in a constant transmissivity of

$$T = 50m^2/day$$

.

6.3.3. Step 3: Start with a large scale model

First of all, a model in large scale is build with the surrounding sea as a head boundary.

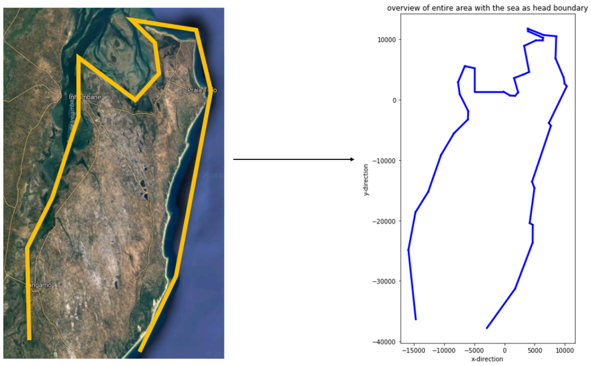


Figure 6.21: Start of the model with sea boundaries

For the model, the latitude and longitude coordinates need to be converted to a system with x- and y-coordinates. For this system, a reference point (0,0) is needed. The latitude and longitude coordinates are converted to x- and y-coordinates with the following formulas:

$$dx = ((origin_{longitude} - longitude) * 40000 \frac{\cos(latitude + origin_{latitude}) * \frac{\pi}{360}}{360}) * 1000 \tag{6.20}$$

$$dy = ((origin_{latitude} - latitude) \frac{40000}{360}) * 1000 \tag{6.21}$$

Note that these conversion formulas lead to an x- and y-coordinates system in the opposite directions, and hence the new x and y coordinates need to be multiplied by -1:

$$x = dx * -1 \tag{6.22}$$

$$y = dy * -1 \tag{6.23}$$

To conclude, the converted sea boundaries coordinates lead to the following schematization of the model:

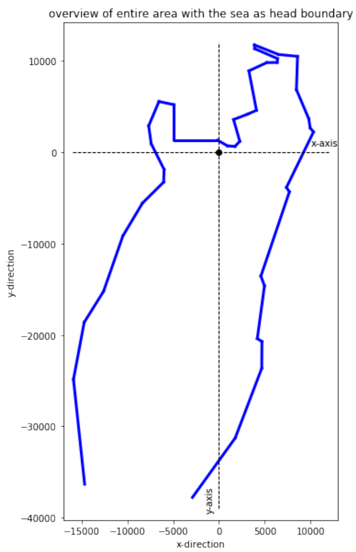


Figure 6.22: Overview model with sea boundaries

6.3.4. Step 4: Adding rainfall and evaporation

The next step in the model is to implement a certain infiltration rate, depending on rainfall, evaporation and the permeability of the top of the aquifer. The annual rainfall rate over the area is equal to 2.3 mm/day.

Since the permeability of the top of the aquifer is enormously (sandy soil & unpaved areas), the rainfall water does not have a lot of time to evaporate, and therefore will infiltrate quite fast into the ground. It is assumed that 2.0 mm/day of the 2.3 mm/day rainfall will infiltrate into the ground, towards the groundwater. The infiltration rate is added to a certain point in the middle of the area, as a circle with a radius of 1 kilometer.

The heads of the sea boundaries are implemented in the model as heads of 0 meters, such that the sea is the reference level of the model.

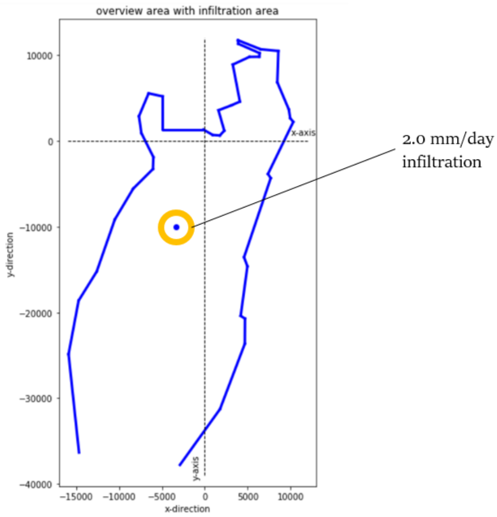


Figure 6.23: Model with infiltration area

Now that the infiltrated rainwater becomes groundwater, the question is how this groundwater flows towards the sea, as is expected that groundwater flows towards the sea in common cases. Therefore, a contour plot is made showing headlines which can be seen in Figure 6.24. Water will flow from large heads to small heads. Moreover, in common cases water will flow towards the sea, resulting in low heads near the sea en larger heads in the inland area. Looking at the contour plot, as expected the infiltrated water will move towards the sea in all directions.

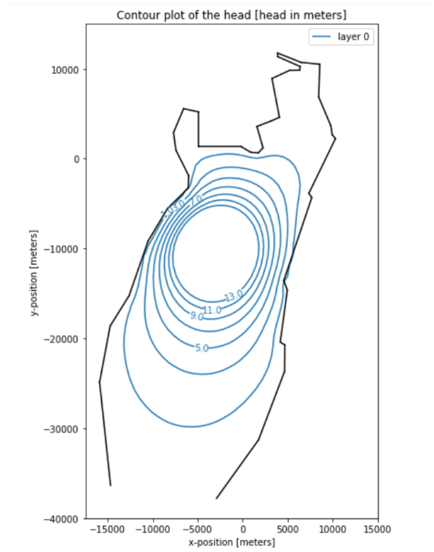


Figure 6.24: Contour plot showing headlines

6.3.5. Step 5: Adding points and lines with known heads

By adding heads of point boundary wells and the head of a measured river in the study area, the model becomes more accurate.

Point boundary wells

As described in the well inventory of Chapter 3, for eight open wells functioning as boundary points in the study area the water level is measured. With the measured water level, the head in these open wells is calculated, relative to the sea level where the head is 0 meters. By adding these points with a known head, the contour plot shows more accurate heads which can be seen in Figure 6.25.

ID	Head [m]
B1	4.54
B2	5.39
B3	1.73
B4	0.31
B5	1.38
B6	3.12
B7	7.74
B8	5.83

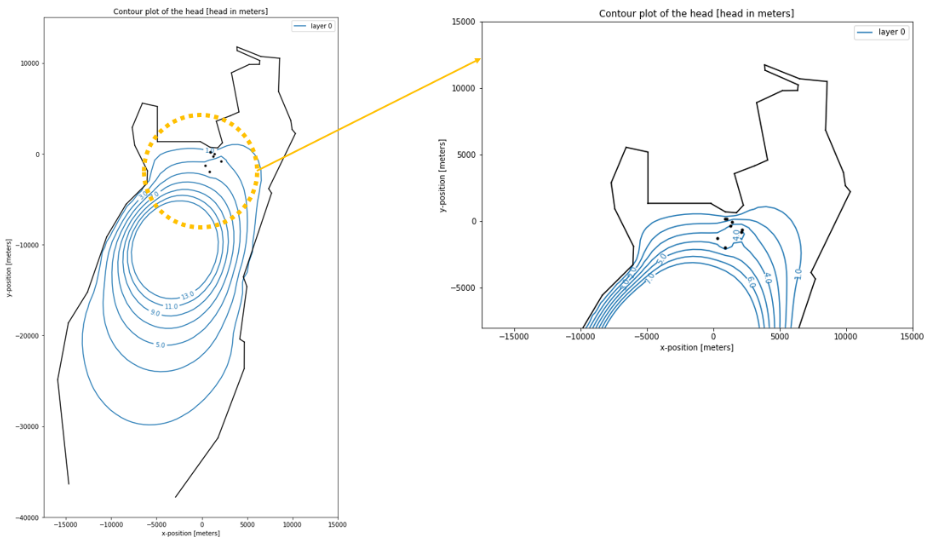


Figure 6.25: Contour plot including boundary wells

River

Furthermore, a river located in the area Salela is added to the model, as shown in Figure 6.26. For this river, only the heads at two points are known, namely in point 1 and 2. The other head points are not known, due to the incapability of field work in that region. Therefore, for the other river points, heads from nearby wells are assumed to be equal to those river points, resulting in the following heads:

ID	Field work?	Nearby well	Head [m]
R1	yes	-	0
R2	yes	-	-1.67
R3	no	F9	6.02
R4	no	B6	2.76
R5	no	B5-B6	6.12-2.76 = +/- 4.44
R6	no	B5	6.12

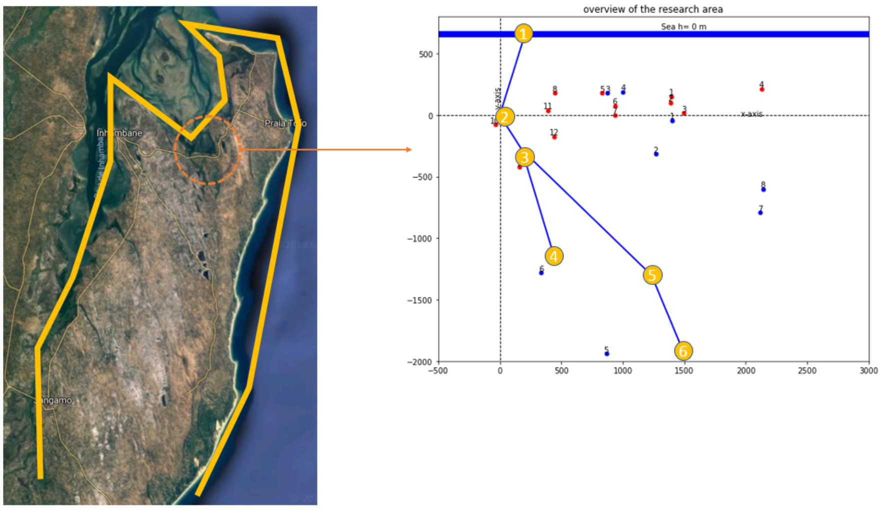


Figure 6.26: Model with point boundaries

The river segments are implemented in the model as line sinks, with known heads at the end and start of the segment. This results again in a more accurate contour plot of headlines, as depicted in Figure 6.27. The model is now ready to add specific discharges in the entire area and to see the effect and adjustments of the headlines in the contour plot.

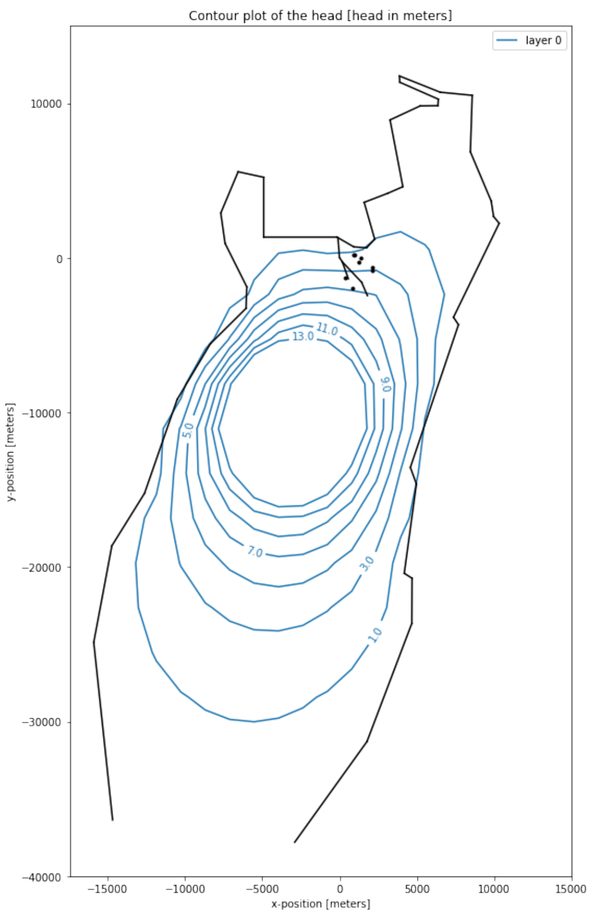


Figure 6.27: Model with point boundaries

6.4. Results geohydrological model

This section shows the results of implementing the discharge wells in the geohydrological model. First of all, the discharge wells in the study area Salela are implemented. Secondly, the effect of the large extractions in Barra, Tofo and from the FIPAG points are investigated (shown in Figure 6.28). Lastly, all the extraction points are added to the model, to examine the total effect of the combined extraction points. Different scenarios will be used for the model: scenario 2019, scenario 2025 and another scenario in the far future. These scenarios are based on a growing extraction amount, which are depicted in Table 6.1.

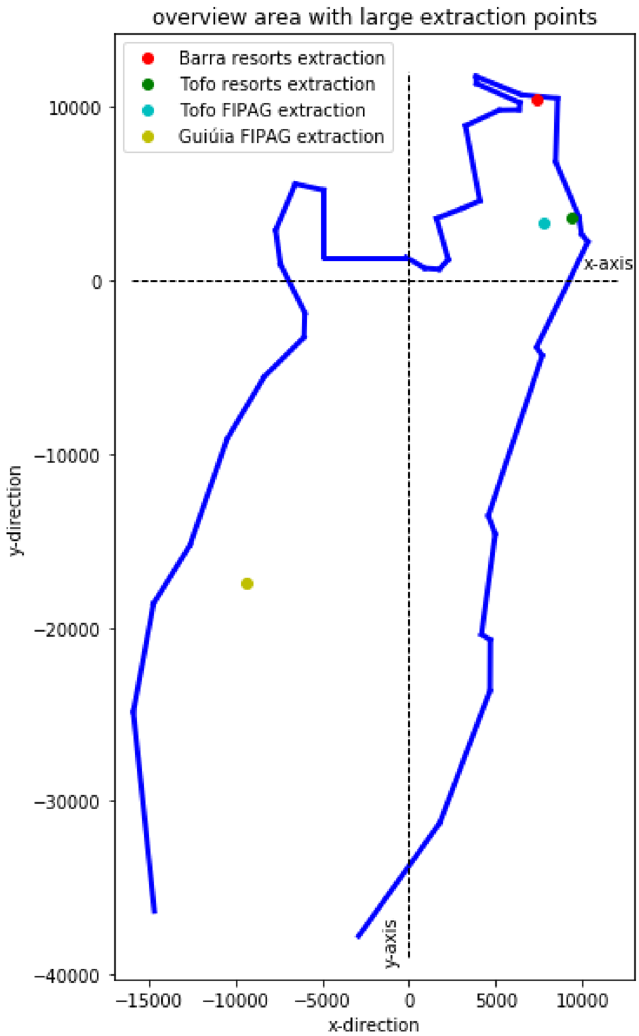


Figure 6.28: Overview Inhambane with large extraction locations

Extraction point	Scenario 1: Discharge 2019	Scenario 2: Discharge 2025	Scenario 3: Discharge far future
Barra resorts	600	785	2500
Tofo resorts	800	1047	3000
Tofo FIPAG	3000	3929	7000
Tofo Total	3800	4976	10000
Guiúia FIPAG	6000	7858	9000

Table 6.1: Scenarios

6.4.1. Effects of discharge wells

Since the discharge wells are open wells and the amount of extraction is very low compared to common pumping extraction amounts, it is expected that these discharge wells will merely influence the heads in the area. And indeed, the geohydrological model shows that the discharge wells in Salela do not influence the contour plot, as is depicted in Figure 6.29.

These discharge wells will not result in seawater intrusion due to very low extraction amounts. The headlines show a flow direction from Salela towards the sea. When open wells in this area have a high salinity, it is most likely due to minerals in the subsurface or external extraction rates.

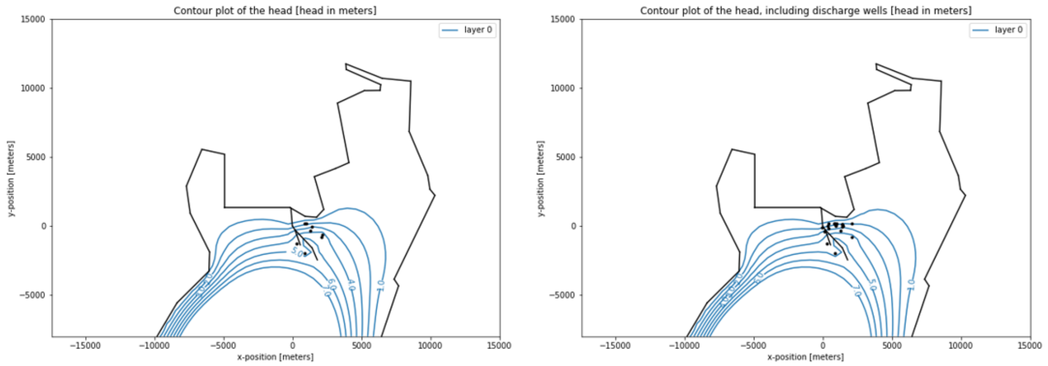


Figure 6.29: Influence of discharge wells in the model

6.4.2. Influence of boreholes in Barra

Taking the extraction point Barra into account in the geohydrological model, it can be seen that it does not impact the heads in the region Salela for the three different scenarios. However, looking only at the area Barra, seawater intrusion will become even a bigger problem when measures are not taken. This can be seen in the geohydrological model as a large circle of headlines around Barra, meaning more fresh groundwater under the sea is flowing towards Barra. As a result, the surface between the fresh groundwater and seawater will shift towards the inland area, meaning seawater intrusion. This is shown in Figure 6.30 and 6.31.

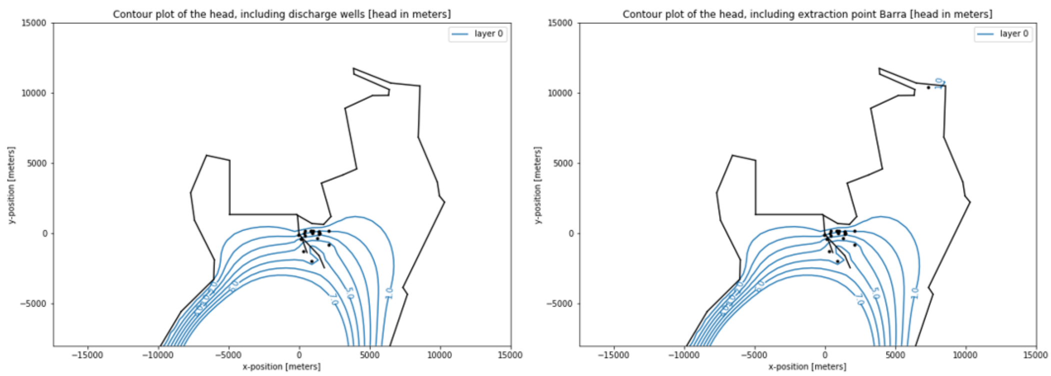


Figure 6.30: Influence of extraction point in Barra 2019

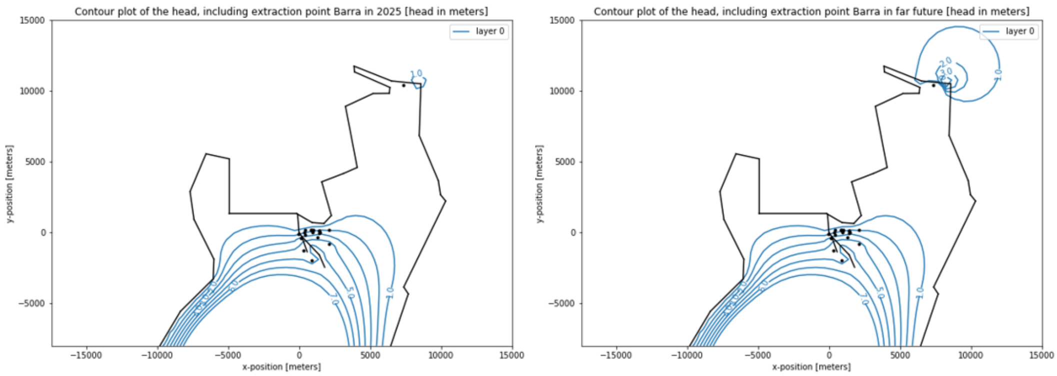


Figure 6.31: Influence of extraction point in Barra 2025 and far future

6.4.3. Influence of boreholes in Tofo

Tofo resorts

In Tofo, resorts are already complaining about the high salinity level in their abstracted groundwater. Therefore, they are already using treatment steps (filters) to get rid of the high salinity in the water. The geohydrological model shows that in scenario 1 seawater intrusion is already a large problem. In the future it will become an even bigger problem when measures are not taken. This can be seen in the scenario 2 and 3 of the geohydrological model.

Moreover, not only groundwater is extracted from the nearest sea side but also the area between Tofo and Salela is impacted due to the abstraction in Tofo. So in the far future, the heads in Salela can be influenced as shown in Figure 6.32 and 6.33.

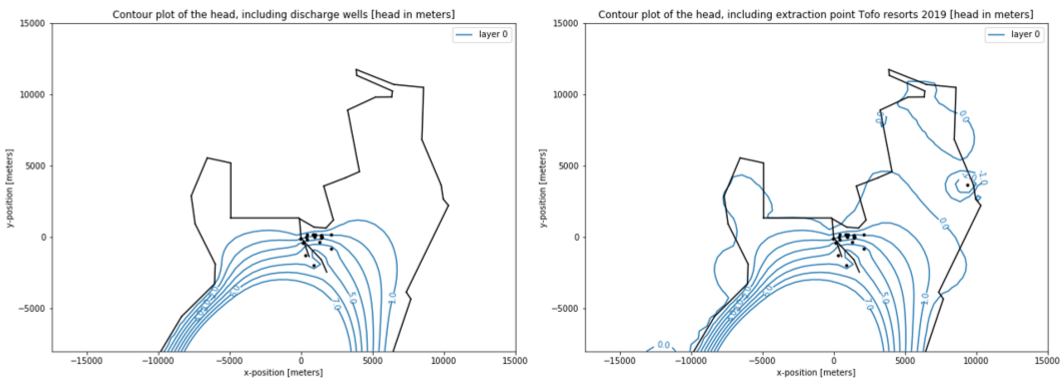


Figure 6.32: Influence of extraction point in Tofo resorts 2019

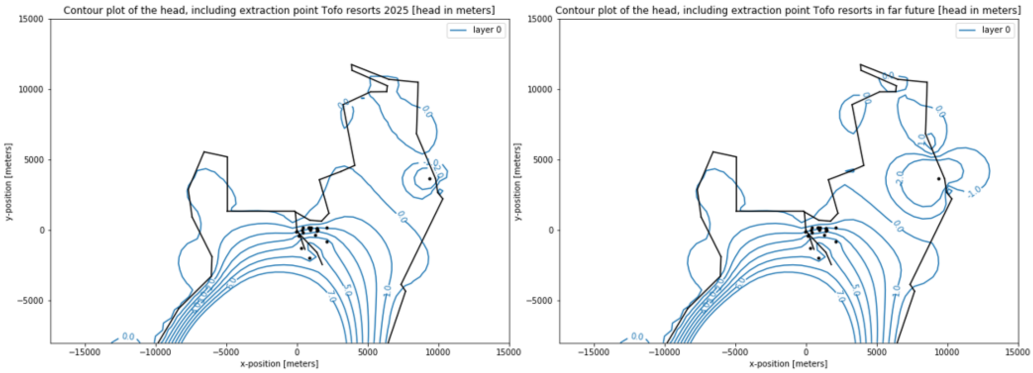


Figure 6.33: Influence of extraction point in Tofo resorts 2025 and far future

Tofo FIPAG

The amount of groundwater extraction in Tofo for FIPAG's distribution system is enormous. This can be seen in the geohydrological model as a large circle around the extraction point. In the future, the circle becomes larger and larger, and will finally influence the groundwater reservoir in Salela itself, as shown in Figure 6.34 and 6.35. More groundwater in Salela area will flow towards the FIPAG extraction point which will result in lower groundwater tables in Salela.

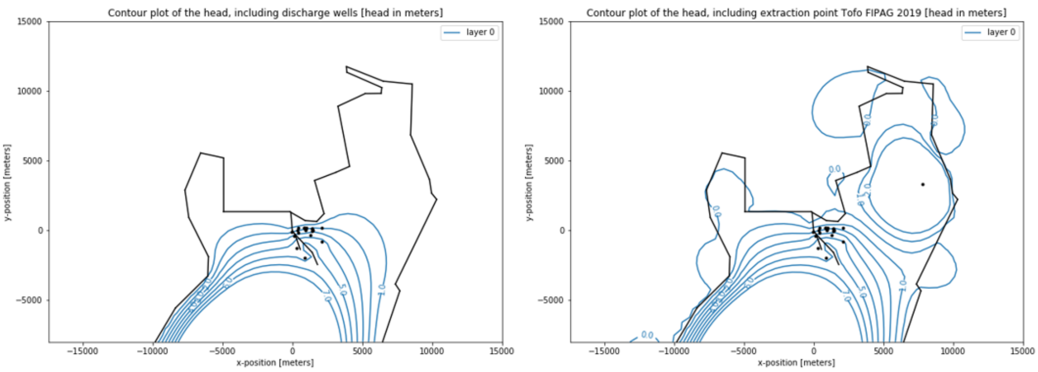


Figure 6.34: Influence of extraction point in Tofo resorts 2019

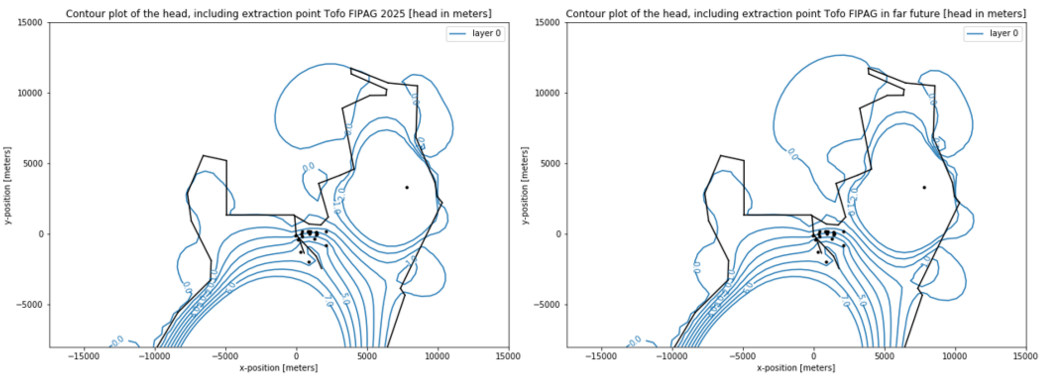


Figure 6.35: Influence of extraction point in Tofo resorts 2025 and far future

Tofo resorts and FIPAG

As discussed in the previous sections, the boreholes owned by the resorts in Tofo have some influence in the surrounding area but the boreholes owned by the resorts in Tofo have a major influence. Note that the combined impact will stimulate these influences even more. This can be seen in the geohydrological model as a large circle around the 'combined' extraction point. This influence will reach the Salela area where the population, which is using the open wells, will feel the consequences of the high extraction rates in Tofo area.

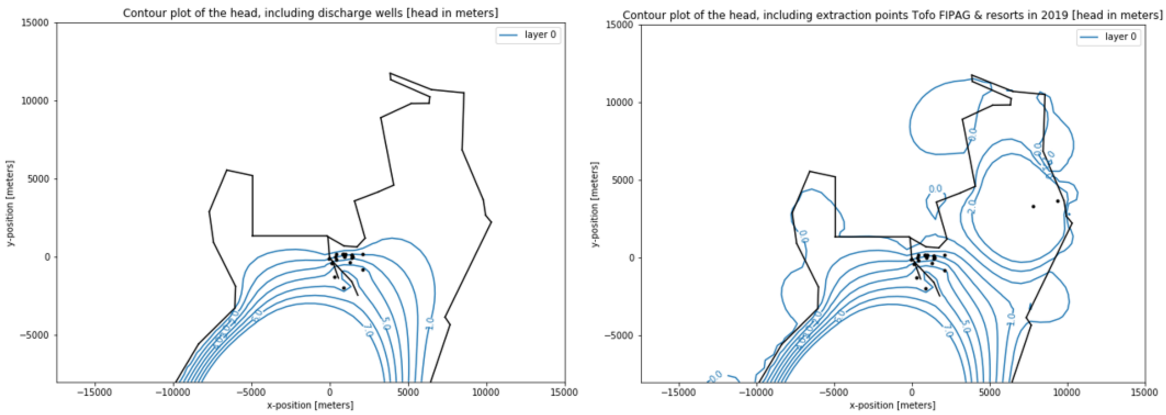


Figure 6.36: Influence of extraction points FIPAG & resorts in Tofo resorts 2019

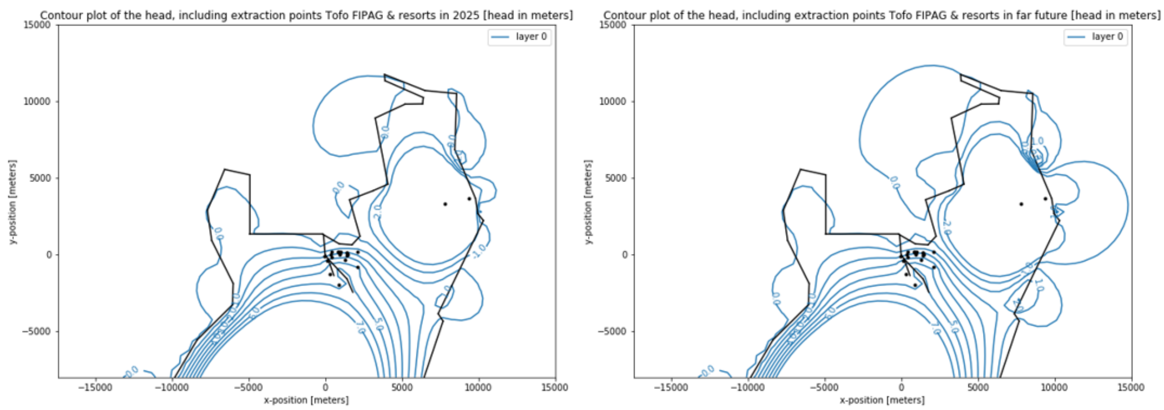


Figure 6.37: Influence of extraction points FIPAG & resorts in Tofo resorts 2025 and in far future

6.4.4. Influence of extraction point Guiúia river FIPAG

The extraction point of FIPAG at the Guiúia river in the south of the Cidade de Inhambane district is influencing the water tables in the southern area of the district as can been seen from the Figures 6.38 and 6.39. Note that the heads in the Salela area are not influenced by this extraction point, also not in the far future. Since the inhabitants of the surrounding area of this extraction point are connected to the FIPAG network, lowered water tables within the area have less impact.

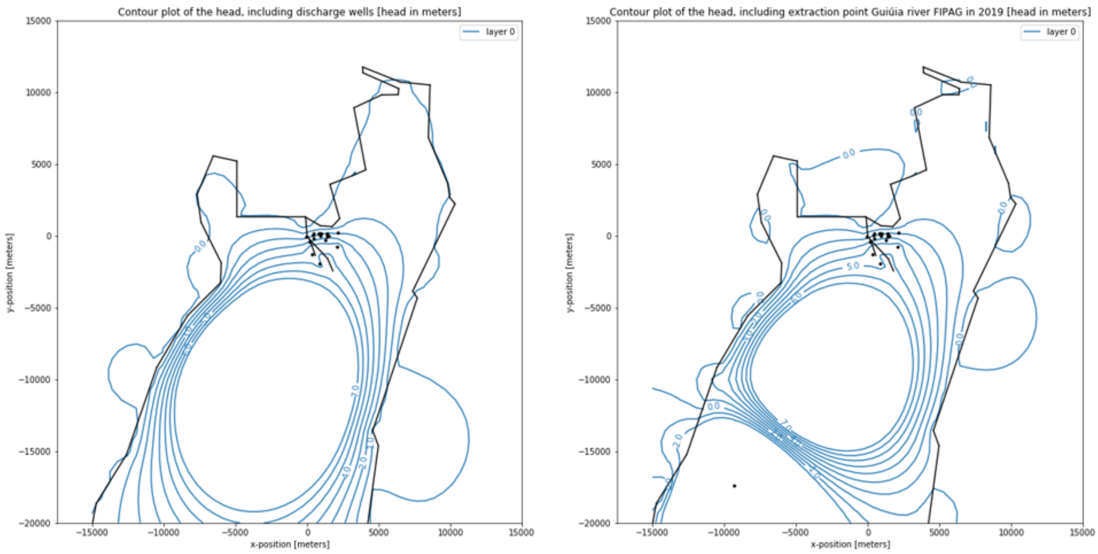


Figure 6.38: Influence of extraction point Guiúia river FIPAG 2019

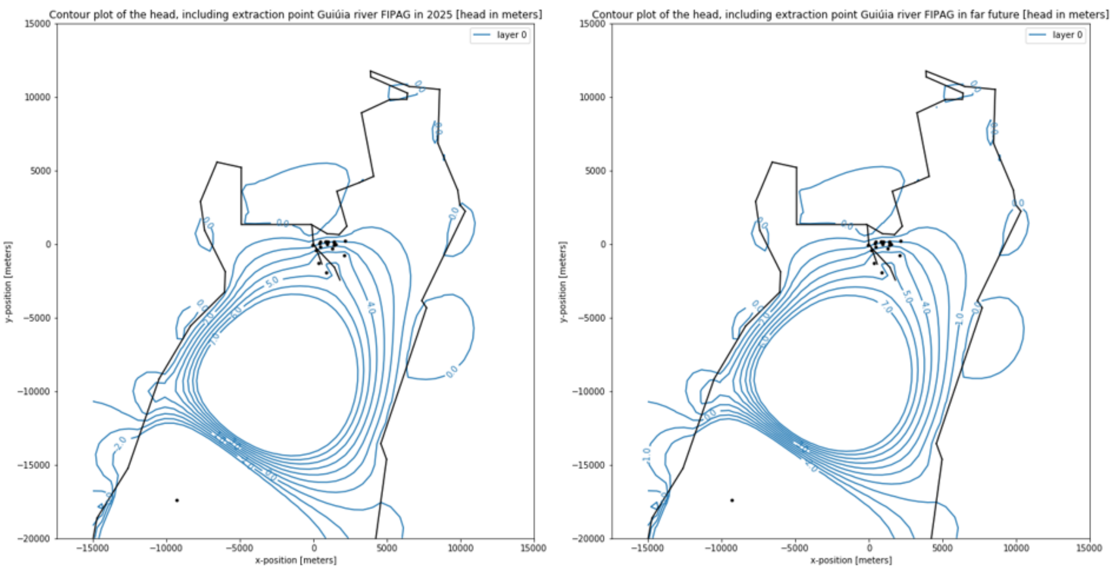


Figure 6.39: Influence of extraction point Guiúia river FIPAG 2025 and in far future

6.4.5. Overall influence of all extraction points

The extraction points in Tofo for the resorts and for the FIPAG distribution network are mostly going to influence the area Salela. Also, salt intrusion will play a big role in Barra and Tofo in the future as can be seen from the Figures 6.40 and 6.41.

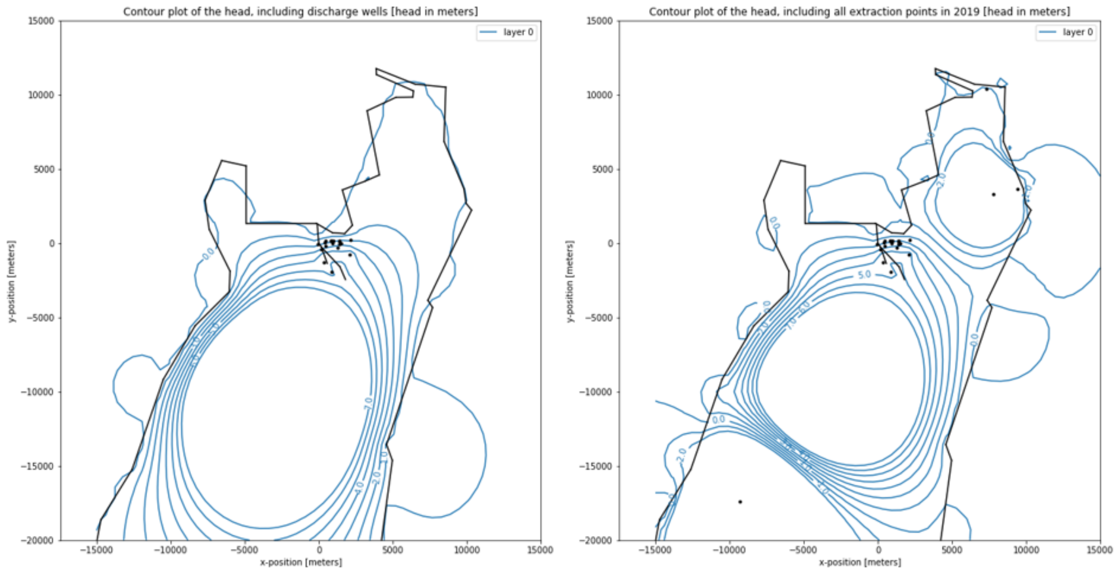


Figure 6.40: Influence of all extraction points 2019

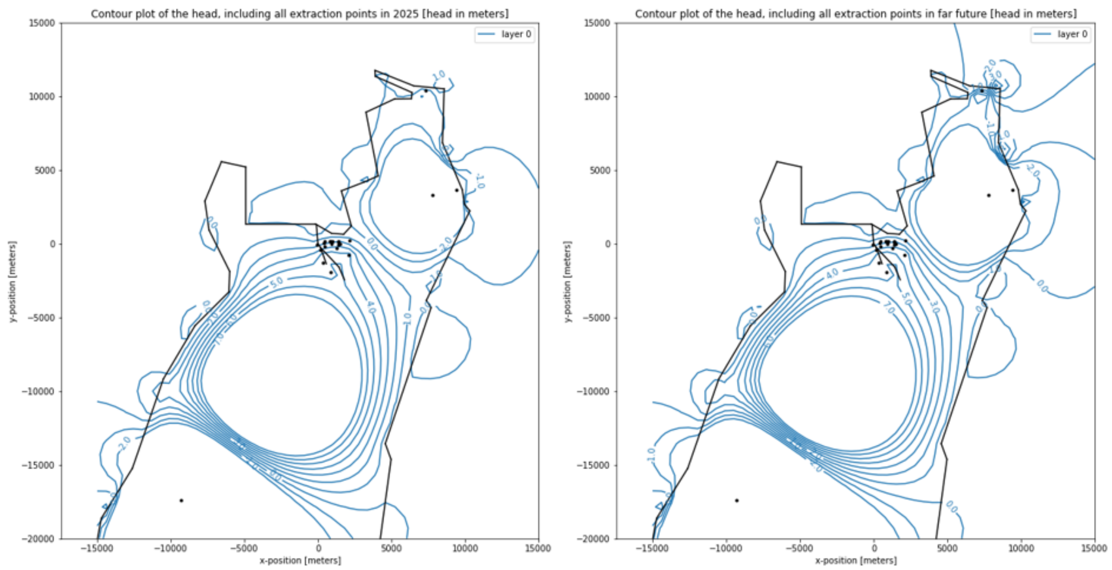


Figure 6.41: Influence of all extraction points 2025 and in far future

6.5. Conclusion

In Salela, the discharges of the open wells do merely influence the heads in that area, as was expected since the wells do not have a discharge rate as common pumping rates. In fact, the open wells can be seen as piezometers.

In Barra there is no seawater intrusion yet, however, in the far future seawater intrusion will occur due to flow from groundwater under the Sea to the area Barra. There are already some resorts in Barra having problems with salt water from their pumps. This is most likely due to the phenomena upconing in the area of the wells in Barra.

In Tofo there is already seawater intrusion (the results show that there is flow from groundwater under the Sea towards the area of Tofo). In the future the problem of seawater intrusion will get worse when measures are not taken.

Moreover, the pumping rate of the FIPAG wells in Tofo is enormously high and will have an influence on the water tables in the wells of Salela.

In the future, it is expected that FIPAG will be more dependent on the abstraction of groundwater then the abstraction of river water in Guiúia due to dry periods. As a consequence, more groundwater will be pumped in Tofo and Salela will even be impacted more. In that case, it is recommended to implement more pumping wells spread over the entire area of Inhambane, such that less water is pumped in Tofo, and Salela will not be influenced that much. Another recommendation is to enlarge the distribution system of FIPAG towards Salela, such that people in Salela are not dependent on their open wells anymore. Note that when more pumping wells are placed, the phenomena of seawater intrusion and upconing must receive extra attention.

7

Conclusion

In this project, a study has been performed about the groundwater quality and -quantity of the Peninsula of Inhambane, Mozambique. The study is performed within a smaller area within the Peninsula of Inhambane. To select an appropriate area, first of all, an area inventory is carried out of the Cidade de Inhambane District. As a result of this inventory, the appropriate area for this study is chosen to be within Salela due to the presence of a lot of groundwater wells and the absence of the Fipag distribution network.

The quality of the abstracted groundwater from the open wells within Salela is tested with in-situ water quality measurements to criticise the drinking water quality of these wells. The measurements do not show significant deviations of the tested parameters that could be directly harmful to consumption. However, some wells do show the presence of coliform bacteria, algae growth and high salinity values. The first two are most likely to occur in open wells due to the fact that open wells are more vulnerable to pollution by faecal matter of animals or pollution from other sources.

To get more insigh into the water quantity of the Salela area and the phenomena of salt intrusion, a geohydrological study is performed as well, by implementing a geohydrological model. In this model, not only the area Salela is included, but also the areas Barra, Tofo and the Fipag extraction points are included in the model. The reason for the inclusion of these areas is the high amount of extraction in these areas.

The abstraction amounts in Salela are relatively low compared to common pumping rates, and therefore do merely influence the heads in that area. On the other hand, the abstraction amounts of Fipag are that high, that they do influence the heads in the Salela area. In the future this will become even a larger problem since the abstraction rate of the Fipag pumps will increase.

Lastly, Tofo and Barra are two areas that have to deal with a lot of extraction for tourism reasons. The tourism sector is growing in these areas and hence the abstraction rate will increase in the future. Whereas Tofo already has to deal with salt intrusion, Barra will phase this problem in the near future (as the geohydrological model output is showing).

8 Recommendations

To manage the water quality and quantity in the peninsula of Cidade de Inhambane it is required to gain more knowledge of water abstraction. Firstly, boreholes are not always registered and the exact abstraction of water can now only be estimated. ARA-Sul is aware of this problem. All civilians and companies should register their boreholes and pay for the amount of water which is abstracted. Groundwater is now seen as inexhaustive and a freehold, while the opposite is true. If the water quality deteriorates, water scarcity occurs without proper treatment. Lodges in Barra and Tofo are not aware of any of these consequences and have never been educated. An educational campaign on the effects of over-abstraction will raise awareness and emphasizes the importance of a sustainable society.

Secondly, the water provided by the FIPAG distribution network in Tofo is not of good quality. Lack of financial capacity was given as a reason for the missing treatment step at FIPAG Tofo. As the water quality in Tofo is not good enough this results in the action that people individually draw their own plans. With better water quality from FIPAG's distribution network also more control of the water quantities could be created.

It has to be said that the above strategy might lead to a robust and sustainable system, but one of the most important aspects of this project is the education of people. Keeping in mind the greater IWAMAMBA-project will take place in the coming years, a local collaboration with the ESUDER University of Vilanculos was made. During two case-days, an introduction of the research was given to 12 students from the department of Rural Engineering. These students performed water quality measurements, geo-hydrological calculations and got to share some interesting ideas on the problems existing on the Inhambane Peninsula. In Appendix 6 the assignment can be found together with the participant details. As the participants were all in the finishing stage of their undergraduate degree, they are hopefully inspired to continue their research on this topic in their coming career.

Bibliography

[1] AccuWeather. *AccuWeather*. 2019. URL: https://www.accuweather.com/en/mz/inhambane/243650/november-weather.

[2] D.W. Ayers R.S. & Westcot. *Water quality for agriculture*. Vol. 29. Food and Agriculture Organization of the United Nations, 1985. URL: http://www.fao.org/docrep/003/T0234E/T0234E01.htm.

[3] M. Bakker. "Principles of Geohydrology: Week 1 Basics". In: (2018).

[4] M. Bakker. "Principles of Geohydrology: Week 2 Steady Wells". In: (2018).

[5] M. Bakker. "Principles of Geohydrology: Week 6 Salt intrusion". In: (2018).

[6] B.M. van Breukelen. "Fundamentals of Water Treatment: Module 1 Water Quality". In: (2017).

[7] Samuel Brudefors and Sofia Kac. "The Relevance of the Sodium Hypochlorite Solution Certeza as a Domestic Water Disinfecatant in Maputo." In: (2014).

[8] World Travel & Tourism Council. "Economic Impact 2018 Mozambique". In: (2018).

[9] YP Dang et al. "High subsoil chloride concentrations reduce soil water extraction and crop yield on Vertosols in north-eastern Australia". In: *Australian Journal of Agricultural Research* 59.4 (2008), pp. 321–330.

[10] EPA. *pH*. 2018. URL: https://www.epa.gov/caddis-vol2/caddis-volume-2-sources-stressors-responses-ph#low.

[11] Instituto Nacional de Estatística. *Estatisticas e Indicadores Sociais*. 2014.

[12] Instituto Nacional de Estatística. *Statísticas do Distrito de Cidade De Inhambane*. 2013.

[13] Lynda Knobeloch et al. "Blue babies and nitrate-contaminated well water." In: *Environmental health perspectives* 108.7 (2000), p. 675.

[14] Lenntech. *Water Conductivity*. 2019. URL: https://www.lenntech.com/applications/ultrapure/conductivity/water-conductivity.htm.

[15] M. Martins Jiji. *Personal Interview*. 2018.

[16] A. Mehta. *Overview of SRTM and ASTER DEM Data*. National Aeronautics and Space Administration, 2017.

[17] Inc. Metcalf & Eddy. *Wastewater engineering : treatment, disposal, and reuse*. McGraw-Hill, 1991.

[18] B. Oram. *Associao de Limpeza e Meio Ambiente*. 2018. URL: http://www.almatofo.org.

[19] B. Oram. *Phosphate in Surface Water Streams Lakes*. 2014. URL: https://www.water-research.net/index.php/phosphate-in-water.

[20] World Health Organization. "Hardness in Drinking-water". In: (2011).

[21] World Health Organization. "Iron in Drinking-water". In: (2003).

[22] World Health Organization. "Nitrate and Nitrite in Drinking-water". In: (2011).

[23] World Health Organization. "Total dissolved solids in Drinking-water". In: (2011).

[24] J. Pedro. 2018.

[25] M. C. Peel, B. L. Finlayson, and T. A. McMahon. "Updated world map of the Köpen-Geiger climate classification". In: *Hydrology and Earth System Sciences* 11.5 (2007), pp. 1633–1644. DOI: 10.5194/hess-11-1633-2007. URL: https://www.hydrol-earth-syst-sci.net/11/1633/2007/.

[26] JD Rhoades and Fernando Chanduvi. *Soil salinity assessment: Methods and interpretation of electrical conductivity measurements*. Vol. 57. Food & Agriculture Org., 1999.

[27] Enrique Sánchez et al. "Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution". In: *Ecological indicators* 7.2 (2007), pp. 315–328.

[28] National Ocean Service. *How frequent are tides?* 2019. URL: https://oceanservice.noaa.gov/facts/tidefrequency.html.

[29] *Tides and Solunar Charts Inhambane*. 2019. URL: https://tides4fishing.com/af/mozambique/inhambane#_tides.

[30] L. Tomas. *How to Convert Tds to Conductivity*. 2018. URL: https://sciencing.com/convert-tds-conductivity-7381015.html.

[31] *Water Quality*. 2019. URL: https://www.fondriest.com/environmental-measurements/parameters/water-quality/.

[32] National Water and Quality Management. *Australian Drinking Water Guidelines 6*. August. 2018. ISBN: 1864965118.

Appendix

1. Area Inventory

(a) 23°53’37"S 35°24’0"E

(b) 23°52’37"S 35°24’8"E

(c) 23°52’03"S 35°33’18"E

(d) 23°52’50"S 35°25’38"E

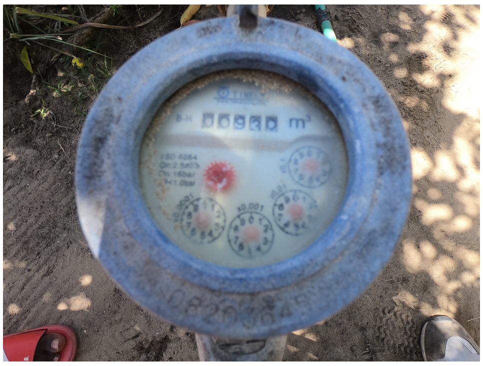
Figure 3: Inhambane and Tofo City


(a) 23°53'11"S 35°28'1"E (b) 23°53'14"S 35°28'5"E


(c) 23°53'5"S 35°24'40"E (d) 23°52'46"S 35°25'40"E

Figure 4: Inhambane Suburbs – Community Wells


(a) 23°55'20"S 35°24'4"E (b) 23°55'21"S 35°24'4"E

(c) 23°55'17"S 35°24'0"E (d) 23°55'17"S 35°24'0"E

Figure 5: Inhambane Suburbs – FIPAG

2. Well & Borehole Inventory

Fonta ID	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Latitude		-23,886201			-23,886647			-23,88743	
Longitude		35,467334			35,467257			35,468339	
Height GIS-SRTM		10			11			19	
Height GIS-ASTGTM		9			8			20	
Height GE		10			11			19	
Shape well		Round			Round			Round	
Construction material		Concrete			Concrete			Concrete	
Inner Diameter [m]		0,55			0,55			0,61	
Bottom level to top level [m]		2,96			4,55			9,57	
Top level to ground level [m]		0,71			0,95			0,77	
Surrounding		Domestic area near road			Domestic area near road			Domestic area on small hill	
Date	27/11/2018	04/12/2018	11/12/2018	27/11/2018	04/12/2018	11/12/2018	27/11/2018	04/12/2018	11/12/2018
Weather	Hot, dry, sunny	Hot, dry, cloudy	Chill, cloudy, lot of rain	Hot, dry, sunny	Hot, dry, cloudy	Chill, cloudy, lot of rain	Hot, dry, sunny	Hot, dry, cloudy	Chill, cloudy, lot of rain
Water level to top level [m]	2,25	2,26	1,95	4,15	4,16	4,15	8,79	8,83	8,45
EC [uS/cm]	489	466	491	412	400	391	663	655	682
Temperature [dC]	28	27,2	26,6	27,8	27,3	27,4	27,8	27,1	26,8
pH	6,77	6,73	7,08	7,06	6,95	7,42	7,1	7,1	7,28
Dissolved Oxygen [mg/L]	3,3	3,6	4,4	4,8	4,7	6,3	6,8	6,2	6,4
Total Nitrogen [mg/L]	10,15	5,2	9	9,65	14,5	9	47,725	45	20,5
Nitrate Nitrogen [mg/L]	2	1	1,8	1,9	2,9	1,8	9,5	9	4,1
Nitrite Nitrogen [mg/L]	0,03	0,05	0	0,03	0	0	0,05	0	0
Total Ammonium [mg/L]	0	0	0	0	0	0	0	0	0
Total Phosphate [mg/L]	6,5	6,5	1,8	6,5	1,8	0,6	9,3	2,4	1,8
Total Iron [mg/L]	0,19	0,57	0,21	0,01	0,09	0,00	0,06	0,06	0,08
Total Chlorine [mg/L]	2,2	2	-	2	2,4	-	3	3,6	-
Free Chlorine [mg/L]	0,20	0,25	-	0,3	0,2	-	0,25	0,25	-
Total Hardness [ppm CaCO3]	-	-	337,5	-	-	250	-	-	250
Coliform Bacteria [MPN]	12	8	18	4	2	9	22	10	25
Water Colour	Yellowish, Turbidity	Little Yellowish, Turbidity	Clear	Clear	Clear	Clear	Clear	Clear	Clear

Figure 6: Community Wells F1-F3

Fonta ID	4.1	4.2	4.3	5.1	5.2	5.3	6.1	6.2	6.3
Latitude		-23,885653			-23,885957			-23,886883	
Longitude		35,474544			35,4618			35,462804	
Height GIS-SRTM		6			12			13	
Height GIS-ASTGTM		21			3			10	
Height GE		9			11			13	
Shape well		Round			Round			Round	
Construction material		Concrete			Concrete			Concrete	
Inner Diameter [m]		1,4			0,70			0,55	
Bottom level to top level [m]		1,45			3,00			7,66	
Top level to ground level [m]		0,42			0,66			0,69	
Surrounding		Argicultural area near sea			Domestic area near road			Domestic area near road	
Date	27/11/2018	04/12/2018	13/12/2018	28/11/2018	05/12/2018	12/12/2018	28/11/2018	05/12/2018	12/12/2018
Weather	Hot, dry, sunny	Hot, dry, little sunny	Hot, dry, sunny	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry, sunny	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry,sunny
Water level to top level [m]	0,63	0,69	0,6	2,58	2,55	2,48	6,92	6,96	6,9
EC [uS/cm]	315	302	389	457	455	473	1162	1167	1121
Temperature [dC]	32	27,3	32,7	27,2	27	26,8	27,5	26.8	26,8
pH	6,6	6,59	6,72	6,62	6,78	6,78	6,69	6.7	6,81
Dissolved Oxygen [mg/L]	6,7	8	7,7	3	3,5	3,7	3,9	3.2	3,3
Total Nitrogen [mg/L]	14,575	7,7	30	30,1	19	22,075	13,08	10	13
Nitrate Nitrogen [mg/L]	2,9	1,5	6	6	3,8	4,4	2,6	2	2,6
Nitrite Nitrogen [mg/L]	0,01	0,03	0	0,03	0	0,01	0,01	0	0
Total Ammonium [mg/L]	0	0	0	0	0	0	0	0	0
Total Phosphate [mg/L]	17,5	6,5	2,1	8,6	1,5	5,1	5,8	0	6,5
Total Iron [mg/L]	0,18	0,45	0,51	0,01	0,08	0,03	0,15	0.08	0,25
Total Chlorine [mg/L]	3,00	10	-	2	2	-	1,5	-	-
Free Chlorine [mg/L]	0,25	0,25	-	0,05	0,3	-	0,25	-	-
Total Hardness [ppm CaCO3]	-	-	185	-	-	250	-	250	250
Coliform Bacteria [MPN]	-	6	-	14	19	-	6/12	10	-
Water Colour	Dirty, Brownish, Turbidity	Clear to Little Turbidity	Turbid	Clear	Clear	Clear	Clear	clear	Clear

Figure 7: Community Wells F4-F6

Fonta ID	7.1	7.2	7.3	8.1	8.2	8.3	9.1	9.2	9.3
Latitude		-23,887548			-23,885959			-23,891364	
Longitude		35,462792			35,457984			35,455138	
Height GIS-SRTM		13			4			10	
Height GIS-ASTGTM		11			3			11	
Height GE		14			7			8	
Shape well		Rectangular			Rectangular			Round	
Construction material		Concrete			None			Concrete	
Inner Diameter [m]		1,06			1,00			0,60	
Bottom level to top level [m]		1,98			0,92			0,73	
Top level to ground level [m]		0,3			0			0,03	
Surrounding		Argicultural area			Argicultural area			Argicultural area near river	
Date	28/11/2018	05/12/2018	12/12/2018	28/11/2018	05/12/2018	12/12/2018	29/11/2018	06/11/2018	13/12/2018
Weather	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry, sunny	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry, sunny	Hot, dry, sunny
Water level to top level [m]	1,84	1,85	1,77	0,33	0,3	0,25	0,03	0,00	0
EC [uS/cm]	359	317	455	270	257	920	278	272	265
Temperature [dC]	26,9	26,7	25,5	30,3	28,1	29	26,2	28,1	27,9
pH	6,35	6,12	6,39	6,06	6,24	6,21	5,43	5,24	5,13
Dissolved Oxygen [mg/L]	3,8	3,3	5,1	4,2	4,2	5,3	2,8	1,9	2
Total Nitrogen [mg/L]	6,6	7,65	8,5	5,575	5,65	13	6,1	6,5	9,5
Nitrate Nitrogen [mg/L]	1,3	1,5	1,7	1,1	1,1	2,6	1,2	1,3	1,9
Nitrite Nitrogen [mg/L]	0,01	0,03	0	0,01	0,03	0	0,01	0	0
Total Ammonium [mg/L]	0	0	0	0	0	0	0	0	0
Total Phosphate [mg/L]	2,7	1,8	8,6	7,2	1,8	2,7	2,1	3	2,1
Total Iron [mg/L]	1	2,3	1,4	0,48	0,48	0,6	0,72	0,64	0,6
Total Chlorine [mg/L]	1,04	-	-	3,4	-	-	2	-	-
Free Chlorine [mg/L]	0,25	-	-	0,25	-	-	0,2	-	-
Total Hardness [ppm CaCO3]	-	-	185	-	85	250	-	50	50
Coliform Bacteria [MPN]	9	7	-	26	35	-	4	19	-
Water Colour	Clear	clear	Clear	Yellowish and Turbidity	Clear	Yellowish, Ducks in the water	Clear	Clear	Algae, turbity

Figure 8: Community Wells F7-F9

Fonta ID	10.1	10.2	10.3	11.1	11.2	11.3	12.1	12.2	12.3
Latitude		-23,888268			-23,887205			-23,889139	
Longitude		35,453231			35,457452			35,457932	
Height GIS-SRTM		8			10			14	
Height GIS-ASTGTM		9			8			21	
Height GE		7			9			12	
Shape well		Round			Round			Round	
Construction material		Concrete			Concrete			Concrete	
Inner Diameter [m]		0,59			0,55			0,60	
Bottom level to top level [m]		1,08			2,96			3,96	
Top level to ground level [m]		0,15			0,92			0,48	
Surrounding		Argicultural area near river			Domestic area near road			Domestic area on small hill	
Date	29/11/2018	06/11/2018	13/12/2018	29/11/2018	06/11/2018	13/12/2018	29/11/2018	06/11/2018	13/12/2018
Weather	Chill, cloudy, rain	Hot, dry, sunny	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry, sunny	Hot, dry, sunny	Chill, cloudy, rain	Hot, dry, sunny	Hot, dry, sunny
Water level to top level [m]	0,68	0,80	0,81	2,74	2,76	2,6	3,17	3,21	3,08
EC [uS/cm]	157,6	153	152	248	233	298	203	201	230
Temperature [dC]	24,4	28,1	26,2	24,3	27,7	28,7	25,2	27,5	28,9
pH	5,77	5,8	5,59	6,6	6,22	6,63	6,36	6,36	6,64
Dissolved Oxygen [mg/L]	2,67	1,9		4,3	3,3	4,8	5,7	4,4	5,1
Total Nitrogen [mg/L]	1,5	6	11,5	0,5	11,5	11,5	2	7	9
Nitrate Nitrogen [mg/L]	0,3	1,2	2,3	0,1	2,3	2,3	0,4	1,4	1,8
Nitrite Nitrogen [mg/L]	0	0	0	0	0	0	0	0	0
Total Ammonium [mg/L]	0	0	0	0	0	0	0	0	0
Total Phosphate [mg/L]	0,9	5,8	1,5	0,3	4,4	1,2	2,1	6,5	14,5
Total Iron [mg/L]	0,15	0,42	0,25	0,1	0,17	0,1	0,15	0,06	0,15
Total Chlorine [mg/L]	7,6	-	-	6,4	-	-	2,8	-	-
Free Chlorine [mg/L]	0,25	-	-	0,25	-	-	0,25	-	-
Total Hardness [ppm CaCO3]	-	85	50	-	85	120	-	85	120
Coliform Bacteria [MPN]	9	43	-	6	61	-	10	28	-
Water Colour	Whiteish and low Turbidity	Whiteish and low Turbidity	Whiteish and low turbity	Clear	Clear	Clear	Clear	Clear	Clear

Figure 9: Community Wells F10-F12

(a) 23°53’10.3"S 35°28’02.4"E

(b) 23°53’08.4"S 35°28’28.4"E

(c) 23°53’12.8"S 35°27’46.1"E

(d) 23°53’09.1"S 35°27’48.5"E

Figure 10: Salela - Community Wells

(a) Extraction

(b) Aeration

(c) Storage

(d) Storage

Figure 11: Tofo FIPAG | 23°51’11"S 35°31’42"E

(a) Aeration

(b) Filtration

(c) Extraction

(d) Extraction

(e) Extraction

(f) Sedimentation

(g) Chlorine Disinfection

(h) Storage

Figure 12: Guiúa FIPAG | 23°58'29"S 35°24'04"E

3. Social Aspects and Habits

Interview with Hílaria Neves, 11th of December 2018

Hílaria Neves is a local inhabitant of Salela and she frequently uses the water of well 3. She lives next to this well and she was so kind to answer some questions during our field work. The translation was carried out by Manuel Martins Jiji.

How much water do you collect on a daily basis?
About 5 buckets of each 20 litres. This is for 3 persons.

For what kind of purposes do you use this water?
We use the water for drinking and all other things around at the house.

Who else is using this well?
Two other houses. One other house with 6 people. They get about 6 buckets daily. The second house are 2 people and they get about 2 buckets daily.

Where do you leave your domestic solid waste?
She points towards a hole located at 10 metres distance from the well
All our solid waste we put at this side.

Do you have a latrine?
Yes. It is located at 20 metres distance of the well.

How do you experience the water from your well?
I am very happy. It is clean and I always have water.

And do you always have good quality?
Sometimes microbes are in the water. Then I am using certeza to clean the water.

Where do you add certeza?
It is added in the water reservoir. But I only add it if I have enough money to buy it. I can buy it at the hospital, which is located just at the other side of the hill.

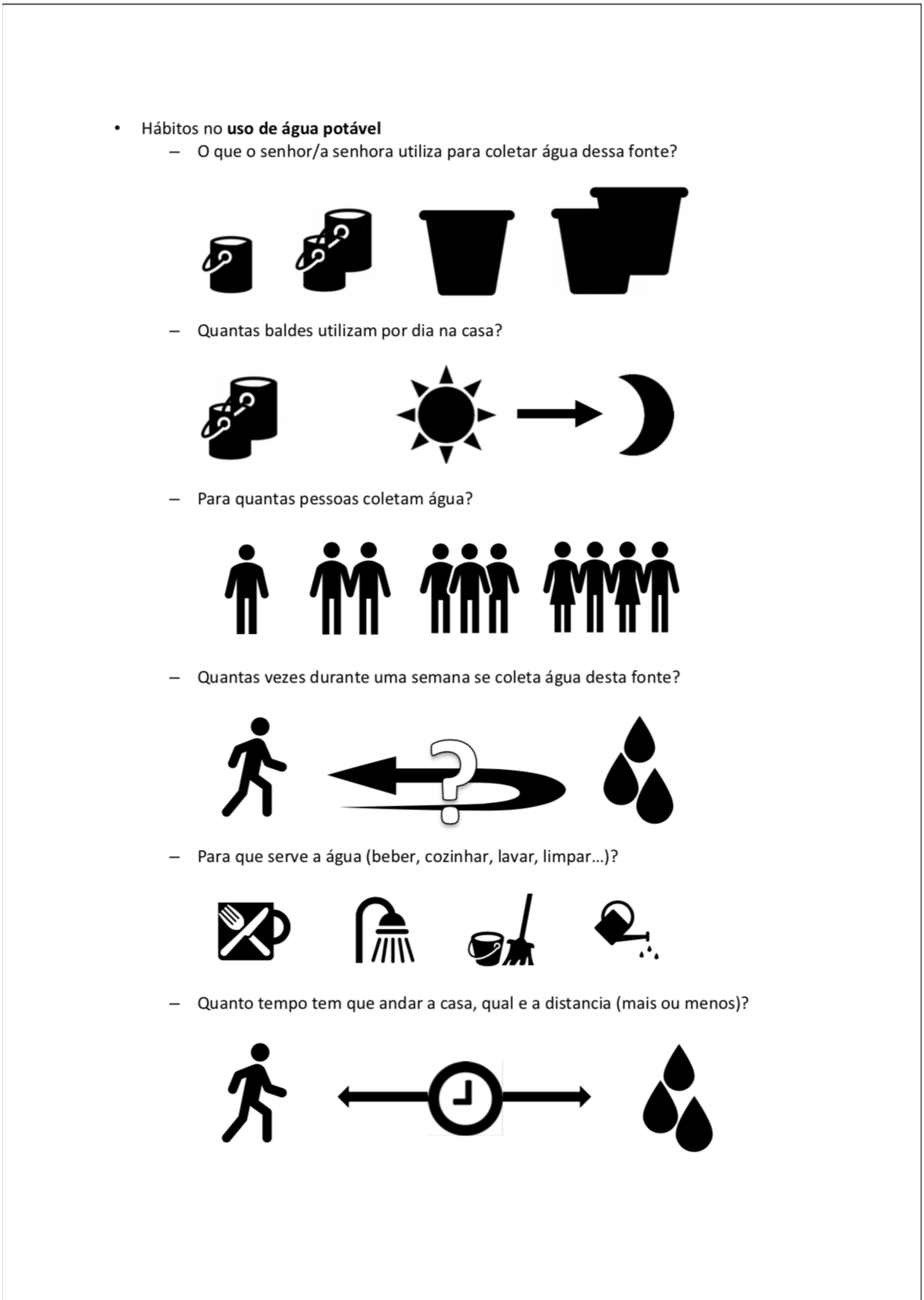
When was the well placed here?
About 6 or 7 years ago. The people adviced to place it at this location.

Would you like to have a FIPAG connection?
I do not know FIPAG very well. FIPAG would cost money and I prefer to have water for free. My water is good.

Could you describe a day and when you are using the water?
I bath in the morning and I wash the clothes in the morning. During the day I work on the field or I rest. The other family also uses most of the water in the morning. I use some water for cooking in the afternoon and evening.

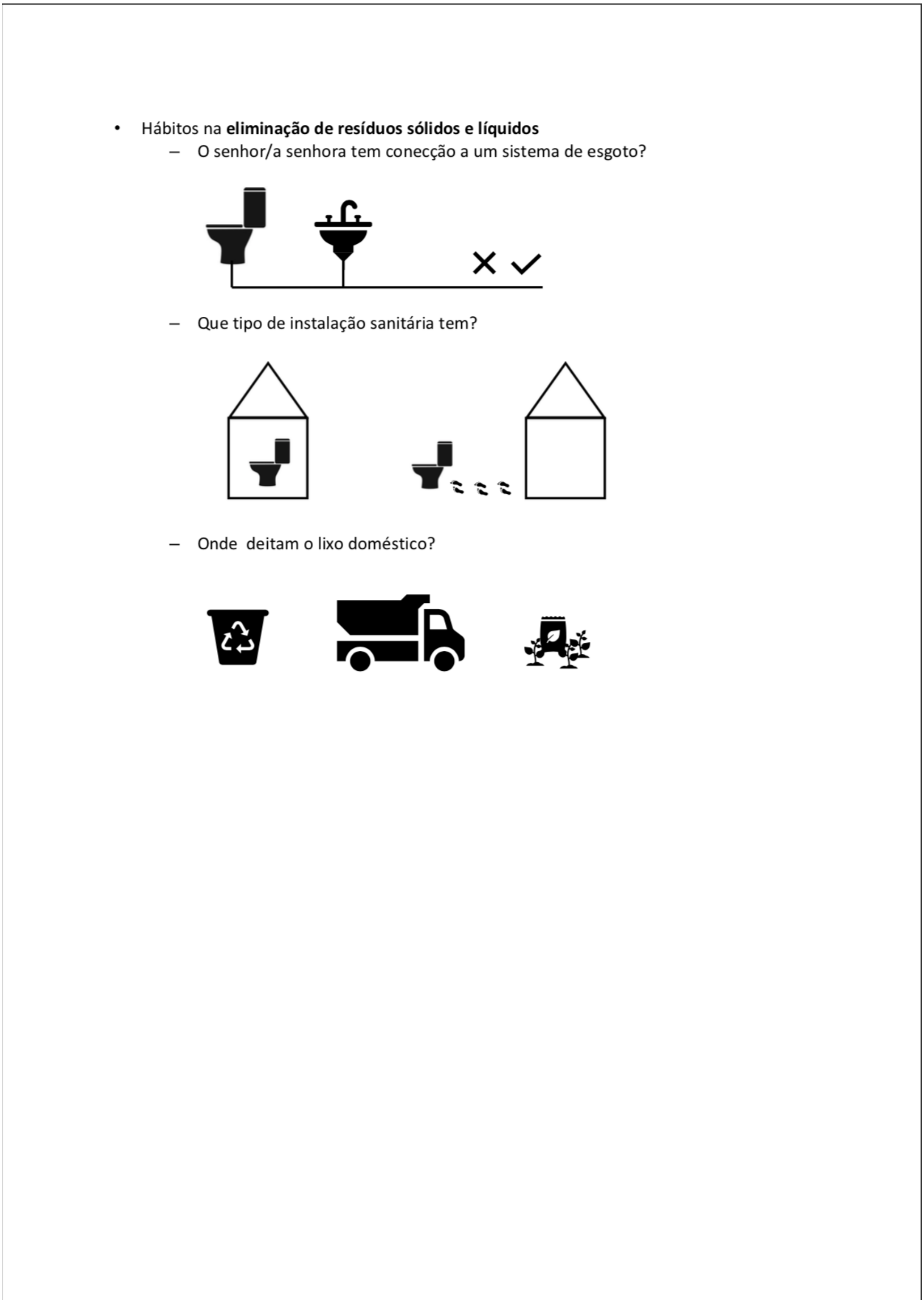
Do you clean the well?
Someone comes to clean the well sometimes. This is 1-2 per year and it costs about 600 meticais.

Figure 13: A photo of Hílaria and her well



- Hábitos no **uso de água potável**
  - O que o senhor/a senhora utiliza para coletar água dessa fonte?
  - Quantas baldes utilizam por dia na casa?
  - Para quantas pessoas coletam água?
  - Quantas vezes durante uma semana se coleta água desta fonte?
  - Para que serve a água (beber, cozinhar, lavar, limpar…)?
  - Quanto tempo tem que andar a casa, qual e a distancia (mais ou menos)?

Figure 14: Survey



- Hábitos na **eliminação de resíduos sólidos e líquidos**
  - O senhor/a senhora tem conecção a um sistema de esgoto?
  - Que tipo de instalação sanitária tem?
  - Onde deitam o lixo doméstico?

Figure 15: Survey

4. Water Quality

Measurement Protocol

Conditions

Measurements and interviews are carried out on 12 different wells in the research area, concerning the nearby stakeholders. These measurements will take place during three consecutive weeks, where each well is measured once a week. This will be done on the same time of the day for every individual well, so that the temperature and other conditions will be approximately the same at the moment of measurement of the individual well. As a result, all wells will be measured three times during three consecutive weeks. For every well, all measurements will be carried out in the same way, following the protocol. Water will be extracted from a well with a bucket of 5L, thus for every measurement of each well the same amount of water is used.

AKVO

For the following parameters the AKVO-application is used: nitrate-nitrite, ammonium, phosphate, total iron, and total hardness. When installed on mobile device, the camera measures color intensity and thereby determines the concentration. Furthermore, the application is used to register the coordinates of each location that is measured or registered as point source pollution.

Protocol

For every measurement a repetition of consecutive actions is carried out to achieve a reliable outcome.

1. Brief Interview
2. Geographical location
3. Photo
4. Location description
5. Water level measurement
6. Electrical conductivity measurement
7. pH measurement
8. Dissolved oxygen measurement
9. Nitrate measurement
10. Ammonium measurement
11. Phosphate measurement
12. Total iron measurement
13. Total Hardness measurement
14. Bacteria measurement

1. Brief Interview

Before any measurement are carried out, interviews with the users of the wells are performed to estimate the different functions of the well. Background information of water usage, water functions and other water related issues are briefly discussed with an available well owner or user. Moreover, an insight in the waste disposal is gained by questions on the habits of people. Permission to carry out measurements and interviews is asked to concerning stakeholders. The following questions are asked during a brief interview about habits on water collection.

1. What are you using to collect water from this source?
2. How many buckets do you use per day/per week in the house?
3. For how many people is this water collection?

4. How many times during a week are you collecting water from this source?
5. What is the water being used for?
6. How much time do you have to walk?

Additionally, insight on waste disposal habits is gained by the following questions:

7. Are you connected to a sewage system?
8. What kind of human waste facility do you have?
9. Where do you leave your domestic waste?

2. Geographical location
The geographical location is given in coordinates by GPS on the telephone. For every well or pollution point, a name is given with the corresponding coordinates. With these coordinates, all points can be visualized on maps with their exact location.

3. Photo
Of each location of the well a photo is taken to inventorise the characteristics of each well location and its surroundings. From these characteristics, the interaction of the surroundings with the well can be estimated. Furthermore, the colour of the water will also be photographed. This will be done with a white background colour, thus the water colour can be seen more clearly. Of all indication strips a photo is taken. All photos that are taken will be saved in the AKVO application corresponding to each individual location according to their coordinates.

4. Location description
For every well its location is of great importance. All details of the location and its surroundings will be collected. Weather conditions and specific local conditions are also inventoried. Furthermore, the coordinates of the location are saved so a map can be constructed in GIS. Other relevant information about the well location are of course also taken into account. General details of each well that are inventoried include:
1. Shape of surface area
2. Dimensions surface area
3. Construction material
4. Age
5. Surroundings
6. Weather conditions

5. Water level measurement
The level of the water is measured with a diver. The height from the water level to the top of the well is measured. The height of the top of well to the ground level is subtracted of this value and gives the depth of the water relative to the ground level. The volume of water is registered by calculating the water depth with the surface area of the well, assuming a constant width of the well.
1. Bottom level well relative to top level well
2. Water level relative to top level well
3. Height of well top relative to ground level

6. Electrical conductivity measurement
The electrical conductivity is measured with a Greisinger Conductivity meter (GMH 3431). Before measuring, the reference temperature is set to 25 degrees Celcius. The EC meter is calibrated daily, before measurements take place.
a. The probe is placed in a KCL solution. The reference value of this solution is 14.13 μS cm^{-1} and any deviations are registered.
b. Hold the probe in medium for several seconds until a steady-state value is reached.
c. Note down temperature and conductivity value. Reference solution is kept in a closed off package to avoid evaporation and condensation, so the reference value of 14.13 μS cm^{-1} is maintained.

7. pH measurement
The pH of the water will be measured with a Greisinger pH meter (G 1500). The electrode is stored in a 3 mol L^{-1} solution. Before measuring, the pH meter needs to be calibrated at the beginning of each measuring day. The calibration is a two-point calibration, one with pH 4 and another with pH 7.
a. Hold Function key for 4 seconds to open the calibration menu and release the function key.
b. Place the electrode in the pH 7 solution. Wait until calibration complete.
c. Enter the water temperature, which was registered with EC-meter.
d. Rinse the electrode with distilled water.
e. Place the electrode in pH 4 solution, the device automatically determines the correct value. Wait until calibration complete.
f. Rinse the electrode again with distilled water.
g. Hold the electrode for several seconds in medium until steady state value is reached. Note down pH value.
For more accurate results, the pH meter is checked at least every 3 hours with solution pH 7.

8. Dissolved oxygen measurement
The dissolved oxygen in the water will be measured with the Greisinger DO-meter (G1610). The electrode is stored in a Potassium hydroxide solution.
a. Remove membrane from solution and dab dry from any droplets.
b. Hold Function key for 4 seconds to open the calibration menu.
c. Hold just above storage bottle, but not in contact with the solution.Release the function key and wait until calibration is finished.
d. Gently swipe the electrode through the medium for 3 minutes, so a steady-state value is measured and stagnant water is avoided. Note down concentration value.

9. Nitrate-Nitrite measurement
Nitrate-Nitrite concentrations are indicated by HACH test strips, within a range of 0-50 NO_3^- ppm a. Dip a strip into water for 1 second and remove. Do not shake excess water from the test strip.
b. Hold the strip level, with the pad side up, for 30 seconds. Compare the nitrite test pad to the nitrite color chart. Take photo.
c. At 60 seconds, compare the nitrate test pad to the color chart. Estimate results if the color on the test pas falls in between two color blocks. Take photo.
d. Check concentration with AKVO Caddisfly.

10. Ammonium measurement
A Macherey Nagel
Low ammonium concentrations of 0-6 mg NH_4^+ L^{-1} a. Dip a strip into water, moving back and forth for approximately 5 seconds. Do not shake excess water from the test strip.
b. Hold the strip level, with the pad side up, for 30 seconds. Compare the test field to the ammonium color chart. Take photo.
c. Optional. When high ammonium concentrations are detected, continue with ammonium test B Quantofix.
B Quantofix
for higher ammonium concentrations of 10-400 mg NH_4^+ L^-1
a. Rinse the measuring vessel with the test water and fill it to the 5 mL mark.
b. Add 10 drops of sodium hydroxide solution (NH_4^+-1) to the sample and shake carefully.
c. Dip the test strip into the test solution for 5 seconds and shake off excess liquid.
d. Compare with the color scale. Take photo.

11. Phosphate measurement
Phosphate concentrations are measured with Quantofix test strips within a 3-100 mg PO_4^{3-} L^{-1} range. a. Rinse the measuring vessel with the test solution and fill it to the 5 mL mark. b. Add 5 drops of nitric acid (PO_4^{3-}-1) to the sample and shake carefully. c. Place the measuring vessel on the benchtop and remove the test tube from the package. d. Add 6 drops of nitric acid (PO_4^{3-}-2) to the test tube. e. Insert

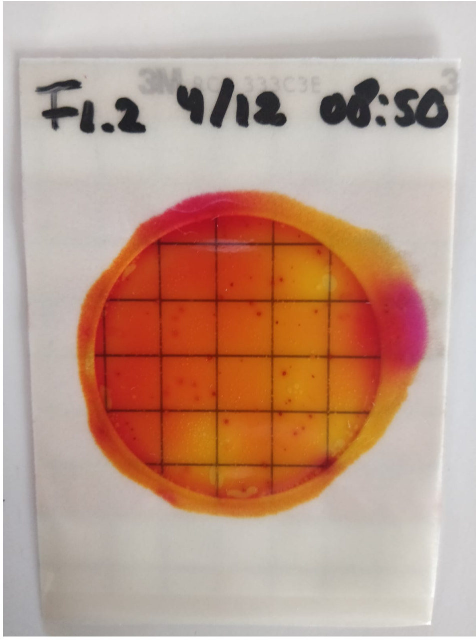
the test strip into the sample and wait 15 seconds. Shake off excess liquid. f. Place test strip into the filled test tube and wait 15 seconds. Shake off excess liquid. g. Wait 60 seconds and compare to color scale. Take photo. h. Check concentration with AKVO Caddisfly

12. Total iron measurement
Iron concentration are measured by Hach Test Strips within a 0-5 mg L^{-1} range. a. Fill sample vial half full with sample water. Open one foil packet of iron reducing powder (Sodium Hydrosulfite; Sodium Metabisulfite) and add the contents to vial. Cap vial and shake rapidly for 5 seconds. Remove cap.
b. Dip a test strip into sample vial and rapidly move back and forth underwater for 15 seconds. Remove and shake excess water from the test strip.
c. Immediately compare test pad to color chart and record results. Estimate results if color on test pad falls between two color blocks. Take photo.
d. Check concentration with AKVO Caddisfly

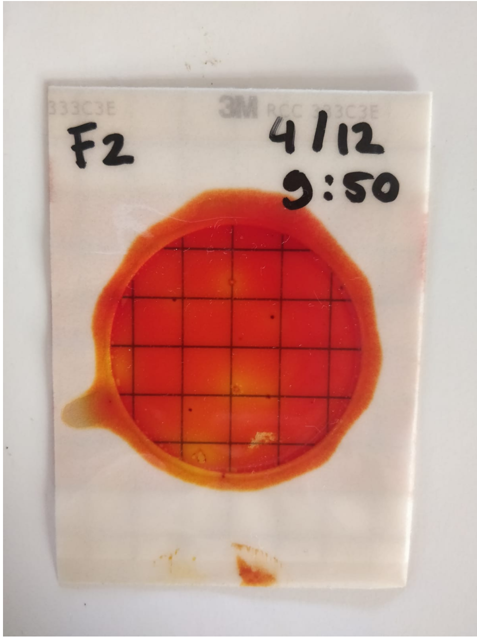
13. Total Hardness measurement
The total hardness, the sum of calcium and magnesium, is measured by Hach strip test within a range of 0-425 mg $CaCO_3$ L^{-1}.
a. Dip the strip into the water for one second and remove. Shake off excess water.
b. Hold the strip level, with the pas side up, for 15 seconds.
c. Compare the total hardness test pad to the color chart. Estimate results if the color on the test pad falls between two color blocks. Take photo.
d. Check concentration with AKVO Caddisfly.

14. Bacteria measurement
Coliform bacterial colonies are measured by 3TM Coliform counting plates.
a. Take 1 mL of water sample using a pipette with a pipette tip.
b. Slowly lift the top film of one count plate and carefully pipet the 1 mL of water sample in the centre of the plate. Slowly roll down the top film.
c. With the flat side down, place the spreader on the top film and carefully apply pressure to spread the water sample over the plate.
d. Water is mixed with the growth medium and will form a gel within one minute. The plate is kept at outdoor temperature (average of 30 °C) for 24 hours.
e. Gas bubbles of CO2 are formed by lactose fermentation, characteristic for coliform bacteria. Count colonies of bacteria associated with gas bubbles of 9 squares and average. Multiply this average by 20 will give the Most Probable Number (MPN) of coliforms per mL of water sample.
f. Take photo of formed coliforms on plate.

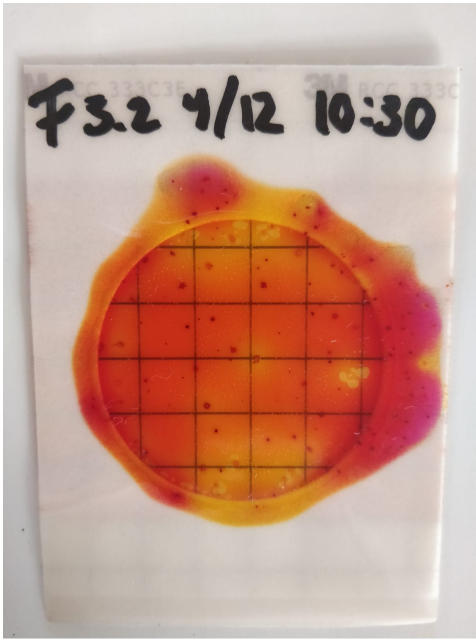
Results - Coliform Counting Plates



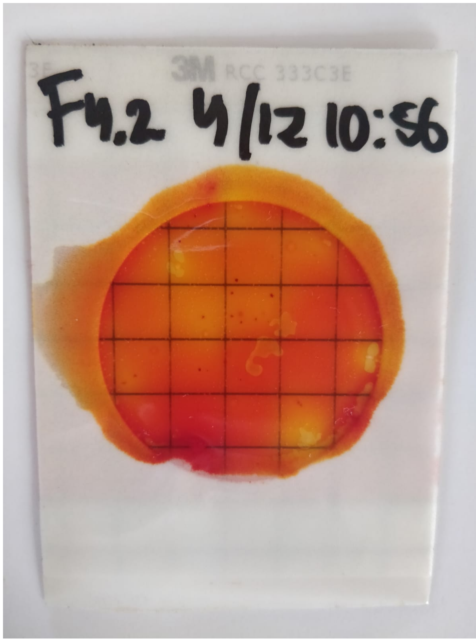
(a) F1: 4-12



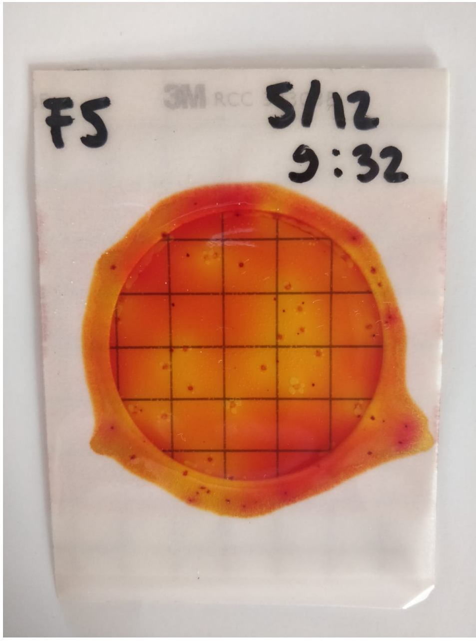
(b) F2: 4-12



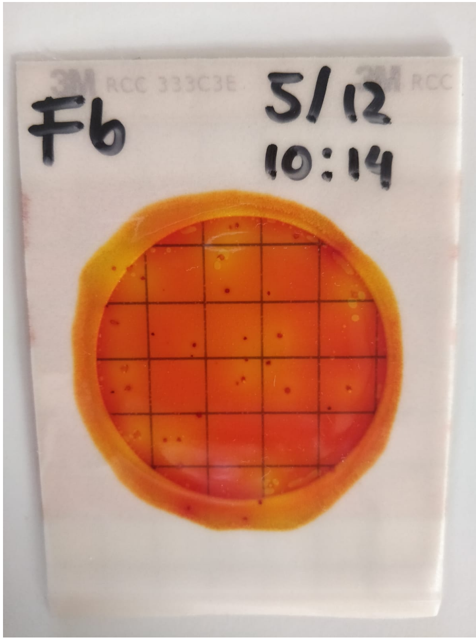
(c) F3: 4-12



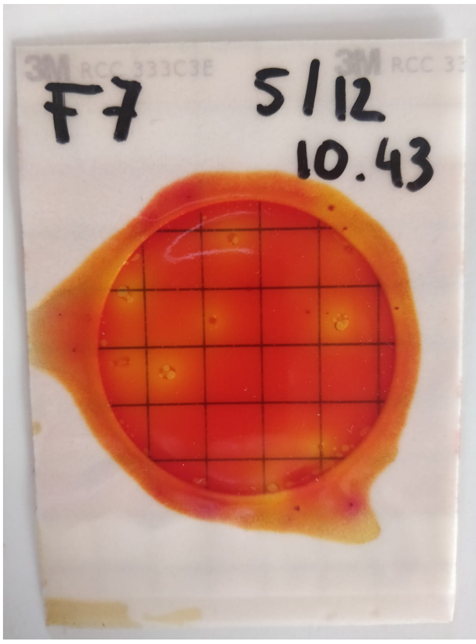
(d) F4: 4-12



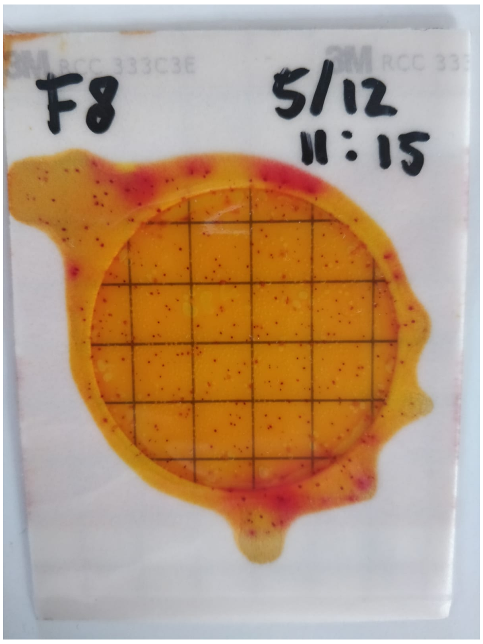
(a) F5: 5-12



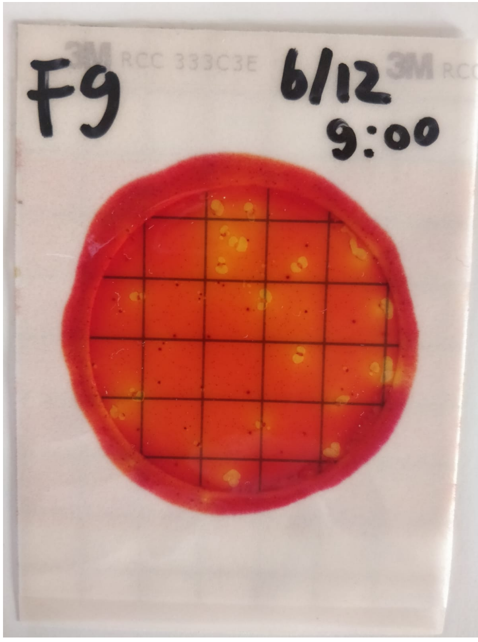
(b) F6: 5-12



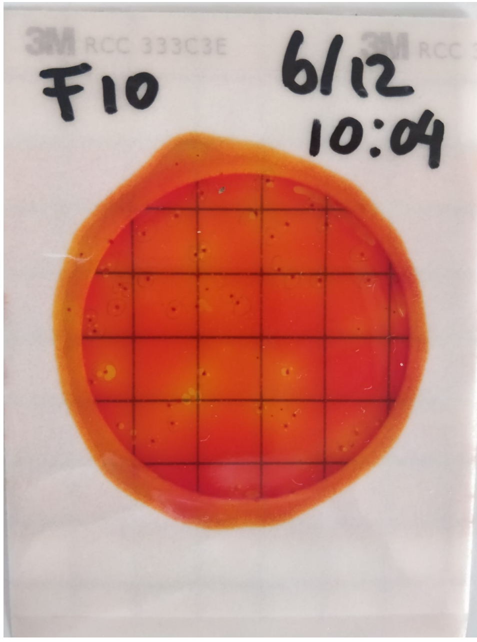
(c) F7: 5-12



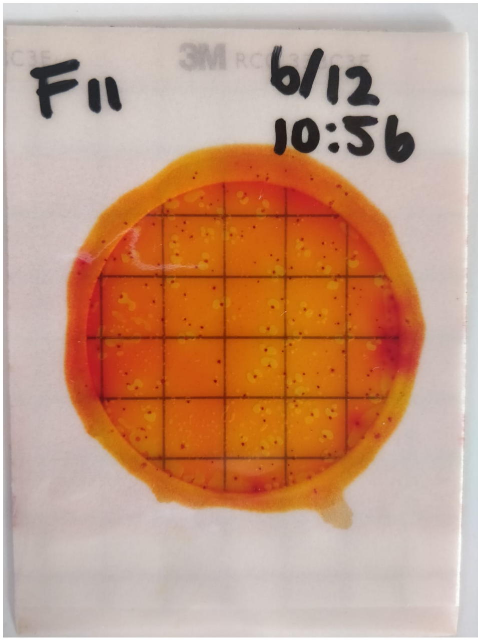
(d) F8: 5-12



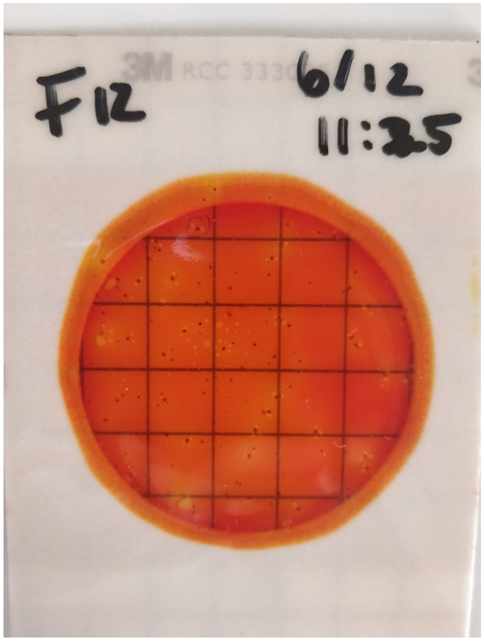
(a) F9: 6-12



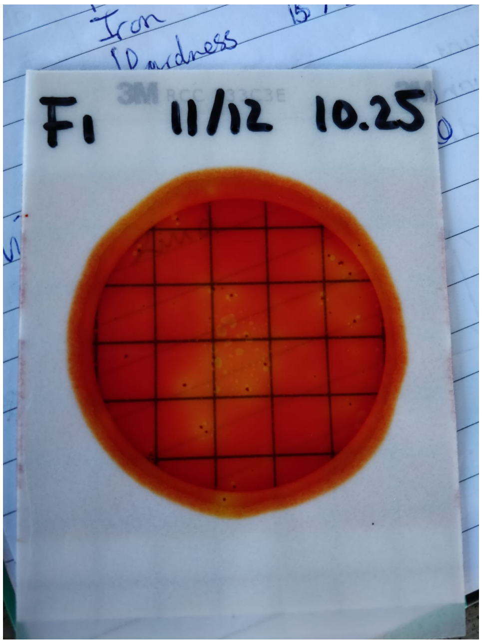
(b) F10: 6-12



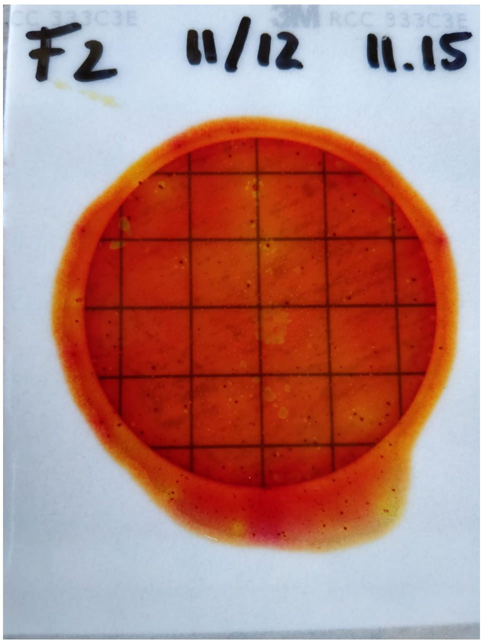
(c) F11: 6-12



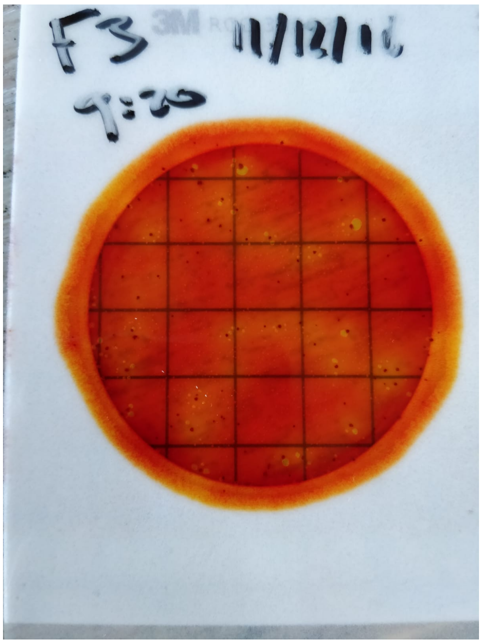
(d) F12: 6-12



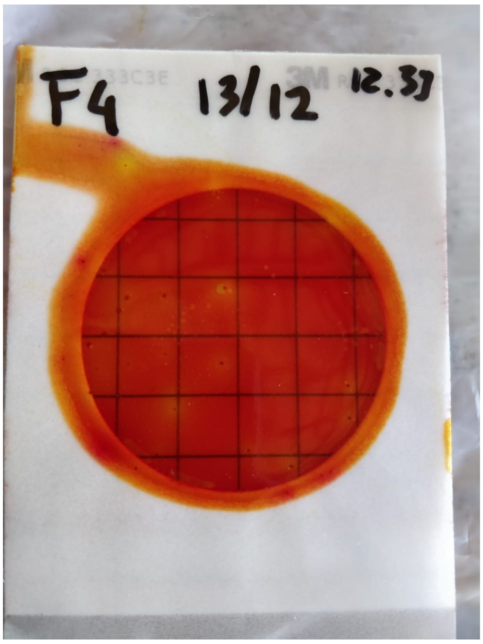
(a) F1: 11-12



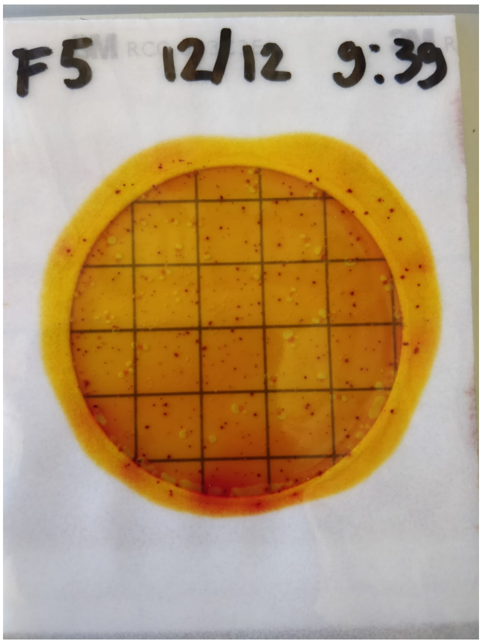
(b) F2: 11-12



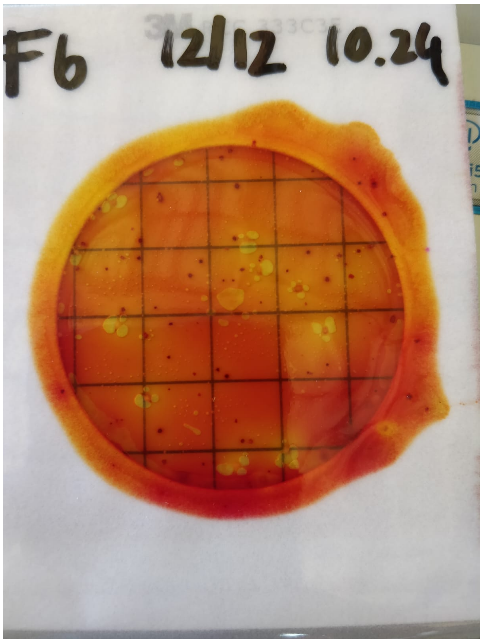
(c) F3: 11-12



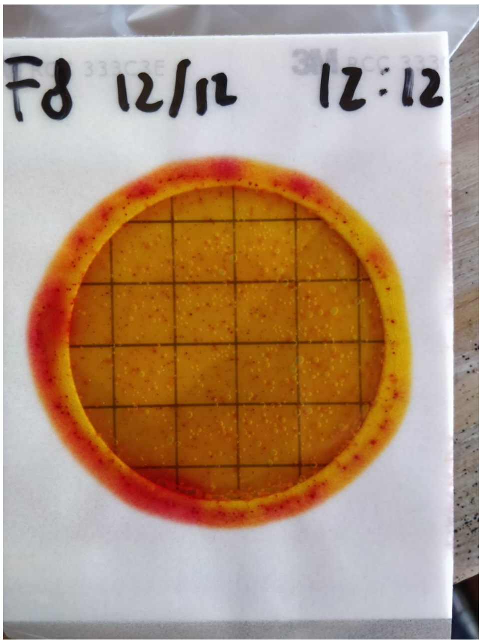
(d) F4: 11-12



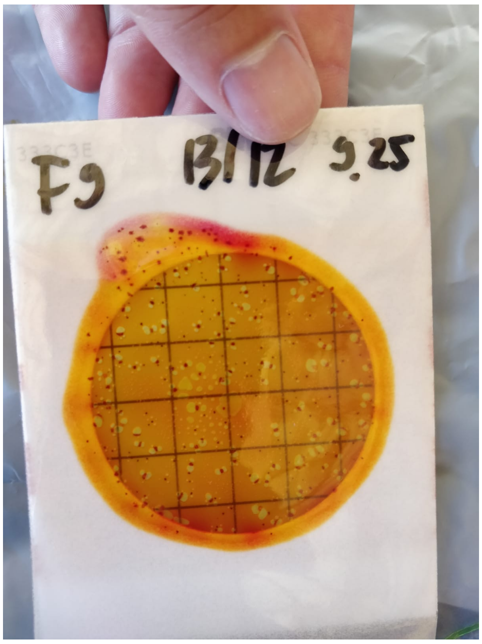
(a) F5: 12-12



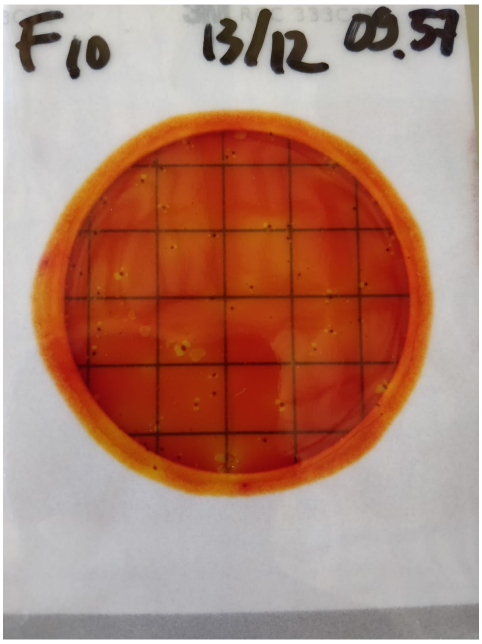
(b) F6: 12-12



(c) F8: 12-12



(a) F9: 13-12



(b) F10: 13-12

(c) F12: 13-12

Barra Measurements

Fonta ID	Bibo Sands	Sia Sente/Bay View	Barra Reef Divers	Casa do Mangal	Sunset Lodge (low)	Sunset Lodge (high)	Chill Bar
Latitude	-23,797816	-23,800073	-23,785769	-23,801370	-23,800073	-23,797935	-23,796360
Longitude	35,526864	35,518487	35,501361	35,515121	35,518487	35,519466	35,534471
Height GIS-SRTM							
Height GIS-ASTGTM							
Height GE							
Shape well	Round	Round	Round	Round	Round	Round	Round
Construction material	PVC	PVC	PVC	PVC	PVC	PVC	PVC
Inner Diameter [m]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Bottom level to top level [m]	35	45	4a5	17	68	48	12
Top level to ground level [m]	0	0	0	0	0	0	0
Surrounding	Lodge	Lodge	Company	Lodge	Lodge	Lodge	Lodge
Date	8-1-2019	8-1-2019	8-1-2019	8-1-2019	8-1-2019	8-1-2019	8-1-2019
Weather	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny
Water level to top level [m]	3	39	1a1.5	6?	18	6?	2
EC [uS/cm]	576	433	6850	284	264	433	614
Temperature [dC]	28.4	29	28.5	27.1	23.1	28.7	27.5
pH	7.79	7.87	7.35	7.84	7.16	8.23	7.99
Dissolved Oxygen [mg/L]	6.5	6.3	3.4	7.5	7.3	6.8	5.9
Nitrate Nitrogen [mg/L]	2.6	0.4	1.4	3.8	3.2	1.6	2.6
Nitrite Nitrogen [mg/L]	0	0	0	0	0	0	0
Total Ammonium [mg/L]	0	0	0	0	0	0	0
Total Phosphate [mg/L]	7.2	1.2	1.8	3.7	8.6	2.4	0.9
Total Iron [mg/L]	0	0.01	0.51	0	0.39	0.00	0.0
Total Chlorine [mg/L]	–	–	–	–	–	–	–
Free Chlorine [mg/L]	–	–	–	–	–	–	–
Total Hardness [ppm CaCO3]	–	250	425	–	120	–	–
Coliform Bacteria [MPN]							
Water Colour	clear	clear	clear	clear	clear	clear	Clear
Extraction period	24/12 to 07/01	1 day	1 day	1 day			
Usage amount	52 m3	25-30 m3	5 m3	7 m3			
Amount people	3*4	16*6	company	6*4	10*5+restaurant	4*5	15*5+restaurant
ARA-Sul (registration)	1500mts	–	–	–	–	–	–
/m3	0.60mts per m3	–	–	–	–	–	–
Personal usage	drinking irrigation household	drinking irrigation household	drinking pool household	drinking irrigation household	drinking irrigation household	drinking irrigation household	drinking irrigation household

Tofo Measurements

Fonta ID	Fipag storage	Agua Para Amigos (B. Treatment)	Agua Para Amigos (A. Treatment)	Well Tofo City	Surfshack (FIPAG)	Tofo Mar
Latitude	-23,8578625	-23,850531	-23,8505308	-23,8581964	-23,8581964	-23,853822
Longitude	35,5291850	35,4983423	35,4983423	35,5369182	35,544666	35,546032
Height GIS-SRTM						
Height GIS-ASTGTM						
Height GE						
Shape well		Round	Round	Round	Round	Round
Construction material		PVC	PVC	Concrete	PVC	PVC
Inner Diameter [m]		<0.1	<0.1	0.6	<0.1	<0.1
Bottom level to top level [m]		50	50	5,4		
Top level to ground level [m]	0	0	0	0,8	0	0
Surrounding	Company	Company	Company	Community	Lodge	Lodge
Date	9-1-2019	9-1-2019	9-1-2019	9-1-2019	9-1-2019	9-1-2019
Weather	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny	Hot, dry, sunny
Water level to top level [m]		3	3			
EC [uS/cm]	238	148	107,8	457	234	235
Temperature [dC]	31	30,5	30	29	30	29,6
pH	6,89	6,05	6,5	6,82	7,14	6,72
Dissolved Oxygen [mg/L]	6,2	5,8	7,2	2,5	7,6	7,3
Nitrate Nitrogen [mg/L]	1,6	1,5	1	2	1	0,8
Nitrite Nitrogen [mg/L]	0	0	0	0	0	0
Total Ammonium [mg/L]	0	0	0	0	0	0
Total Phosphate [mg/L]	5,1	3	5,8	2,1	1,8	5,8
Total Iron [mg/L]	2	0	0	0,22	0,57	2,3
Total Chlorine [mg/L]	–	–	–	–	–	–
Free Chlorine [mg/L]	–	–	–	–	–	–
Total Hardness [ppm CaCO3]	–	–	–	–	–	–
Coliform Bacteria [MPN]						
Water Colour	Brownish	Clear	Clear	Clear	Little turbidity	Brownish
Extraction period	-		1 year			month
Usage amount	-		425 m3			15-20 m3 low season
Amount people	-			25		
ARA-Sul (registration)	–	–	–	–	–	–
/m3	–	–	–	–	–	–
Personal usage						

5. Geohydrology

Levelling F-1 to F-2 (2 steps) results in a height difference Δh of 1,75m.

backward	*forward*	*difference*
1,56	0,56	1,00
1,53	0,78	0,75
		1,75

Levelling F-2 to F-3 (3 steps) results in a height difference Δh of 4,69m.

backward	*forward*	*difference*
0,91	0,68	0,23
2,54	0,64	1,90
2,63	0,07	2,56
		4,69

Levelling B-3 to F-6 (3 steps) results in a height difference Δh of 3,90m.

backward	*forward*	*difference*
2,63	0,60	2,03
1,36	0,54	0,82
2,08	1,03	1,05
		3,90

Levelling F-6 to F-7 (2 steps) results in a height difference Δh of -4,24m.

backward	*forward*	*difference*
1,96	3,43	-1,47
0,83	3,60	-2,77
		-4,24

Levelling F-8 to F-11 (3 steps) results in a height difference Δh of 1,52m.

backward	*forward*	*difference*
2,73	0,55	2,18
1,94	1,45	0,49
0,41	1,56	-1,15
		1,52

Levelling F-11 to BRIDGE (5 steps) results in a height difference Δh of -0,94m.

backward	*forward*	*difference*
1,23	1,78	-0,55
1,57	1,88	-0,31
1,65	2,05	-0,40
1,80	2,00	-0,20
1,74	1,22	0,52
		-0,94

Levelling BRIDGE to F-10 (2 steps) results in a height difference Δh of 0,41m.

backward	*forward*	*difference*
2,78	1,28	1,50
0,96	2,05	-1,09
		0,41

Levelling F-10 to F-9 (5 steps) results in a height difference Δh of -1,39m.

backward	*forward*	*difference*
2,05	0,91	1,14
1,42	2,31	-0,89
1,84	1,36	0,48
2,11	1,85	0,26
2,02	4,40	-2,38
		-1,39

Python model Step 1-15

```
In [1]: %matplotlib notebook
        import numpy as np
        import matplotlib.pyplot as plt
        from timml import *
        %matplotlib inline
```

1 Data of the point boundary wells

```
In [2]: B_Lat = [-23.887948, -23.890402, -23.885955, -23.885867, -23.905022, -23.899097,
        -23.894698, -23.892972]
        B_Lon = [35.467412, 35.466073, 35.462234, 35.463457, 35.462121, 35.456906, 35.474435,
        35.474663]

        origin_lat = -23.887568
        origin_lon = 35.453593

        dx_B = np.zeros(len(B_Lat))
        dy_B = np.zeros(len(B_Lon))

        for i in range(len(B_Lat)):
            dx_B[i] = ((origin_lon-B_Lon[i])*40000*np.cos((B_Lat[i]+origin_lat)*
            np.pi/360)/360)*1000
            dy_B[i] = ((origin_lat-B_Lat[i])*40000/360)*1000

In [3]: X_B = dx_B*-1
        Y_B = dy_B*-1

In [4]: h_b = [4.54, 5.39, 1.73, 0.31, 1.38, 3.12, 7.74, 5.82]
```

2 Data of the measured wells

```
In [5]: Lat = [-23.886201, -23.886647, -23.88743, -23.885653, -23.885957, -23.886883,
        -23.887548, -23.885959, -23.891364, -23.888268, -23.887205, -23.889139]

        Lon = [35.467334, 35.467257, 35.468339, 35.474544, 35.4618, 35.462804, 35.462792,
        35.457984, 35.455138, 35.453231, 35.457452, 35.457932]

        origin_lat = -23.887568
        origin_lon = 35.453593

        dx = np.zeros(len(Lat))
        dy = np.zeros(len(Lon))

        for i in range(len(Lat)):
            dx[i] = ((origin_lon-Lon[i])*40000*np.cos((Lat[i]+origin_lat)*np.pi/360)/360)*1000
            dy[i] = ((origin_lat-Lat[i])*40000/360)*1000
```

```
new_y = dy *-1
new_x = dx * -1

X = new_x
Y = new_y

#measured wells
Q_w = [5.58, 0.14, 0.7, 8.8, 0.26, 3.2, 1.76, 0.2, 0.96, 0.5, 0.5, 0.3]
r_w = [0.55/2, 0.55/2, 0.61/2, 1.4/2, 0.7/2, 0.55/2, 1.06/2, 1.00/2, 0.60/2, 0.59/2,

0.55/2, 0.60/2]
h_w = [4.45, 3.8, 6.96, 1.75, 6.09, 2.75, 7.46, -0.31, 6.01, 3.40, 4.17, 7.29]

x_M = [-24.020734]
y_M = [35.420951]
```

3 Data of the sea boundaries

```
In [6]: #Latitude and Longitude coordinates of the sea
Lat_sea=[-23.793003, -23.825907, -23.854565, -23.863523, -23.867512, -23.922215,
-23.926553, -24.009634,  -24.019240, -24.071243, -24.074154,
-24.100488, -24.169173, -24.227797, -24.214818, -24.111443,
-24.055254, -24.024683, -23.970085, -23.937639, -23.916988,
-23.904516, -23.879203, -23.861532, -23.837507, -23.840731,
-23.875567, -23.875567, -23.881221, -23.881798, -23.876718,
-23.855315, -23.850028, -23.846204, -23.807327, -23.799179,
-23.799033, -23.795285, -23.785407, -23.781762, -23.791187]
Lon_sea=[35.538023, 35.536871, 35.550130, 35.551641, 35.555215, 35.526158,
35.529323, 35.498705, 35.502557, 35.494830, 35.499798,
35.499622, 35.471097, 35.425022, 35.308946, 35.296983,
35.308559, 35.329388, 35.350182, 35.371331, 35.394078,
35.394559, 35.380725, 35.377998, 35.389061,  35.405286,
35.405286, 35.451989,  35.462673, 35.470811, 35.475956,
35.469286, 35.484316, 35.493893, 35.485750, 35.504901,
35.516134,  35.516543, 35.491967, 35.491709, 35.517618]

#Latitude and Longitude coordinates of 0,0 point
origin_lat = -23.887568
origin_lon = 35.453593

#convertion to x- and y-coordinates
dx_S = np.zeros(len(Lat_sea))
dy_S = np.zeros(len(Lon_sea))

for i in range(len(Lat_sea)):
    dx_S[i] = ((origin_lon-Lon_sea[i])*40000*np.cos((Lat_sea[i]+origin_lat)*np.
    pi/360)/360)*1000
```

```
    dy_S[i] = ((origin_lat-Lat_sea[i])*40000/360)*1000

#x- and y coordinates of the sea
X_S = dx_S*-1
Y_S = dy_S*-1
```

4 River data

```
In [7]: #river points
        Lat_river=[-23.869473,-23.887476,-23.889996, -23.899838, -23.901812, -23.909634]
        Lon_river=[35.452563,35.453574, 35.455395, 35.459216, 35.467641, 35.471346]

        #Latitude and Longitude coordinates of 0,0 point
        origin_lat = -23.887568
        origin_lon = 35.453593

        #convertion to x- and y-coordinates
        dx_R = np.zeros(len(Lat_river))
        dy_R = np.zeros(len(Lon_river))

        for i in range(len(Lat_river)):
            dx_R[i] = ((origin_lon-Lon_river[i])*40000*np.cos((Lat_river[i]+origin_lat)*np.
            pi/360)/360)*1000
            dy_R[i] = ((origin_lat-Lat_river[i])*40000/360)*1000

        #x- and y coordinates of the river
        X_R = dx_R*-1
        Y_R = dy_R*-1
```

5 Barra and Tofo well

```
In [8]: #first well is Barra
        #second well is Tofo resorts
        # third well is Fipag Tofo
        # fourth well is Fipag Guiuia river
        Lat_bigwell=[-23.793950, -23.854585, -23.857703, -24.044343]
        Lon_bigwell=[35.525876,  35.546140,  35.530426,  35.361762]

        #Latitude and Longitude coordinates of 0,0 point
        origin_lat = -23.887568
        origin_lon = 35.453593

        #convertion to x- and y-coordinates
        dx_BW = np.zeros(len(Lat_bigwell))
        dy_BW = np.zeros(len(Lon_bigwell))

        for i in range(len(Lat_bigwell)):
```

```
    dx_BW[i] = ((origin_lon-Lon_bigwell[i])*40000*np.cos((Lat_bigwell[i]+origin_lat)*
    np.pi/360)/360)*1000
    dy_BW[i] = ((origin_lat-Lat_bigwell[i])*40000/360)*1000

#x- and y coordinates of the river
X_BW = dx_BW*-1
Y_BW = dy_BW*-1
```

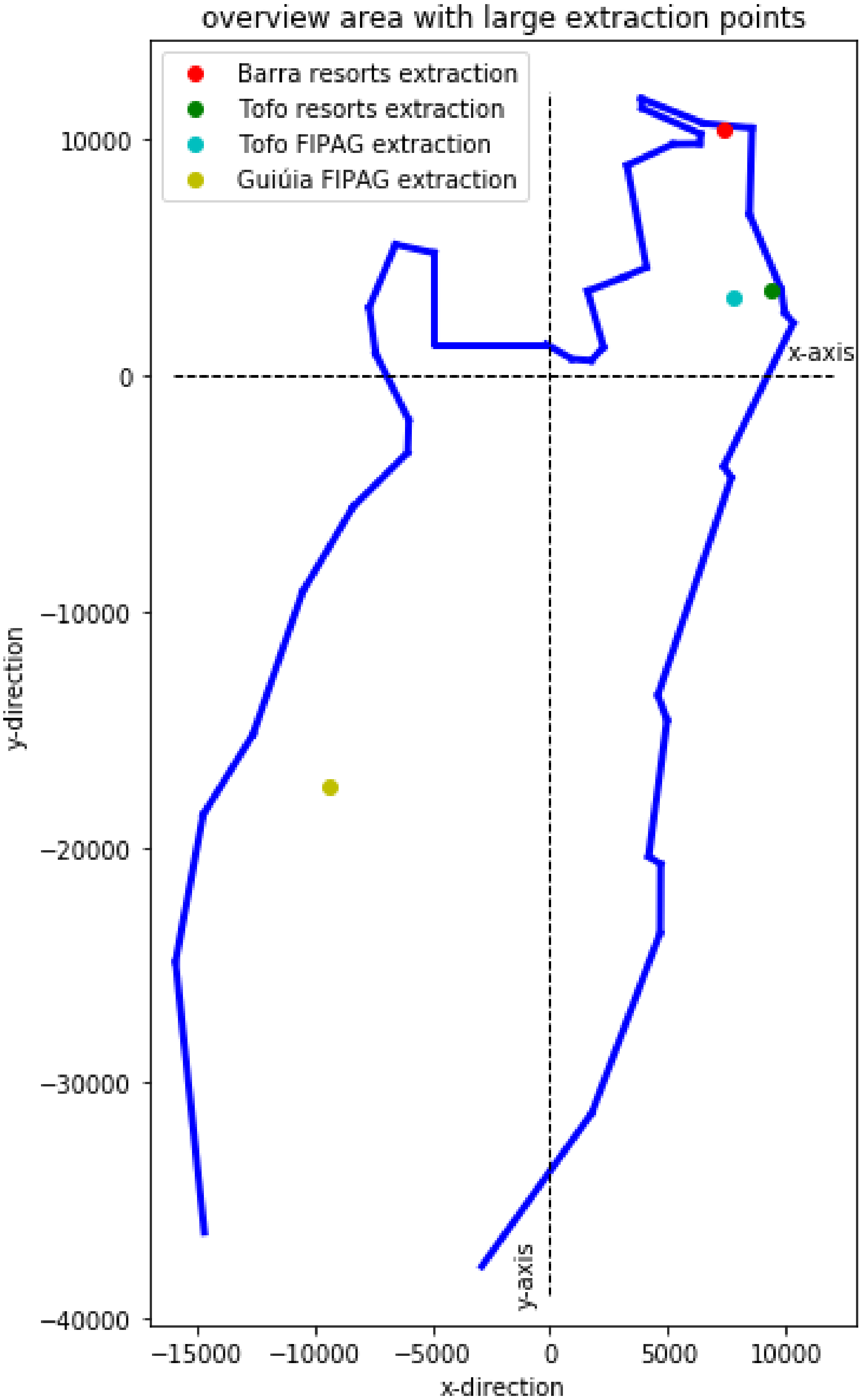
6 Overview project area on large scale

```
In [9]: plt.figure(figsize=(10,10))
        plt.plot([X_S[0], X_S[1]], [Y_S[0], Y_S[1]], 'b', lw=3)
        plt.plot([X_S[1], X_S[2]], [Y_S[1], Y_S[2]], 'b', lw=3)
        plt.plot([X_S[2], X_S[3]], [Y_S[2], Y_S[3]], 'b', lw=3)
        plt.plot([X_S[3], X_S[4]], [Y_S[3], Y_S[4]], 'b', lw=3)
        plt.plot([X_S[4], X_S[5]], [Y_S[4], Y_S[5]], 'b', lw=3)
        plt.plot([X_S[5], X_S[6]], [Y_S[5], Y_S[6]], 'b', lw=3)
        plt.plot([X_S[6], X_S[7]], [Y_S[6], Y_S[7]], 'b', lw=3)
        plt.plot([X_S[7], X_S[8]], [Y_S[7], Y_S[8]], 'b', lw=3)
        plt.plot([X_S[8], X_S[9]], [Y_S[8], Y_S[9]], 'b', lw=3)
        plt.plot([X_S[9], X_S[10]], [Y_S[9], Y_S[10]], 'b', lw=3)
        plt.plot([X_S[10], X_S[11]], [Y_S[10], Y_S[11]], 'b', lw=3)
        plt.plot([X_S[11], X_S[12]], [Y_S[11], Y_S[12]], 'b', lw=3)
        plt.plot([X_S[12], X_S[13]], [Y_S[12], Y_S[13]], 'b', lw=3)
        #plt.plot([X_S[13], X_S[14]], [Y_S[13], Y_S[14]], 'b', lw=5)
        plt.plot([X_S[14], X_S[15]], [Y_S[14], Y_S[15]], 'b', lw=3)
        plt.plot([X_S[15], X_S[16]], [Y_S[15], Y_S[16]], 'b', lw=3)
        plt.plot([X_S[16], X_S[17]], [Y_S[16], Y_S[17]], 'b', lw=3)
        plt.plot([X_S[17], X_S[18]], [Y_S[17], Y_S[18]], 'b', lw=3)
        plt.plot([X_S[18], X_S[19]], [Y_S[18], Y_S[19]], 'b', lw=3)
        plt.plot([X_S[19], X_S[20]], [Y_S[19], Y_S[20]], 'b', lw=3)
        plt.plot([X_S[20], X_S[21]], [Y_S[20], Y_S[21]], 'b', lw=3)
        plt.plot([X_S[21], X_S[22]], [Y_S[21], Y_S[22]], 'b', lw=3)
        plt.plot([X_S[22], X_S[23]], [Y_S[22], Y_S[23]], 'b', lw=3)
        plt.plot([X_S[23], X_S[24]], [Y_S[23], Y_S[24]], 'b', lw=3)
        plt.plot([X_S[24], X_S[25]], [Y_S[24], Y_S[25]], 'b', lw=3)
        plt.plot([X_S[25], X_S[26]], [Y_S[25], Y_S[26]], 'b', lw=3)
        plt.plot([X_S[26], X_S[27]], [Y_S[26], Y_S[27]], 'b', lw=3)
        plt.plot([X_S[27], X_S[28]], [Y_S[27], Y_S[28]], 'b', lw=3)
        plt.plot([X_S[28], X_S[29]], [Y_S[28], Y_S[29]], 'b', lw=3)
        plt.plot([X_S[29], X_S[30]], [Y_S[29], Y_S[30]], 'b', lw=3)
        plt.plot([X_S[30], X_S[31]], [Y_S[30], Y_S[31]], 'b', lw=3)
        plt.plot([X_S[31], X_S[32]], [Y_S[31], Y_S[32]], 'b', lw=3)
        plt.plot([X_S[32], X_S[33]], [Y_S[32], Y_S[33]], 'b', lw=3)
        plt.plot([X_S[33], X_S[34]], [Y_S[33], Y_S[34]], 'b', lw=3)
        plt.plot([X_S[34], X_S[35]], [Y_S[34], Y_S[35]], 'b', lw=3)
        plt.plot([X_S[35], X_S[36]], [Y_S[35], Y_S[36]], 'b', lw=3)
```

```python
plt.plot([X_S[36], X_S[37]], [Y_S[36], Y_S[37]], 'b', lw=3)
plt.plot([X_S[37], X_S[38]], [Y_S[37], Y_S[38]], 'b', lw=3)
plt.plot([X_S[38], X_S[39]], [Y_S[38], Y_S[39]], 'b', lw=3)
plt.plot([X_S[39], X_S[40]], [Y_S[39], Y_S[40]], 'b', lw=3)
plt.plot([X_S[40], X_S[0]], [Y_S[40], Y_S[0]], 'b', lw=3)

print (len(X_S))
print (len(Y_S))

plt.axis('scaled')
#plt.plot(-3324.3, -10000,'bo')



# x- and y-axis
plt.plot([-16000, 12000], [0, 0], '--', lw=1, color='k')
plt.text(11500,1000, 'x-axis', ha='center', va='center')

plt.plot([0, 0], [-39000, 12000], '--', lw=1, color='k')
plt.text(-1000,-38000, 'y-axis', rotation=90, ha='center', va='center')
plt.xlim(-17000, 13000)

plt.xlabel("x-direction")
plt.ylabel("y-direction")
plt.title("overview area with large extraction points")

plt.plot(X_BW[0], Y_BW[0], 'ro', label='Barra resorts extraction')
plt.plot(X_BW[1], Y_BW[1], 'go', label='Tofo resorts extraction')
plt.plot(X_BW[2], Y_BW[2], 'co', label='Tofo FIPAG extraction')
plt.plot(X_BW[3], Y_BW[3], 'yo', label='Guiúia FIPAG extraction')
plt.legend()
```

```
41
41
```

```
Out[9]: <matplotlib.legend.Legend at 0x6223ed0a90>
```



overview area with large extraction points
Barra resorts extraction
Tofo resorts extraction
Tofo FIPAG extraction
Guiúia FIPAG extraction
x-axis
y-axis
y-direction
x-direction
10000
0
−10000
−20000
−30000
−40000
−15000
−10000
−5000
0
5000
10000

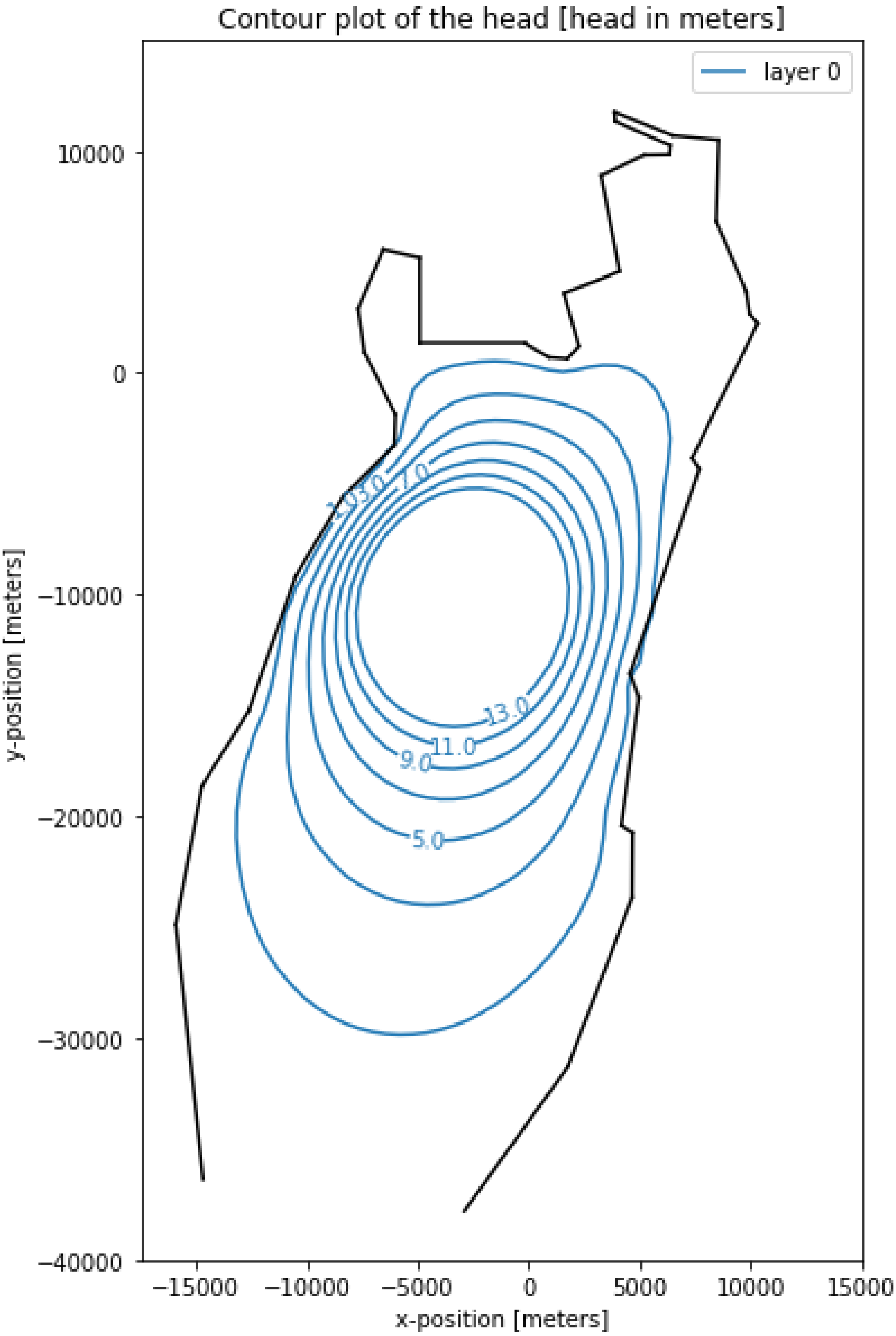
7 First plot with sea boundaries and infiltration rate

In [10]:
```
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

#b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
```

```
         #b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
         #b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
         #b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
         #b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
         #b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
         #b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

         ml.solve(silent=True)
```

```
In [11]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,15,2),
        labels=True, decimals=1, figsize=(10,10))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 1.19016171]
[ 1.60225353]
```



Contour plot of the head [head in meters]
layer 0
10000
0
−10000
−20000
−30000
−40000
y-position [meters]
−15000
−10000
−5000
0
5000
10000
15000
x-position [meters]
7.0
13.0
11.0
9.0
5.0

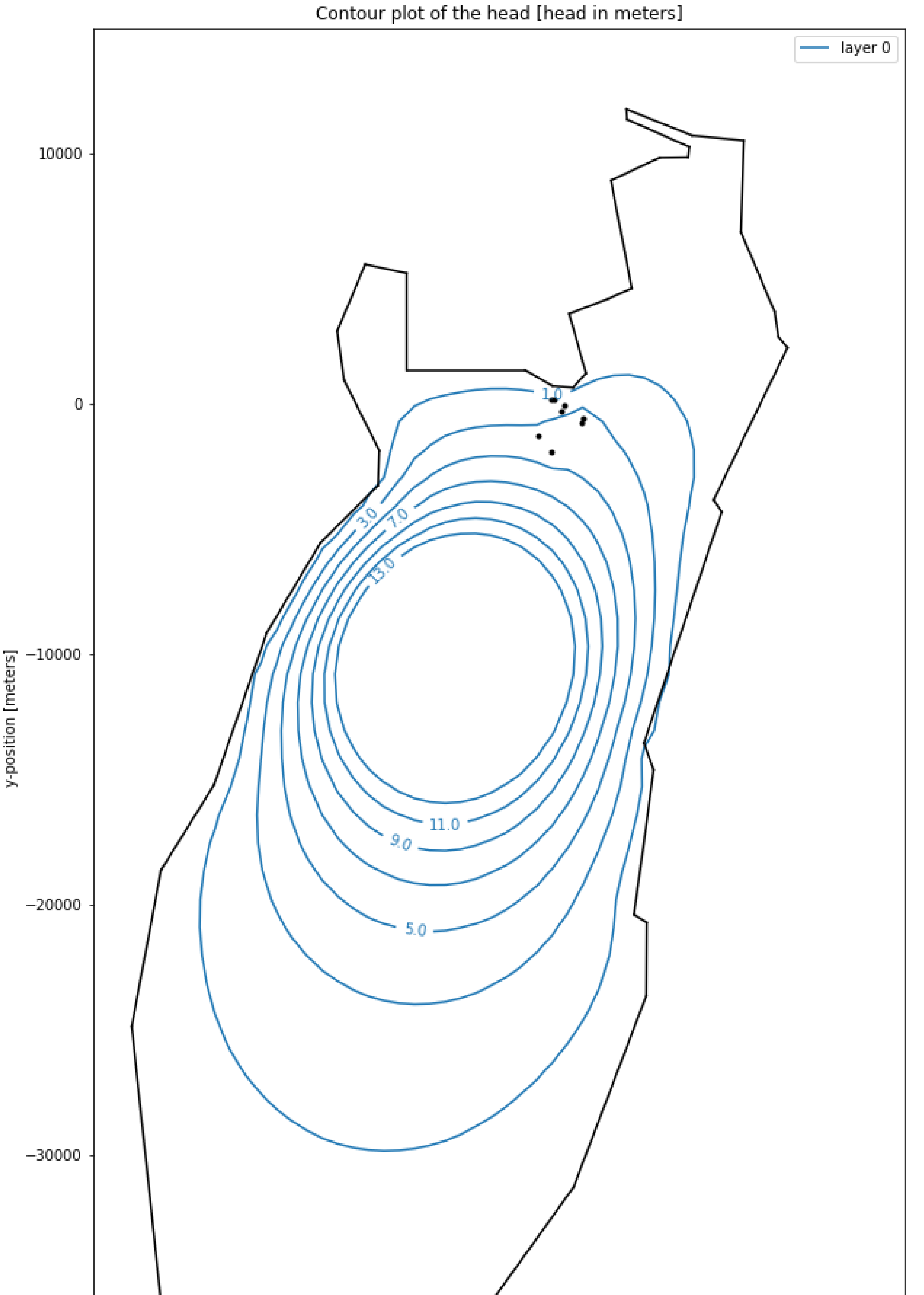
8 Second plot with sea boundaries, infiltration rate and head point boundary conditions

In [12]:
```
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)
```

```
b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])
b8 = HeadWell(ml, X_B[7], Y_B[7], hw=h_b[7])

ml.solve(silent=True)
```

```
In [13]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,15,2),
        labels=True, decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

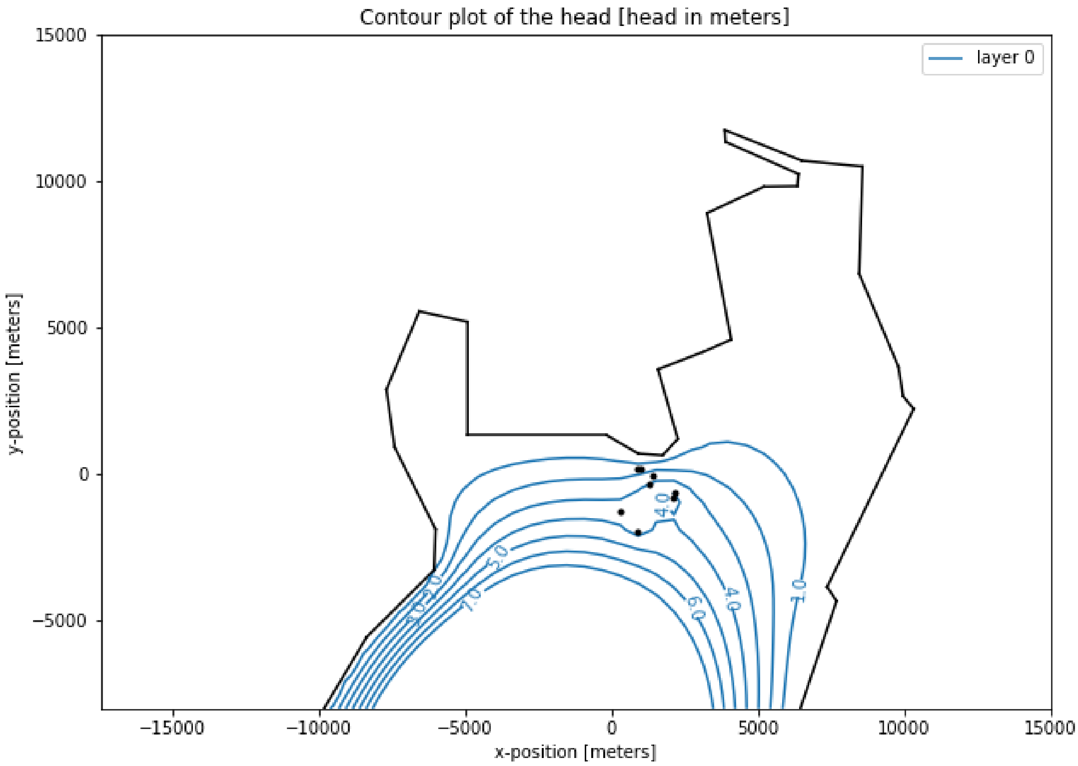
```
[ 4.53997769]
[ 5.38990527]
```



Contour plot of the head [head in meters]
layer 0
10000
0
−10000
−20000
−30000
−40000
y-position [meters]
−15000
−10000
−5000
0
5000
10000
15000
x-position [meters]
1.0
3.0
7.0
13.0
11.0
9.0
5.0

```
In [14]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(1,8,1),
        labels=True, decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.53997769]
[ 5.38990527]
```



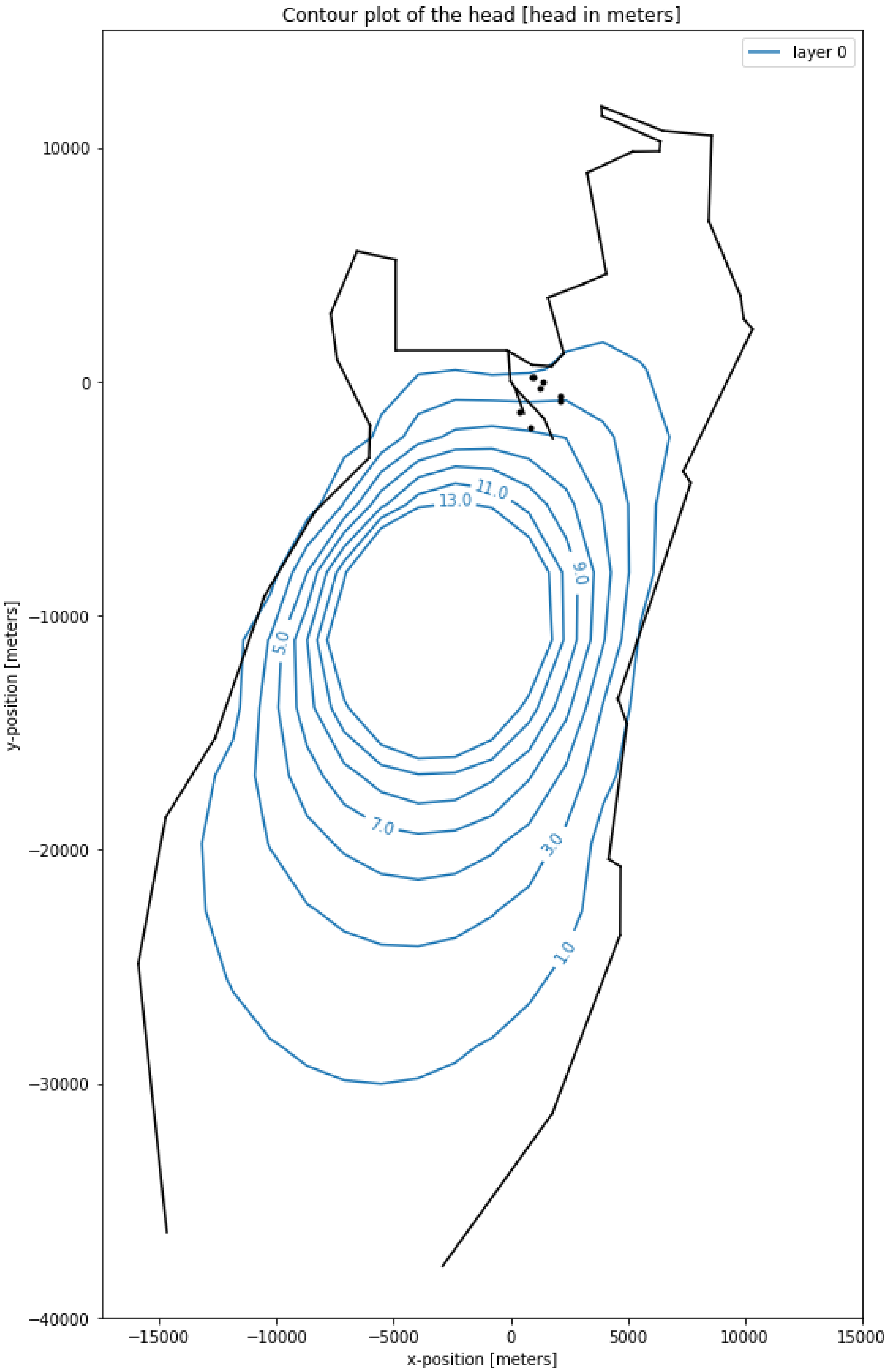

```
In [15]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h1 = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h2 = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
```

```
h3= HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h4= HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h5 = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h6 = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h7 = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h8 = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h9 = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h10 = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h11 = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h12 = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h13 = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h14 = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h15 = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h16 = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h17 = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h18 = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h19 = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h20 = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h21 = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h22 = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h23 = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h24 = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h25 = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h26 = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h27 = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h28 = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h29 = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h30 = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h31 = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h32 = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h33 = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h34 = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h35 = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h36 = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h37 = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h38 = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h39 = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h40 = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])
b8 = HeadWell(ml, X_B[7], Y_B[7], hw=h_b[7])
```

```
#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

ml.solve(silent=True)
```

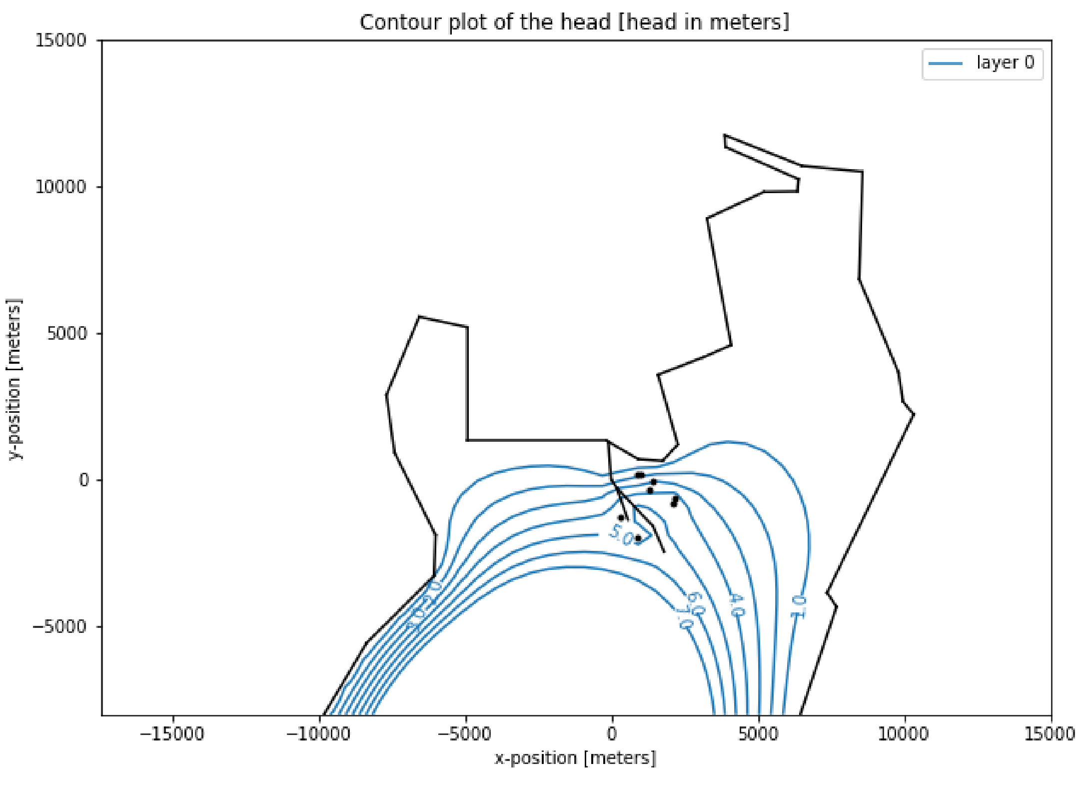
In [16]:
```
ml.contour([-15000,15000,-40000,15000], ngr=20, levels=np.arange(-1,15,2),
labels=True, decimals=1, figsize=(10,15))
plt.title("Contour plot of the head [head in meters]")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
```

Out[16]:
```
(-17441.60545269891, 15000.0, -40000.0, 15000.0)
```


Contour plot of the head [head in meters]
layer 0
10000
0
−10000
−20000
−30000
−40000
y-position [meters]
−15000
−10000
−5000
0
5000
10000
15000
x-position [meters]
13.0
11.0
9.0
7.0
5.0
3.0
1.0

```
In [17]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(1,8,1),
        labels=True, decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.53998726]
[ 5.38995653]
```



9 Third plot with sea boundaries, infiltration rate and head point boundary conditions, including discharge wells

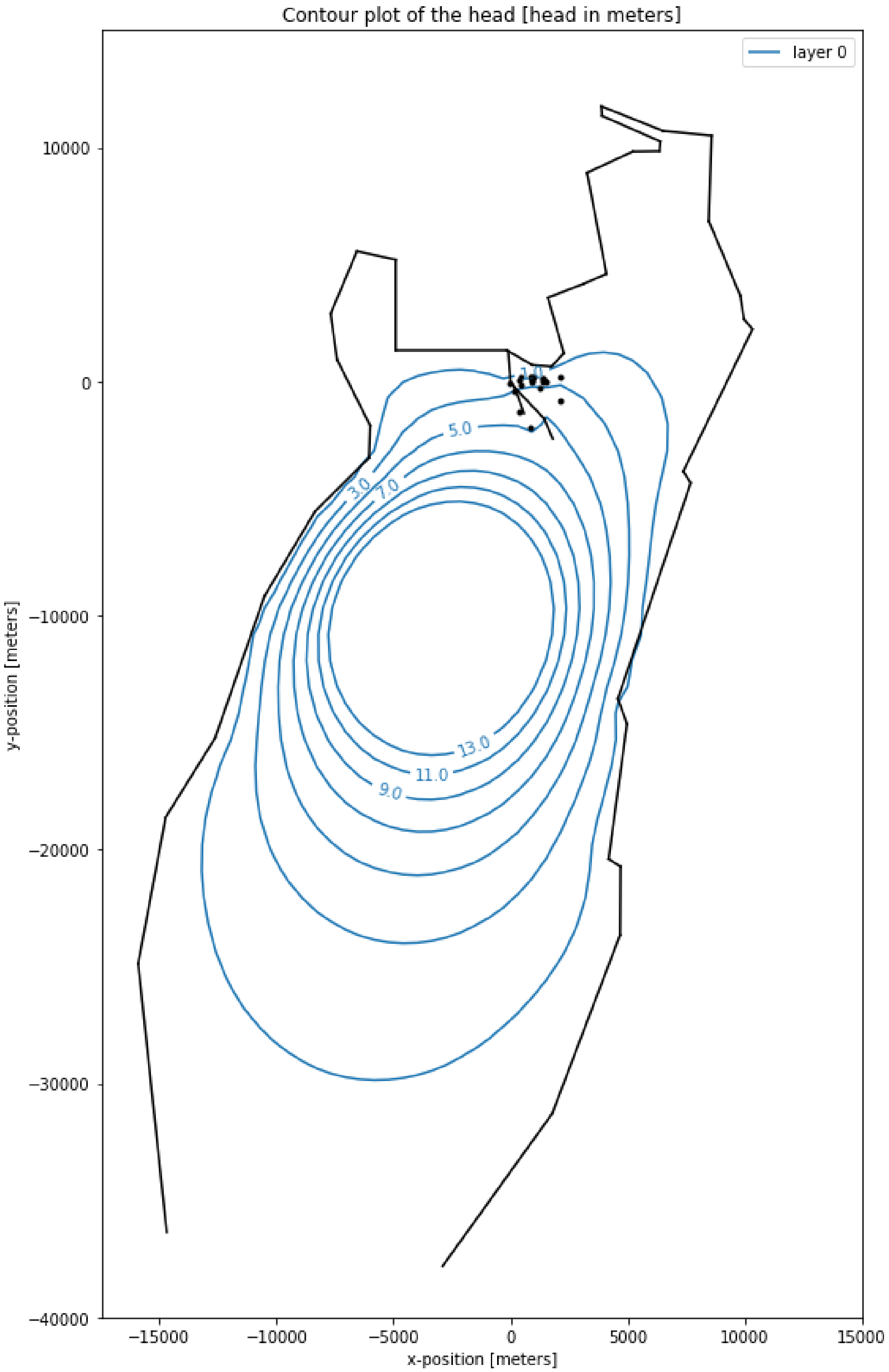
```
In [18]: ml = ModelMaq(kaq=1, z=[0,-50])
```

```
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)
h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
```

```
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])



w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

ml.solve(silent=True)
```

```
In [19]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,14,2),
        labels=True, decimals=1, figsize=(10,15))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X[0], Y[0]))
         print (ml.head(X[1], Y[1]))
```

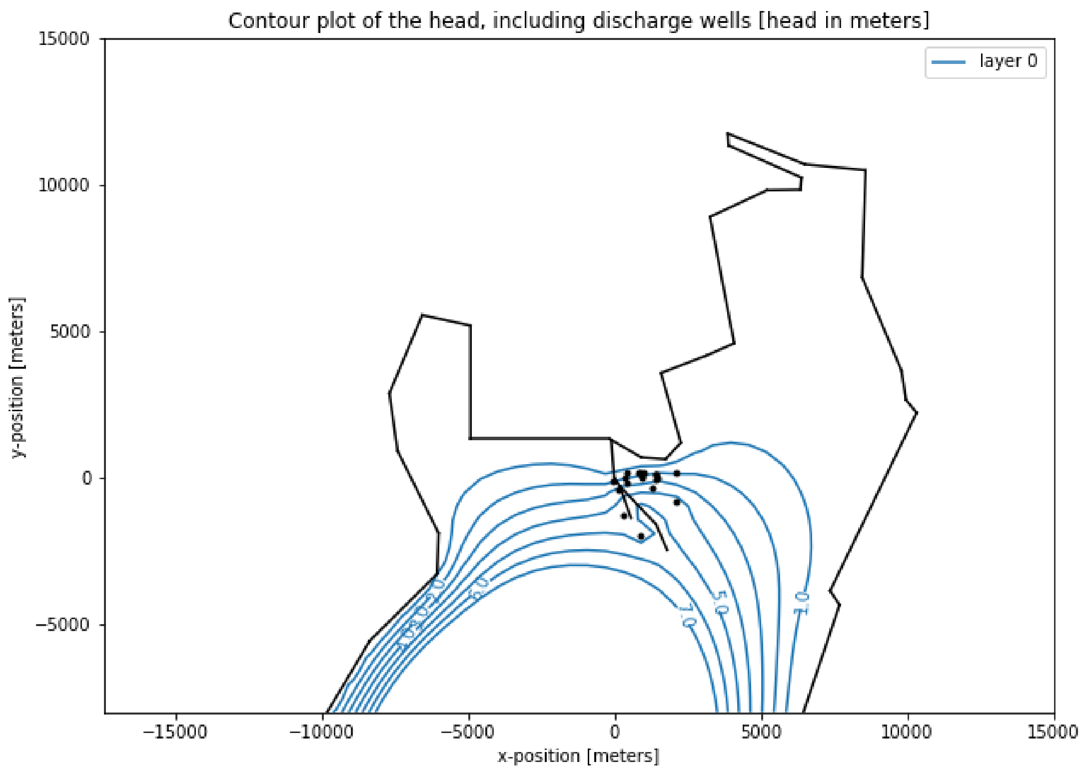
```
[ 1.96606738]
[ 2.29618389]
```



Contour plot of the head [head in meters]
layer 0
1.0
3.0
5.0
7.0
9.0
11.0
13.0
10000
0
−10000
−20000
−30000
−40000
y-position [meters]
−15000
−10000
−5000
0
5000
10000
15000
x-position [meters]

```
In [20]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(1,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including discharge wells [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000547]
[ 5.38997257]
```



10 Influence of wells in Barra

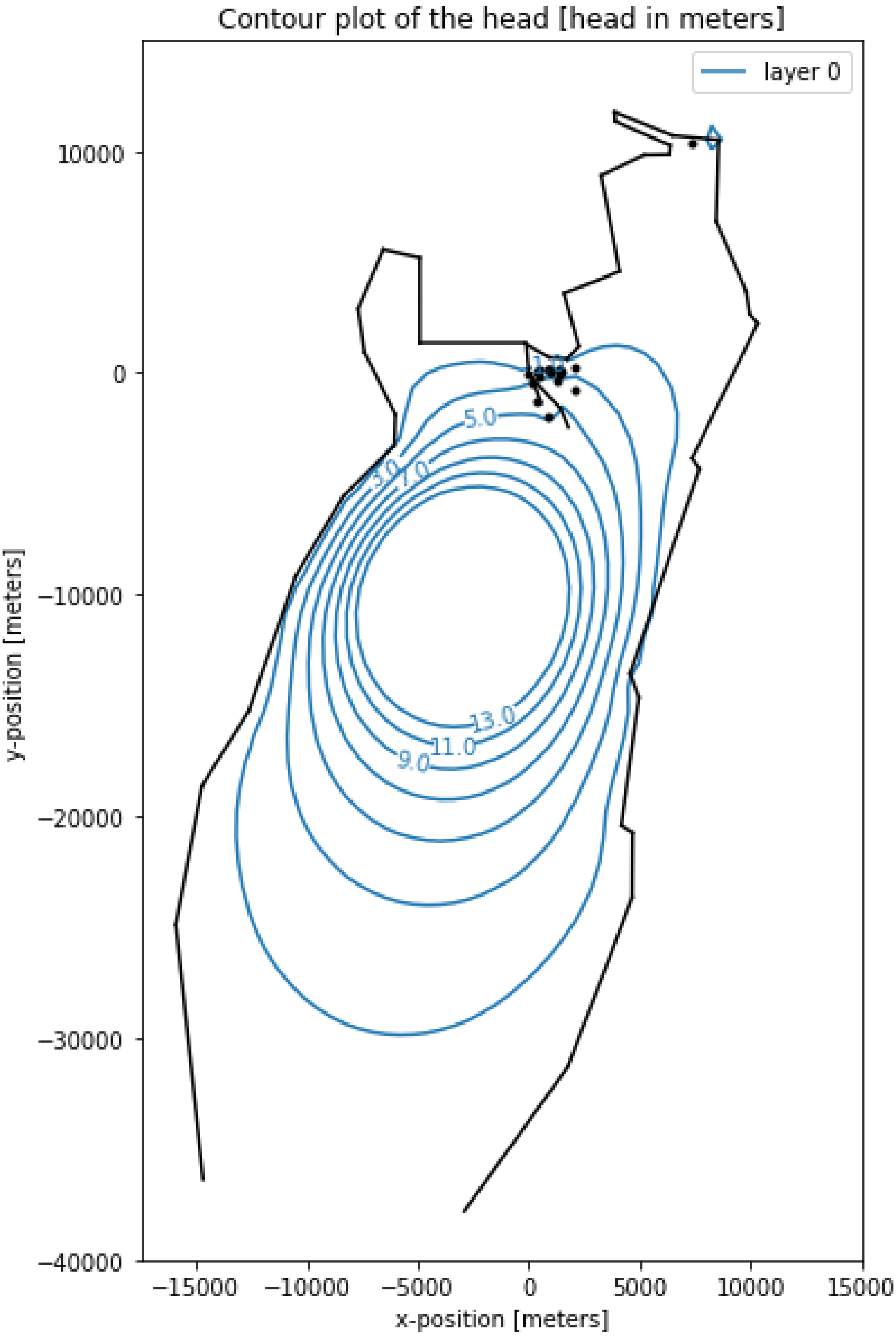
```
In [21]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])
```

```
w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[0], Y_BW[0], Qw=600, rw=1.00/2)

ml.solve(silent=True)
```

```
In [22]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,14,2), labels=True,
        decimals=1, figsize=(10,10))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X[0], Y[0]))
         print (ml.head(X[1], Y[1]))
```

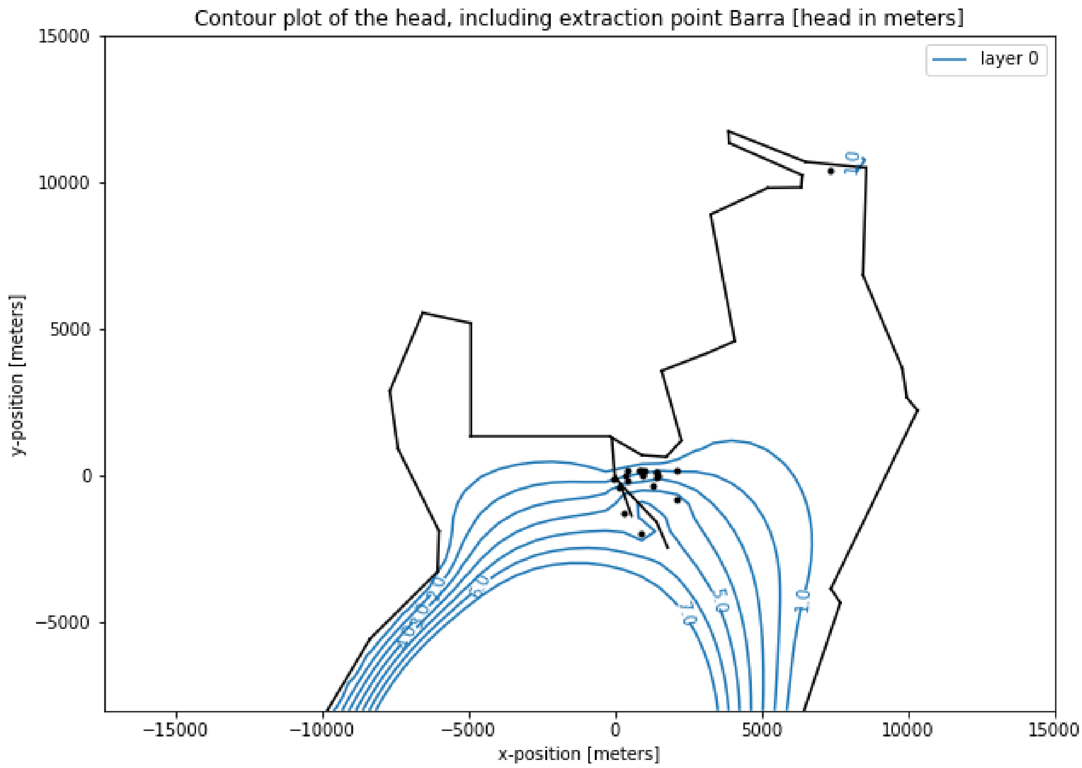
```
[ 1.96602412]
[ 2.29614091]
```




```
In [23]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(1,8,1),labels=True,
```

```
decimals=1, figsize=(10,20))
 plt.title("Contour plot of the head, including extraction point Barra")
 plt.xlabel("x-position")
 plt.ylabel("y-position [meters]")
 plt.axis('scaled')
 plt.ylim(-8000,15000)

 print (ml.head(X_B[0], Y_B[0]))
 print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000549]
[ 5.38997258]
```



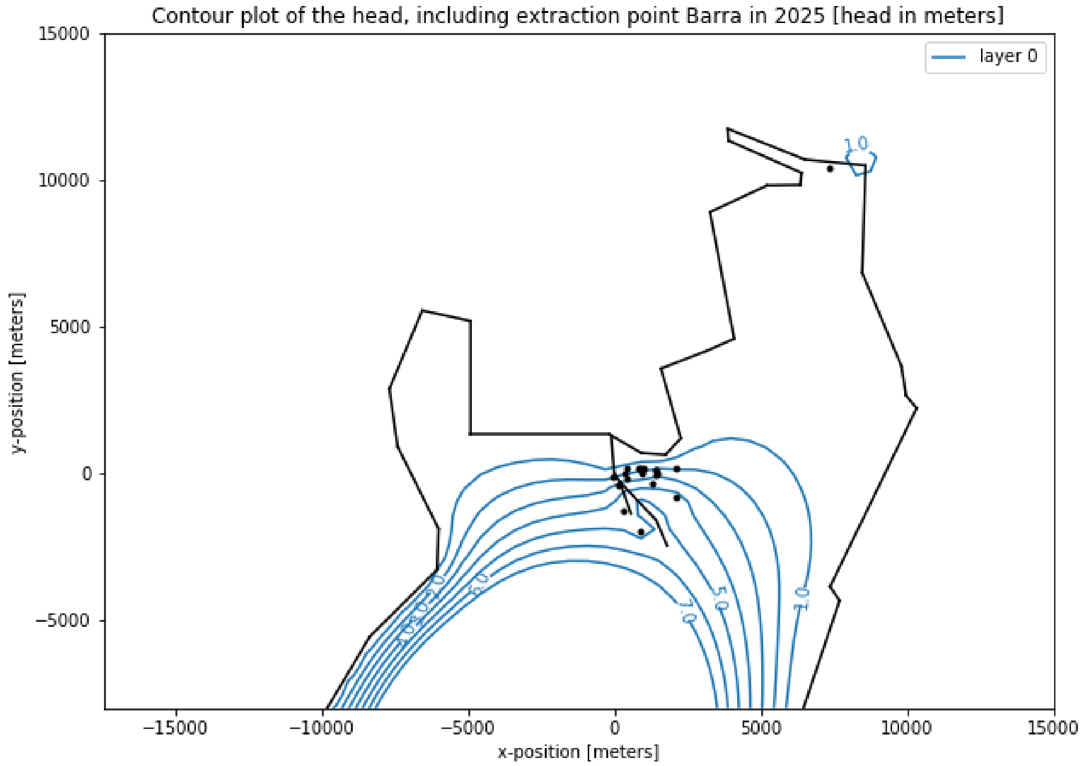

```
In [24]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
```

```
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[0], Y_BW[0], Qw=785, rw=1.00/2)

ml.solve(silent=True)
```

In [25]:
```
ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(1,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including extraction point Barra in 2025")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-8000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000549]
[ 5.38997258]
```



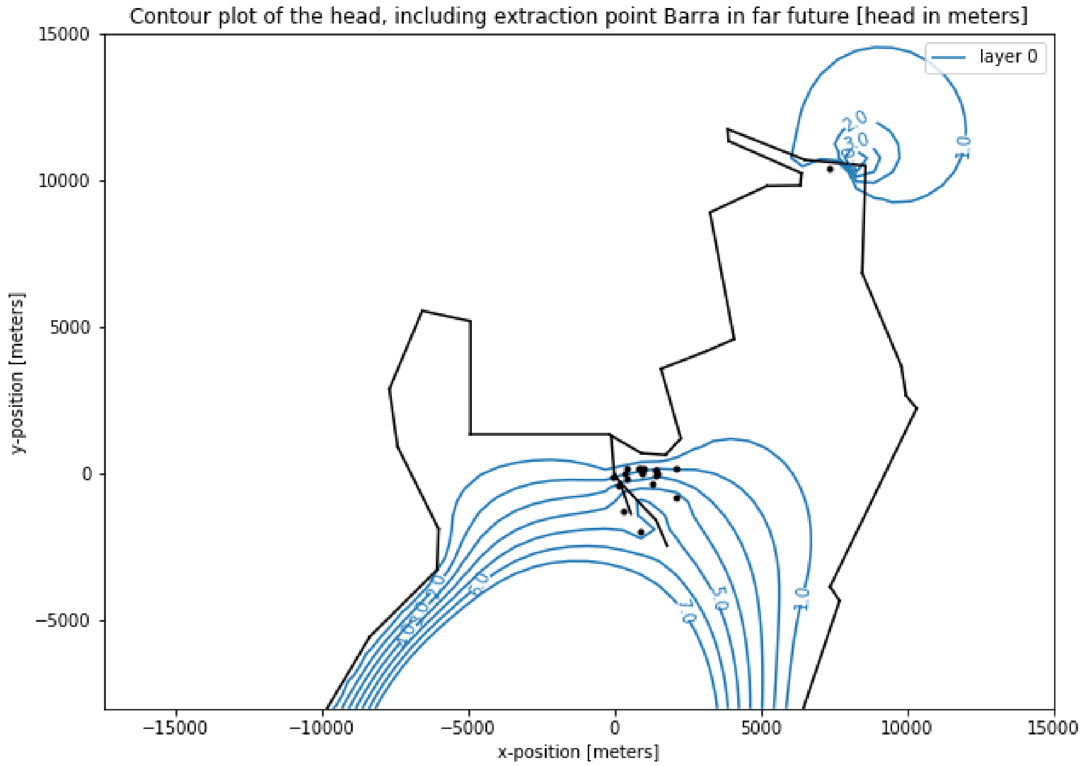

```
In [26]: #playing with values
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
```

```python
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])
```

```
#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[0], Y_BW[0], Qw=2500, rw=1.00/2)

ml.solve(silent=True)
```

In [27]:
```
ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(1,8,1),labels=True,
decimals=1, figsize=(10,20))
 plt.title("Contour plot of the head, including extraction point Barra in far future")
 plt.xlabel("x-position [meters]")
 plt.ylabel("y-position [meters]")
 plt.axis('scaled')
 plt.ylim(-8000,15000)

 print (ml.head(X_B[0], Y_B[0]))
 print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000553]
[ 5.38997261]
```



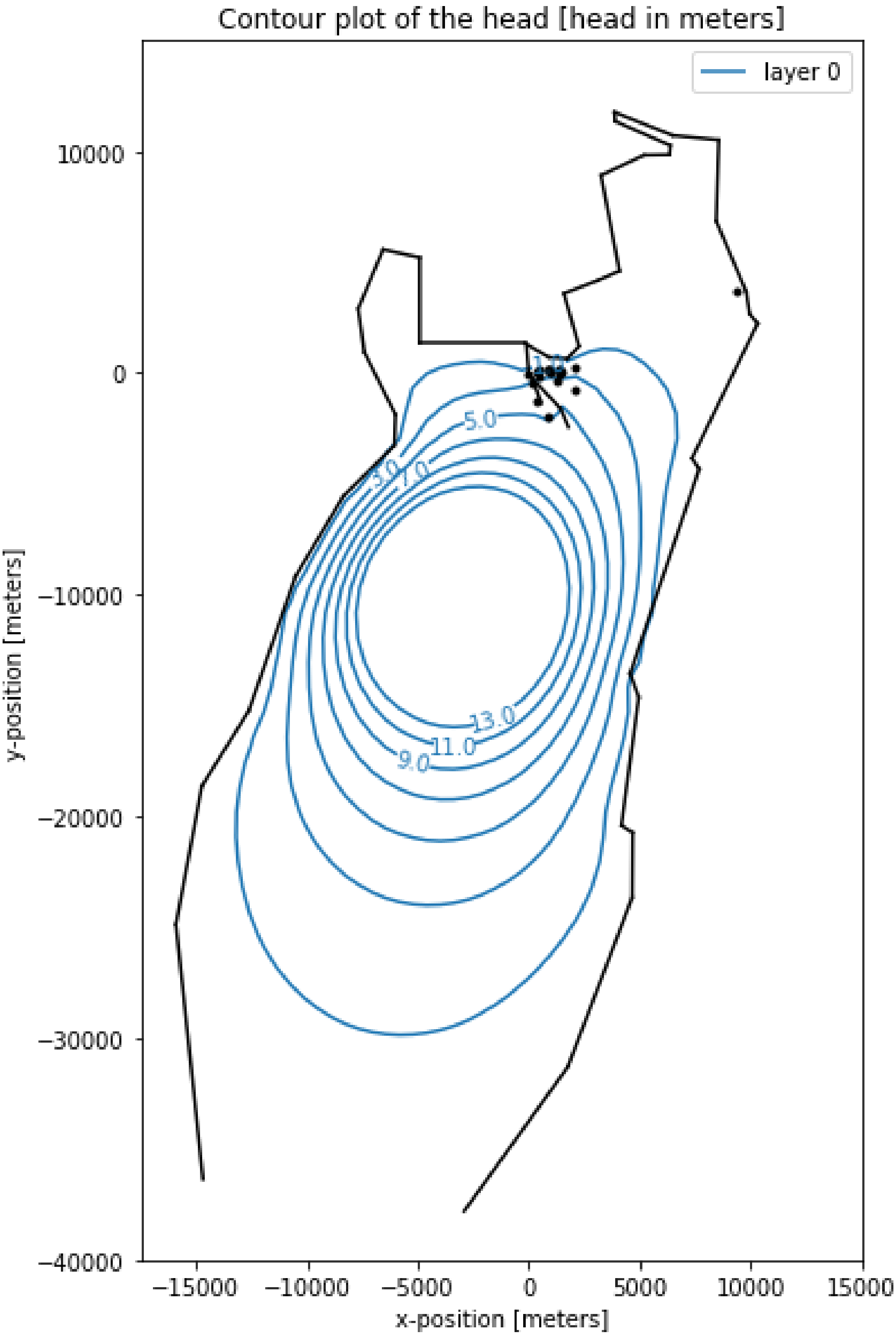
11 Influence of wells in Tofo

```
In [28]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

         b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
```

```
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[1], Y_BW[1], Qw=800, rw=1.00/2)

ml.solve(silent=True)
```

```
In [29]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,14,2), labels=True,
        decimals=1, figsize=(10,10))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X[0], Y[0]))
         print (ml.head(X[1], Y[1]))
```

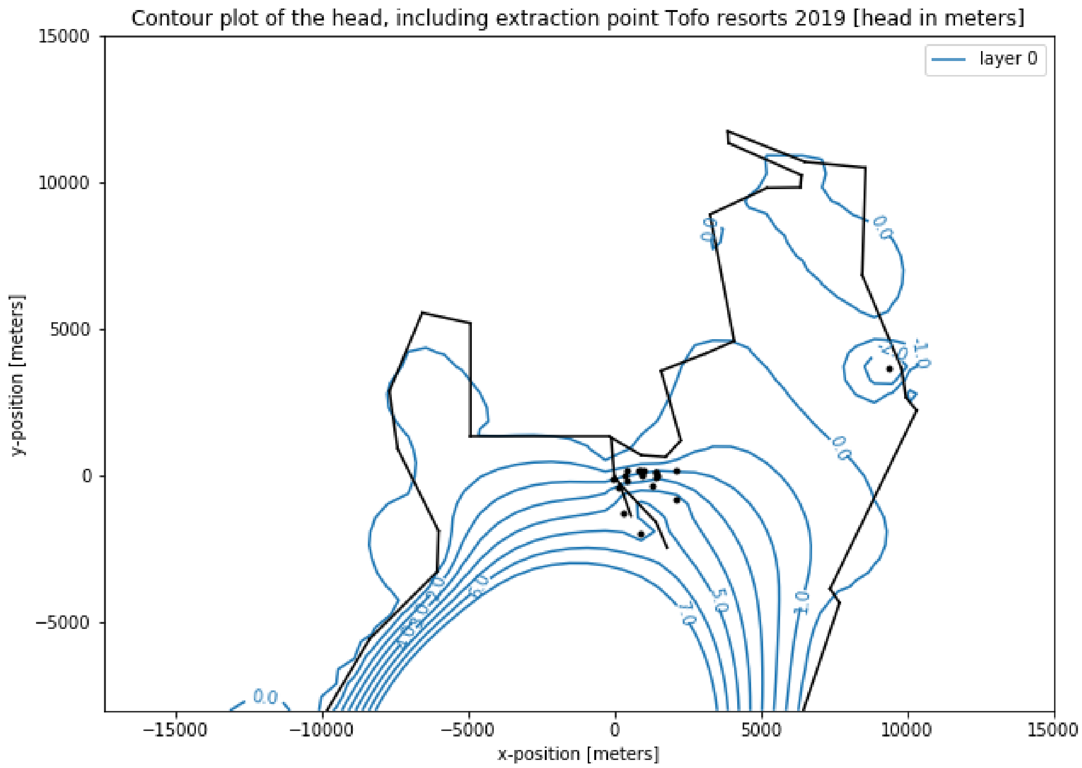
```
[ 1.96201856]
[ 2.29215391]
```




```
In [30]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
```

```
decimals=1, figsize=(10,20))
 plt.title("Contour plot of the head, including extraction point Tofo resorts 2019")
 plt.xlabel("x-position [meters]")
 plt.ylabel("y-position [meters]")
 plt.axis('scaled')
 plt.ylim(-8000,15000)

 print (ml.head(X_B[0], Y_B[0]))
 print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000675]
[ 5.38997354]
```



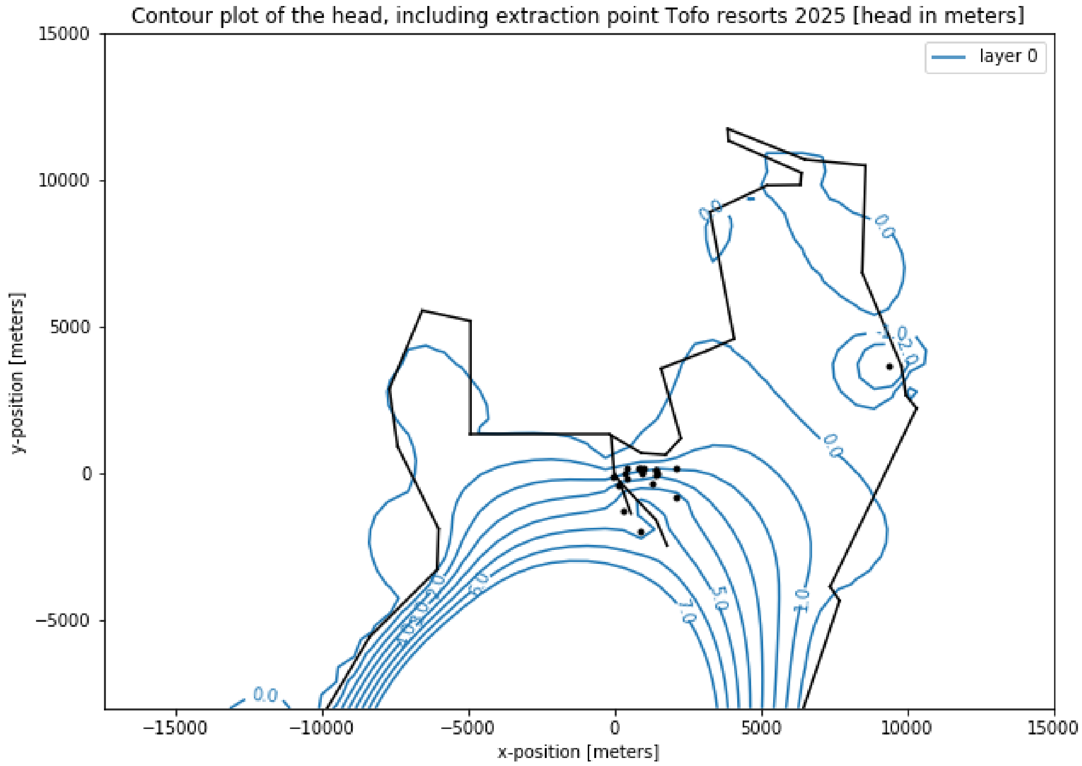

```
In [31]: #future 2025
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
```

```
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[1], Y_BW[1], Qw=1047, rw=1.00/2)

ml.solve(silent=True)
```

```
In [32]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including extraction point Tofo resorts 2025")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000715]
[ 5.38997384]
```



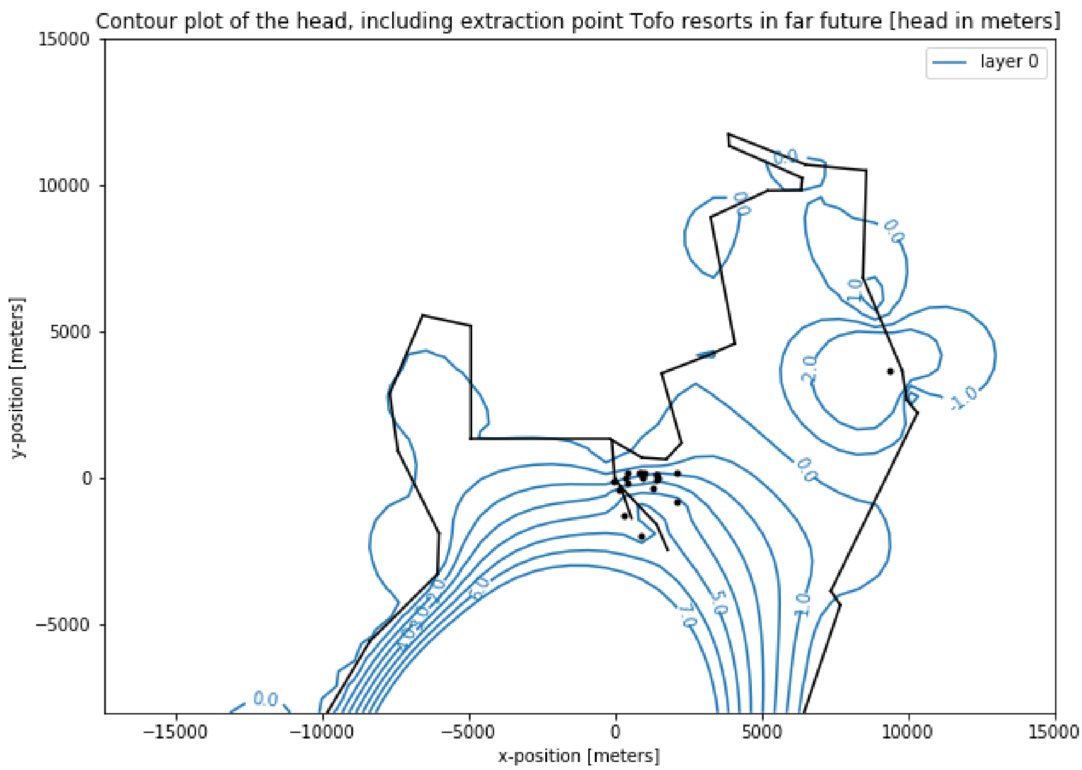
In [33]:
```
#playing with discharge
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
```

```python
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])
```

```
#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[1], Y_BW[1], Qw=3000, rw=1.00/2)

ml.solve(silent=True)
```

In [34]:
```
ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including extraction point Tofo resorts in future"
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-8000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54001026]
[ 5.38997621]
```



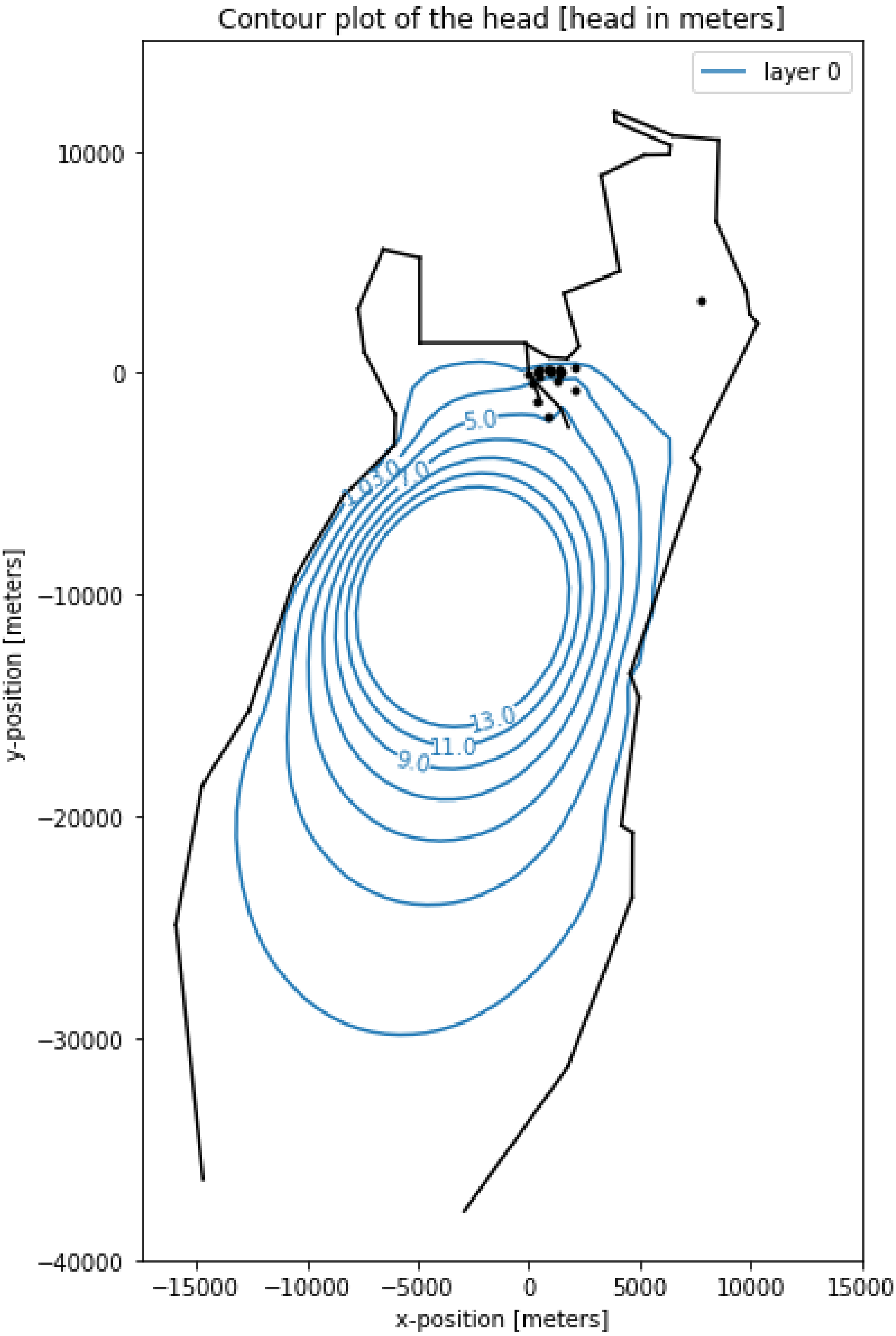
12 Influence of boreholes Tofo FIPAG

In [35]:
```
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
```

```
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[2], Y_BW[2], Qw=3000, rw=1.00/2)

ml.solve(silent=True)
```

```
In [36]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,14,2), labels=True,
        decimals=1, figsize=(10,10))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X[0], Y[0]))
         print (ml.head(X[1], Y[1]))
```

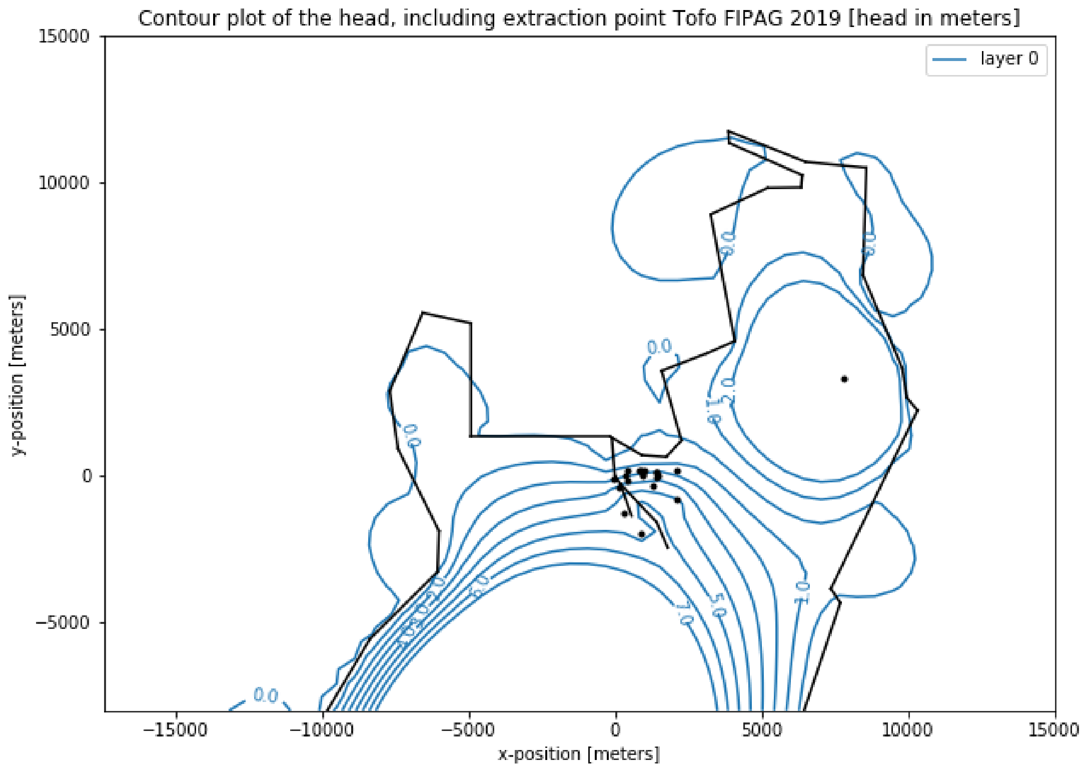
```
[ 1.89428127]
[ 2.22472997]
```




```
In [37]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
```

```
decimals=1, figsize=(10,20))
 plt.title("Contour plot of the head, including extraction point Tofo FIPAG 2019")
 plt.xlabel("x-position [meters]")
 plt.ylabel("y-position [meters]")
 plt.axis('scaled')
 plt.ylim(-8000,15000)

 print (ml.head(X_B[0], Y_B[0]))
 print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54002812]
[ 5.38998979]
```



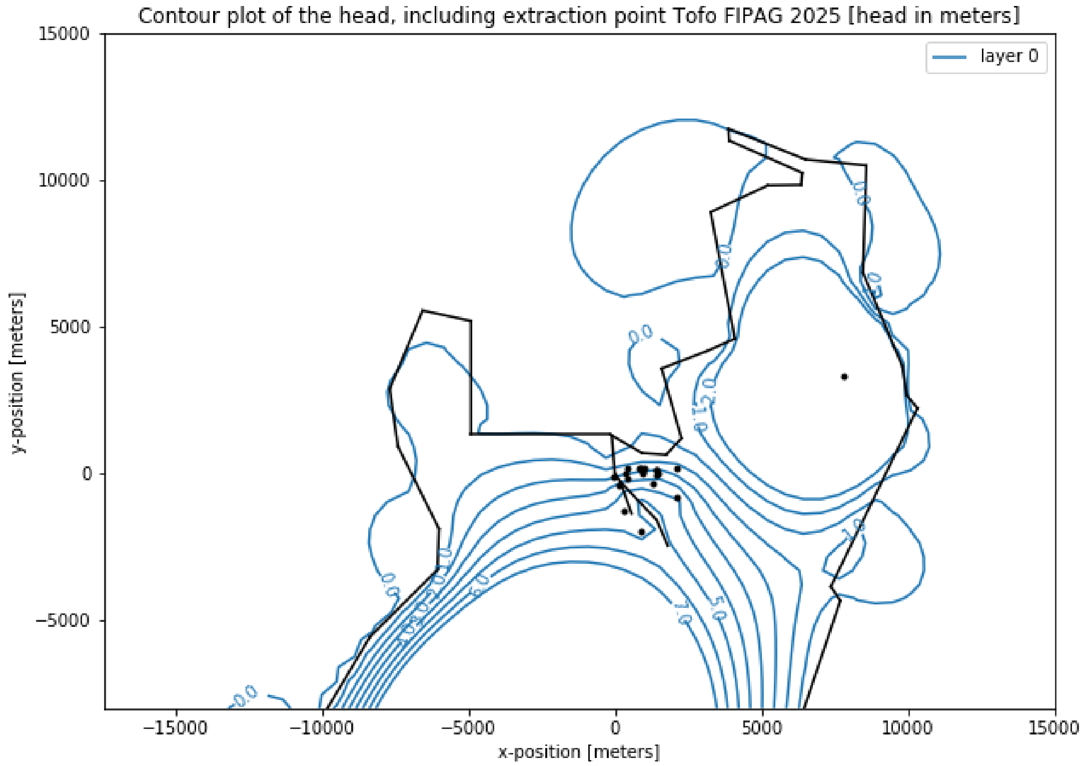

```
In [38]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
```

```
    w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
    w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
    w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
    w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
    w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
    w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
    w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
    w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

    #left side river
    h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
    h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
    h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

    #right side river
    h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
    h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


    w = Well(ml, X_BW[2], Y_BW[2], Qw=4976, rw=1.00/2)

    ml.solve(silent=True)
```

```
In [39]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including extraction point Tofo FIPAG 2025")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54004304]
[ 5.39000113]
```



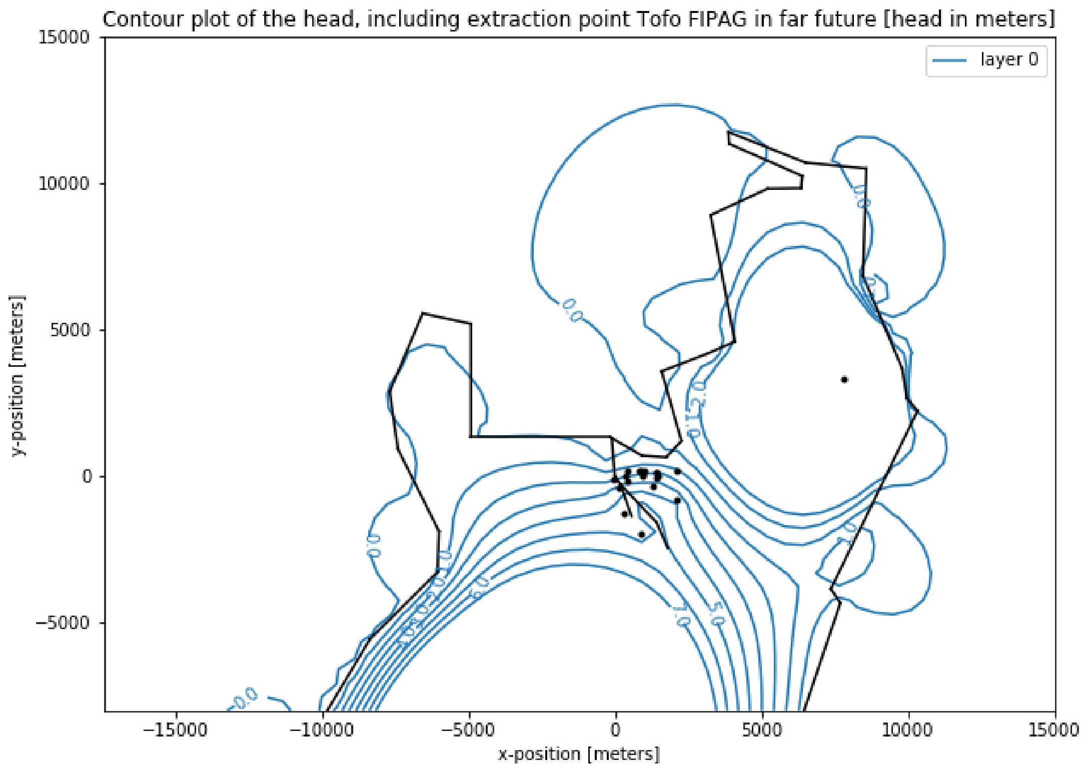

```
In [40]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
```

```python
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])
```

```
#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])


w = Well(ml, X_BW[2], Y_BW[2], Qw=7000, rw=1.00/2)

ml.solve(silent=True)
```

In [41]:
```
ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including extraction point Tofo FIPAG in future")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-8000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54005832]
[ 5.39001274]
```



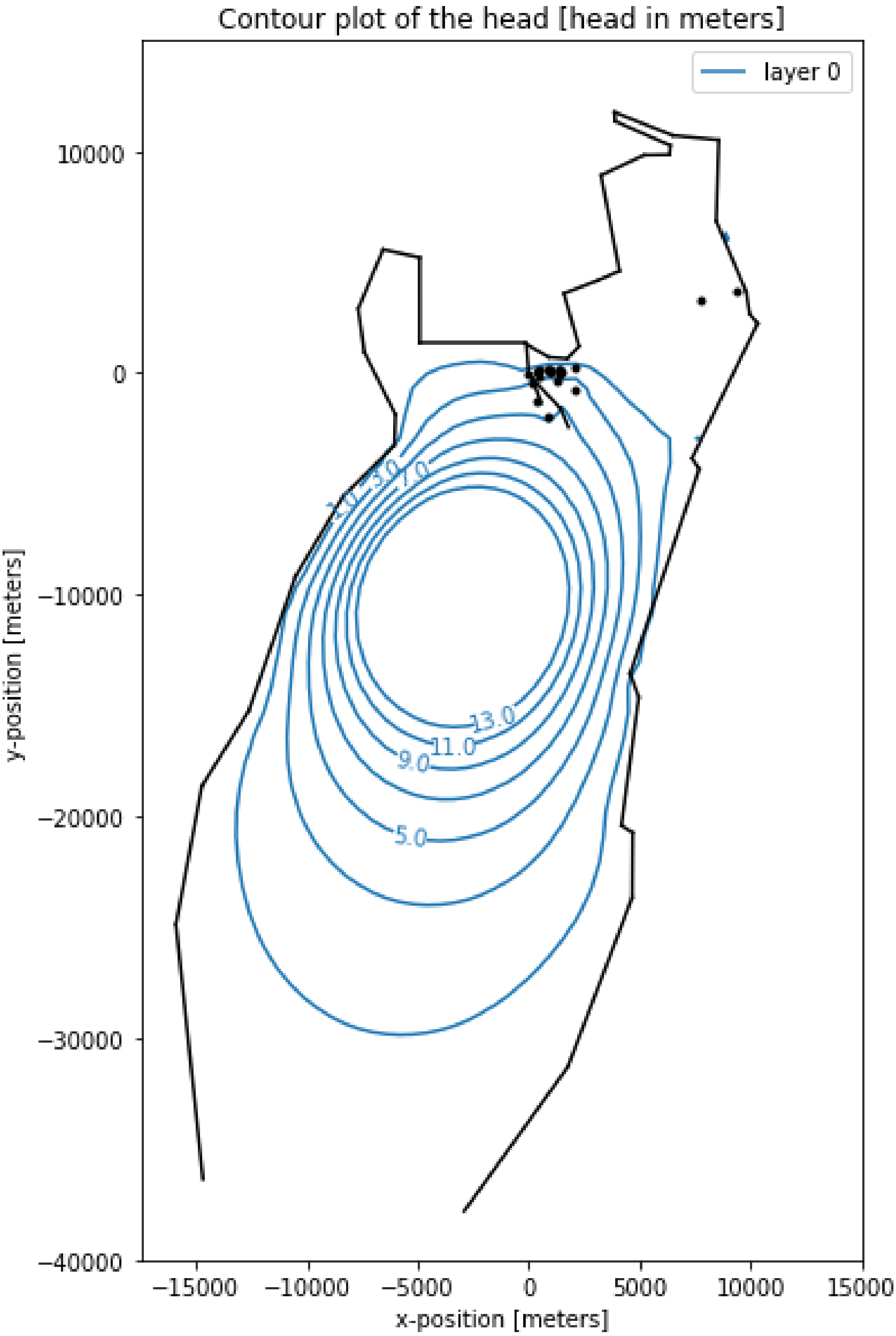
13 Influence of total boreholes Tofo (resorts and FIPAG)

```
In [42]: ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

         b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
```

```
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[1], Y_BW[1], Qw=800, rw=1.00/2)
w = Well(ml, X_BW[2], Y_BW[2], Qw=3000, rw=1.00/2)

ml.solve(silent=True)
```

In [43]:
```
ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,14,2), labels=True,
decimals=1, figsize=(10,10))
plt.title("Contour plot of the head [head in meters]")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')

print (ml.head(X[0], Y[0]))
print (ml.head(X[1], Y[1]))
```

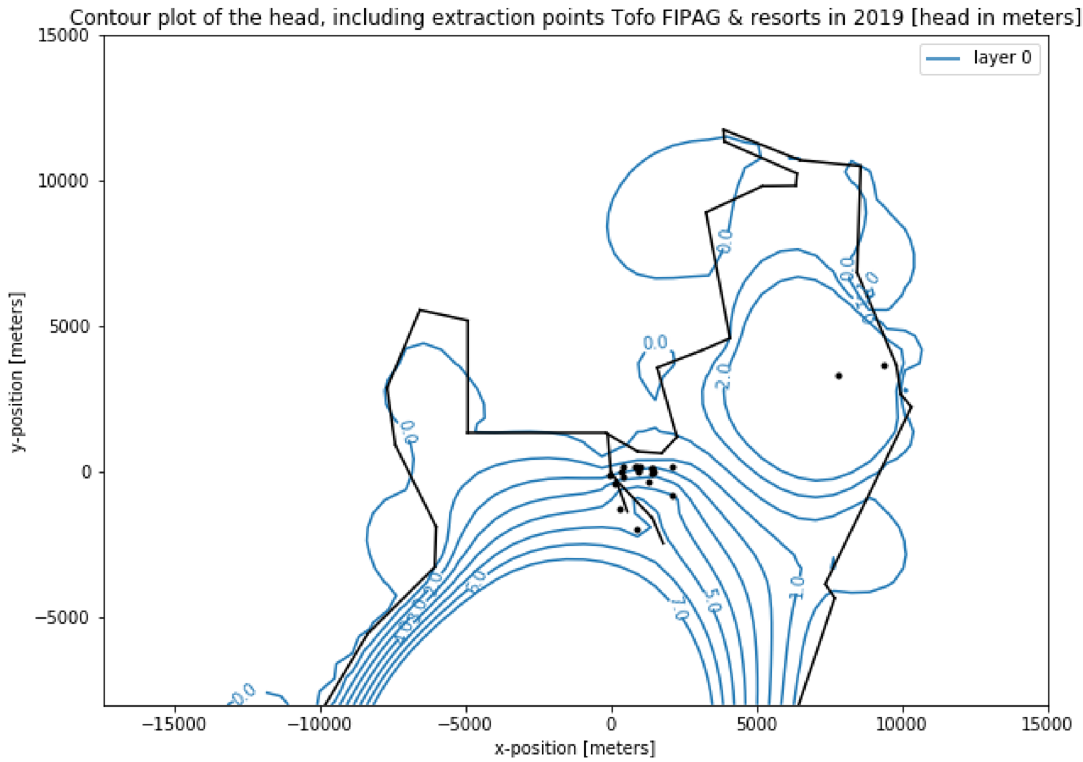
```
[ 1.89023245]
[ 2.22069999]
```




```
In [44]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
```

```
decimals=1, figsize=(10,20))
 plt.title("Contour plot of the head, including extraction points Tofo FIPAG & resorts")
 plt.xlabel("x-position [meters]")
 plt.ylabel("y-position [meters]")
 plt.axis('scaled')
 plt.ylim(-8000,15000)

 print (ml.head(X_B[0], Y_B[0]))
 print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.5400294]
[ 5.38999076]
```



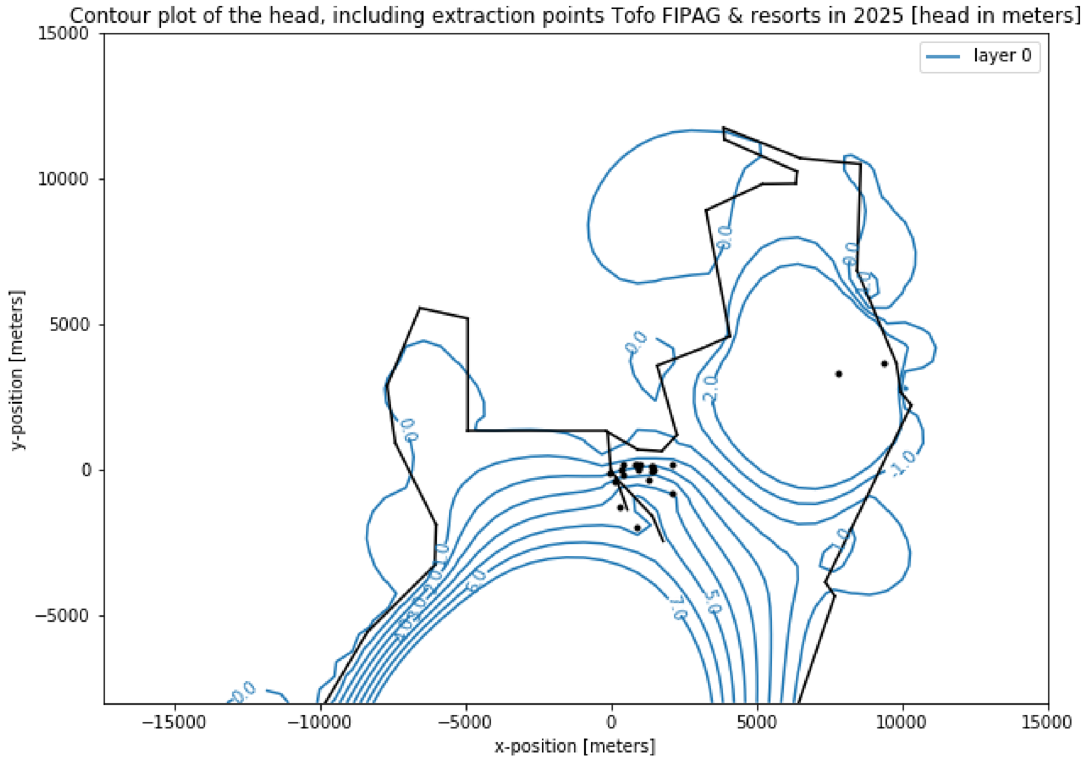
In [45]:
```
#future 2025
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
```

```
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[1], Y_BW[1], Qw=1047, rw=1.00/2)
w = Well(ml, X_BW[2], Y_BW[2], Qw=3929, rw=1.00/2)

ml.solve(silent=True)
```

```
In [46]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including extraction points Tofo FIPAG & resorts")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54003681]
[ 5.38999639]
```



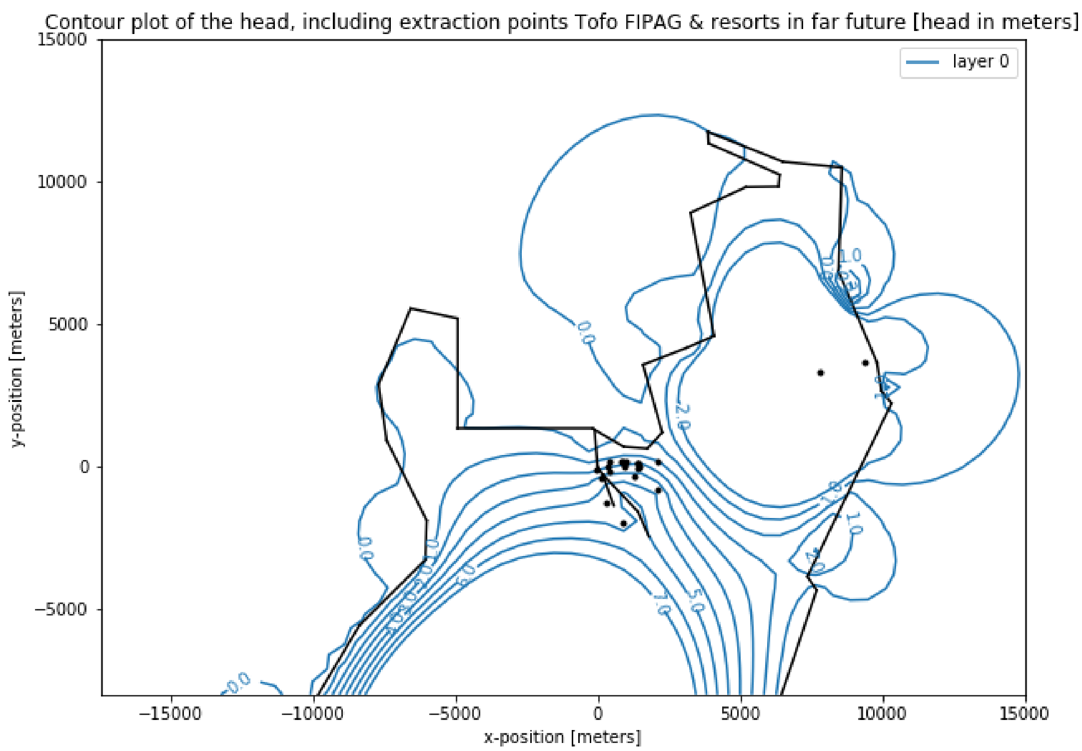
In [47]:
```
#far future
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])
```

```
#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[1], Y_BW[1], Qw=3000, rw=1.00/2)
w = Well(ml, X_BW[2], Y_BW[2], Qw=7000, rw=1.00/2)

ml.solve(silent=True)
```

```
In [48]: ml.contour([-15000,15000,-8000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including extraction points Tofo FIPAG & resorts i
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-8000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54006311]
[ 5.39001638]
```



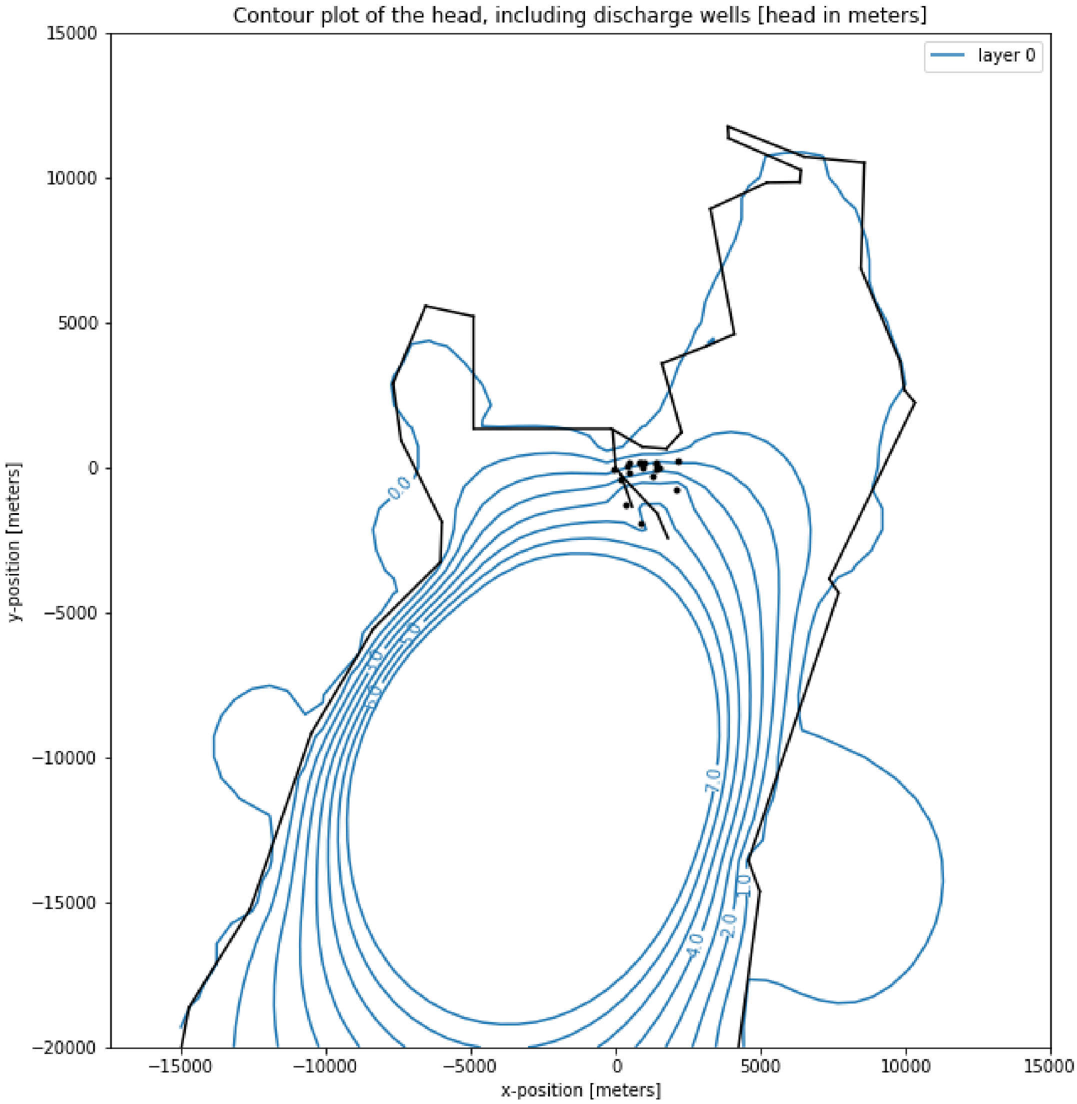
14 Influence of extraction point Guiúia river FIPAG

```
In [49]: #without extraction point
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)
```

```
b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

ml.solve(silent=True)
```

In [50]:
```
ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including discharge wells [head in meters]")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-20000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000547]
[ 5.38997257]
```



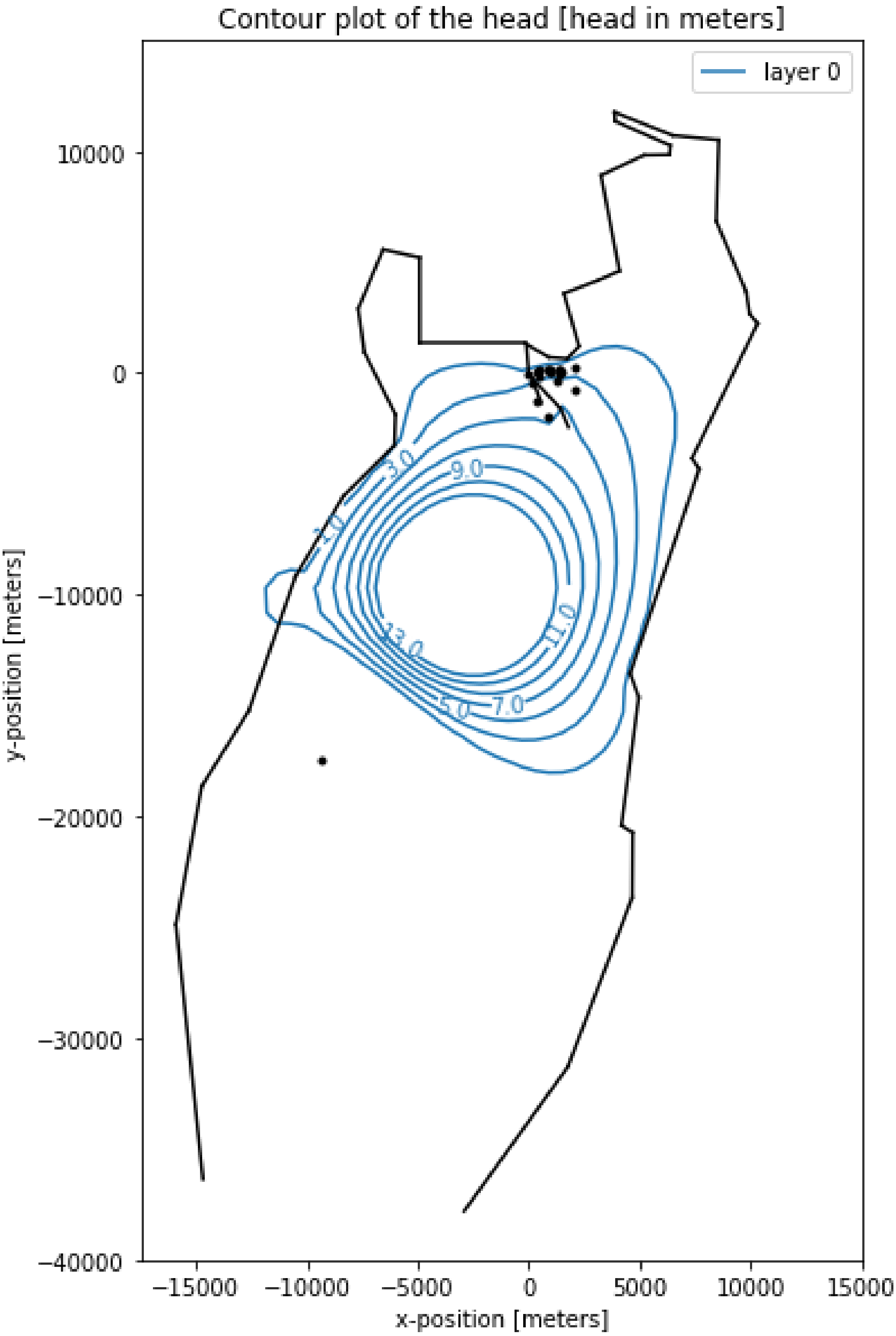

```
In [51]: #with extraction point 2019
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
```

```
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[3], Y_BW[3], Qw=6000, rw=1.00/2)


ml.solve(silent=True)
```

```
In [52]: ml.contour([-15000,15000,-40000,15000], ngr=50, levels=np.arange(1,14,2),
        labels=True, decimals=1, figsize=(10,10))
         plt.title("Contour plot of the head [head in meters]")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')

         print (ml.head(X[0], Y[0]))
         print (ml.head(X[1], Y[1]))
```

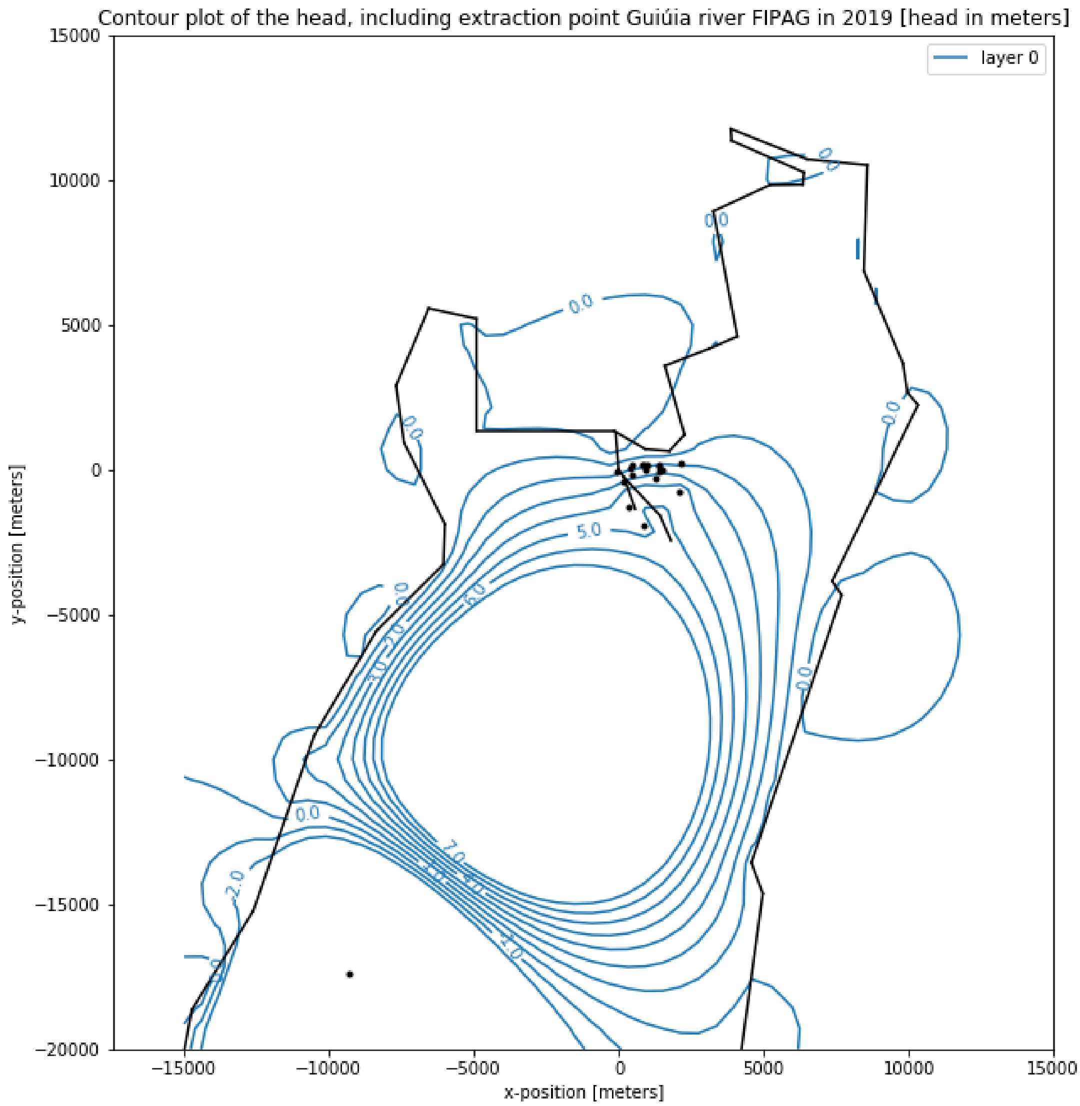
```
[ 1.96124689]
[ 2.29132382]
```




```
In [53]: ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
```

```
decimals=1, figsize=(10,20))
 plt.title("Contour plot of the head, including extraction point Guiúia river FIPAG")
 plt.xlabel("x-position [meters]")
 plt.ylabel("y-position [meters]")
 plt.axis('scaled')
 plt.ylim(-20000,15000)

 print (ml.head(X_B[0], Y_B[0]))
 print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.5400072]
[ 5.3899744]
```

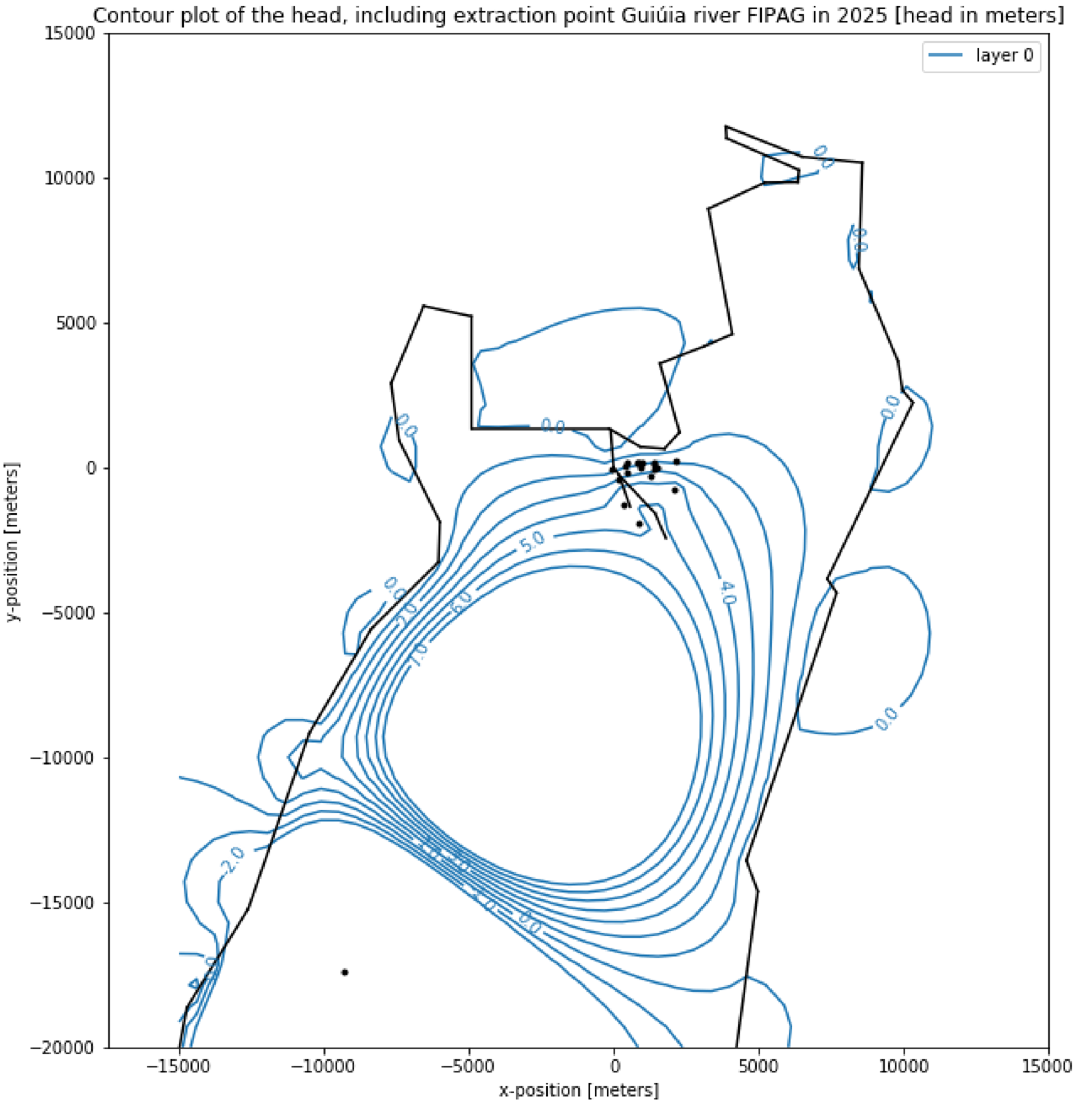


In [54]:
```python
# future 2025
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
```

```
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[3], Y_BW[3], Qw=7858, rw=1.00/2)


ml.solve(silent=True)
```

```
In [55]: ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including extraction point Guiúia river FIPAG")
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-20000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000773]
[ 5.38997496]
```



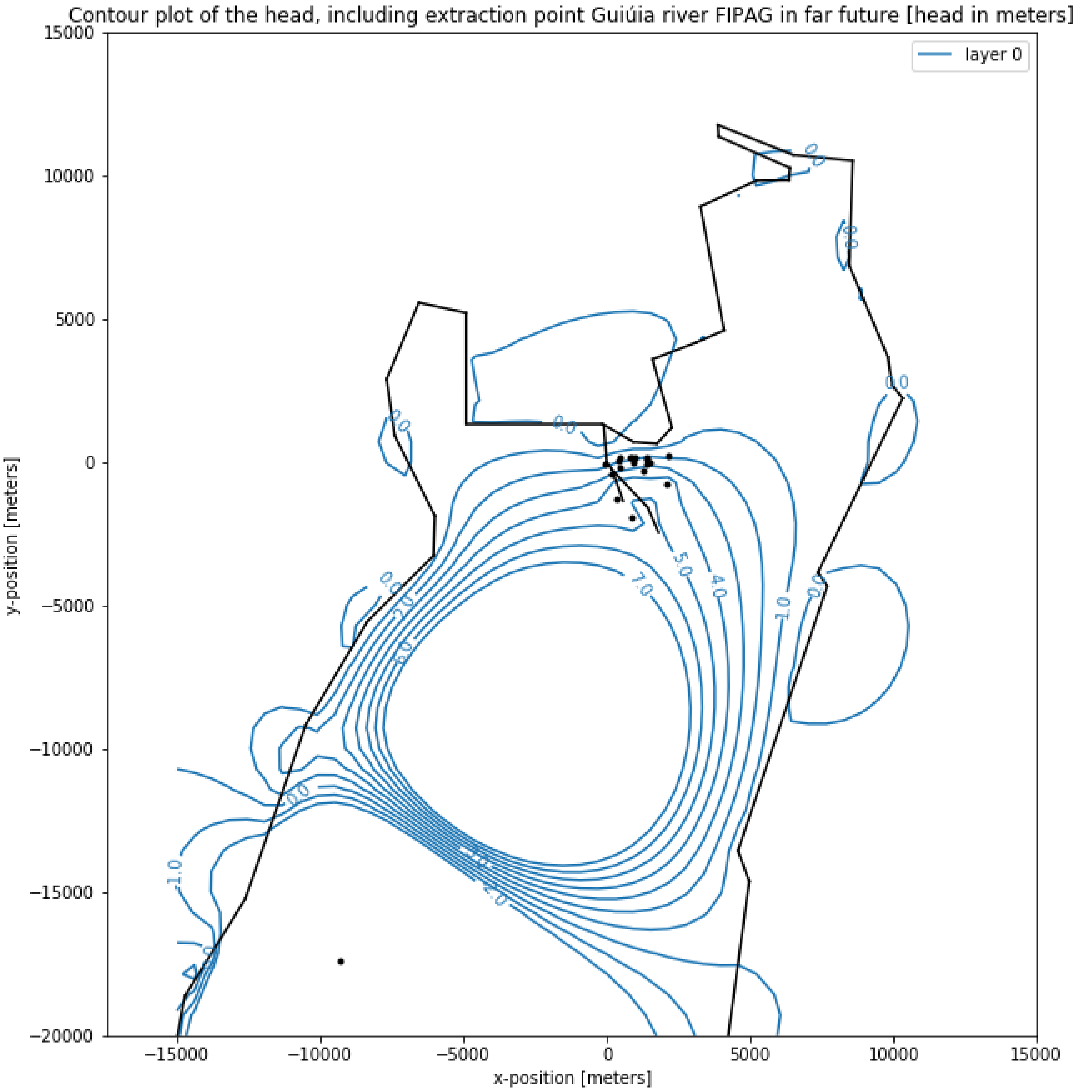

```
In [56]: # far future
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
```

```
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[3], Y_BW[3], Qw=9000, rw=1.00/2)


ml.solve(silent=True)
```

```
In [57]: ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
        decimals=1, figsize=(10,20))
         plt.title("Contour plot of the head, including extraction point Guiúia river FIPAG in f
         plt.xlabel("x-position [meters]")
         plt.ylabel("y-position [meters]")
         plt.axis('scaled')
         plt.ylim(-20000,15000)

         print (ml.head(X_B[0], Y_B[0]))
         print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54000806]
[ 5.38997531]
```



15 All boreholes together

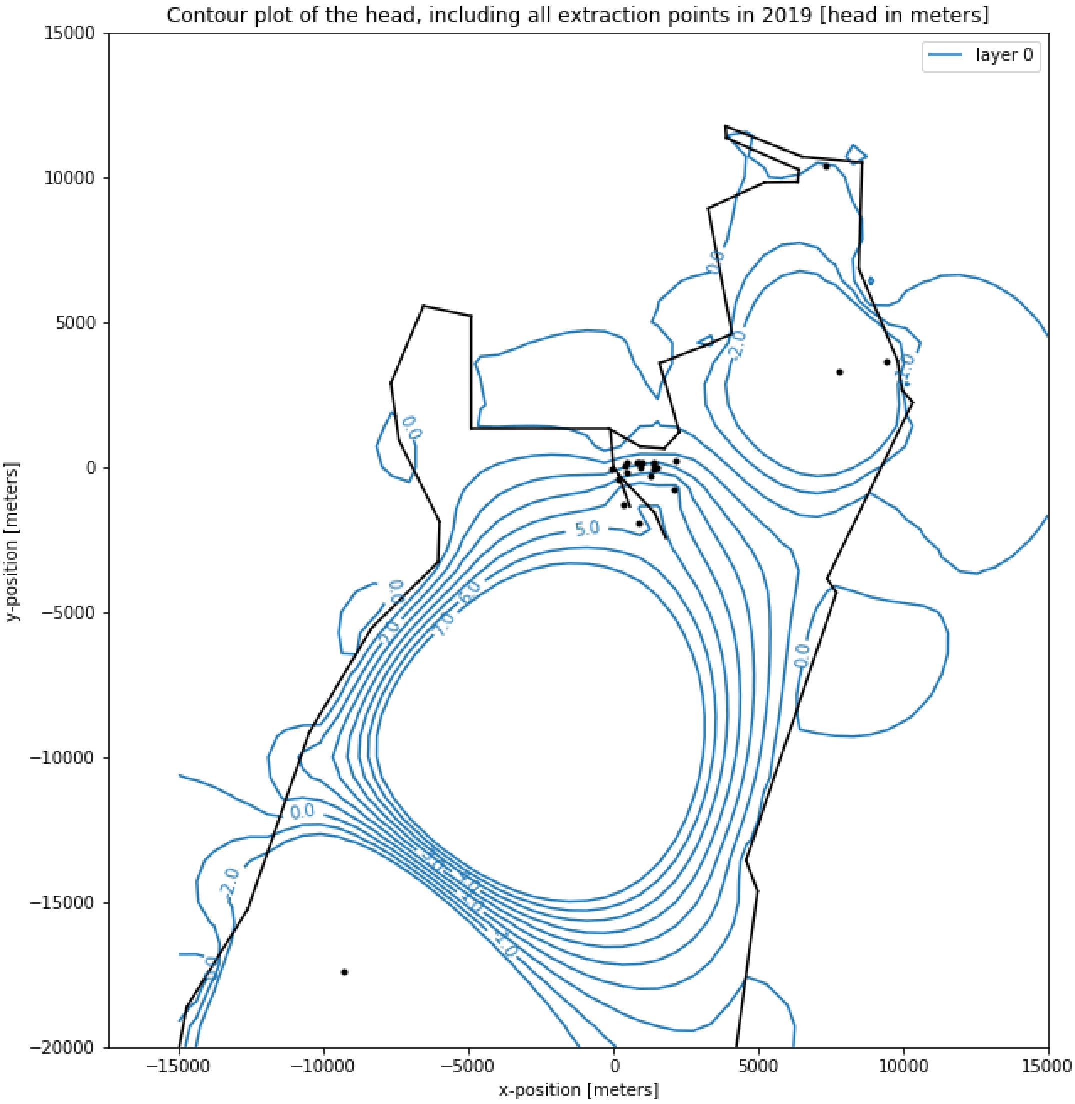
In [58]:
```
ml = ModelMaq(kaq=1, z=[0,-50])
c = Constant(ml, xr=-5000, yr=-40000, hr=0)
N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
```

```
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[0], Y_BW[0], Qw=600, rw=1.00/2)
w = Well(ml, X_BW[1], Y_BW[1], Qw=800, rw=1.00/2)
w = Well(ml, X_BW[2], Y_BW[2], Qw=3000, rw=1.00/2)
w = Well(ml, X_BW[3], Y_BW[3], Qw=6000, rw=1.00/2)

ml.solve(silent=True)
```

In [59]:
```
ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including all extraction points in 2019")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-20000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54003113]
[ 5.38999259]
```



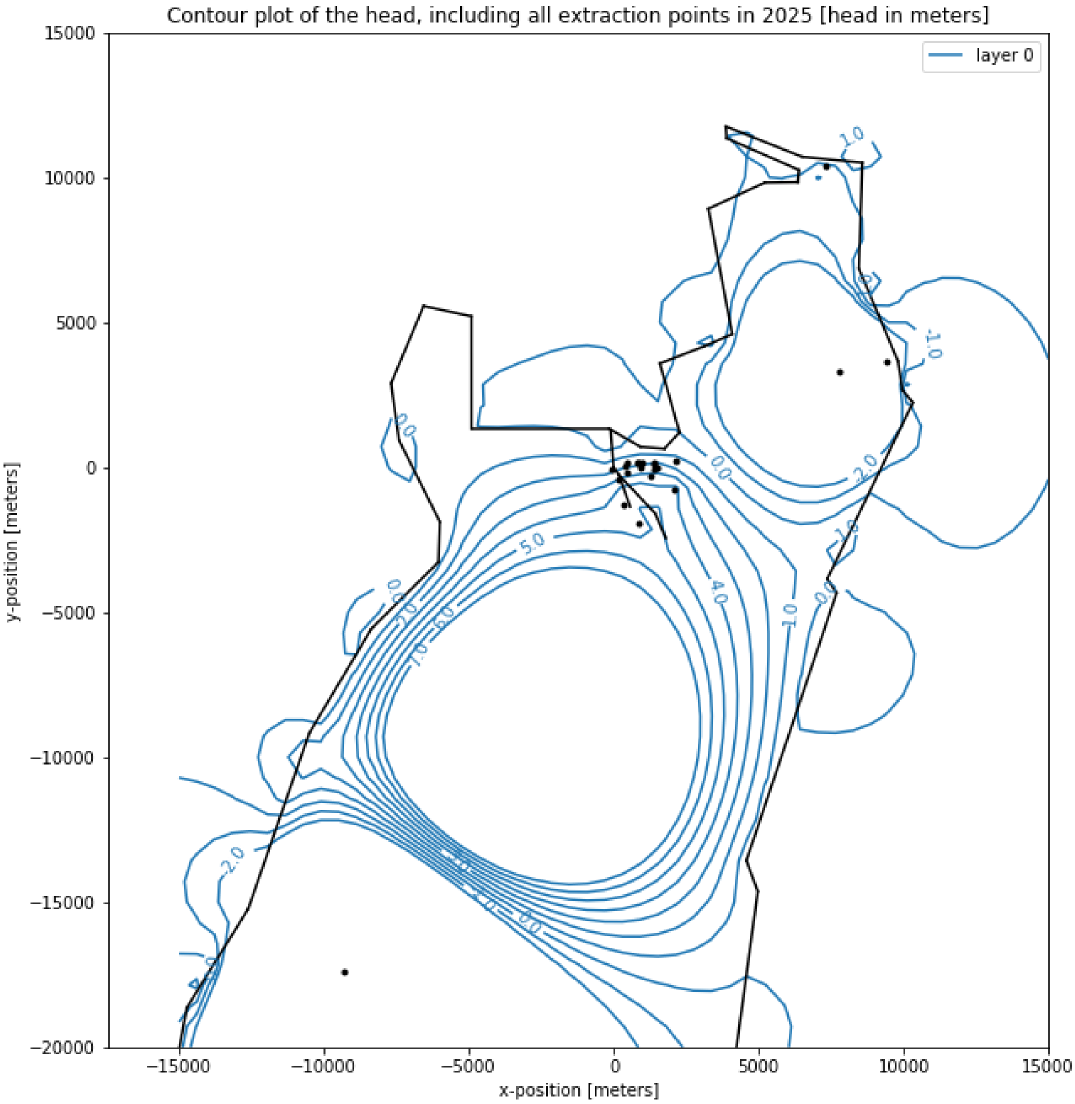

```
In [60]: #in 2025
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
```

```
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[0], Y_BW[0], Qw=785, rw=1.00/2)
w = Well(ml, X_BW[1], Y_BW[1], Qw=1047, rw=1.00/2)
w = Well(ml, X_BW[2], Y_BW[2], Qw=3929, rw=1.00/2)
w = Well(ml, X_BW[3], Y_BW[3], Qw=7858, rw=1.00/2)

ml.solve(silent=True)
```

In [61]:
```
ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including all extraction points in 2025")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-20000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54003908]
[ 5.38999879]
```



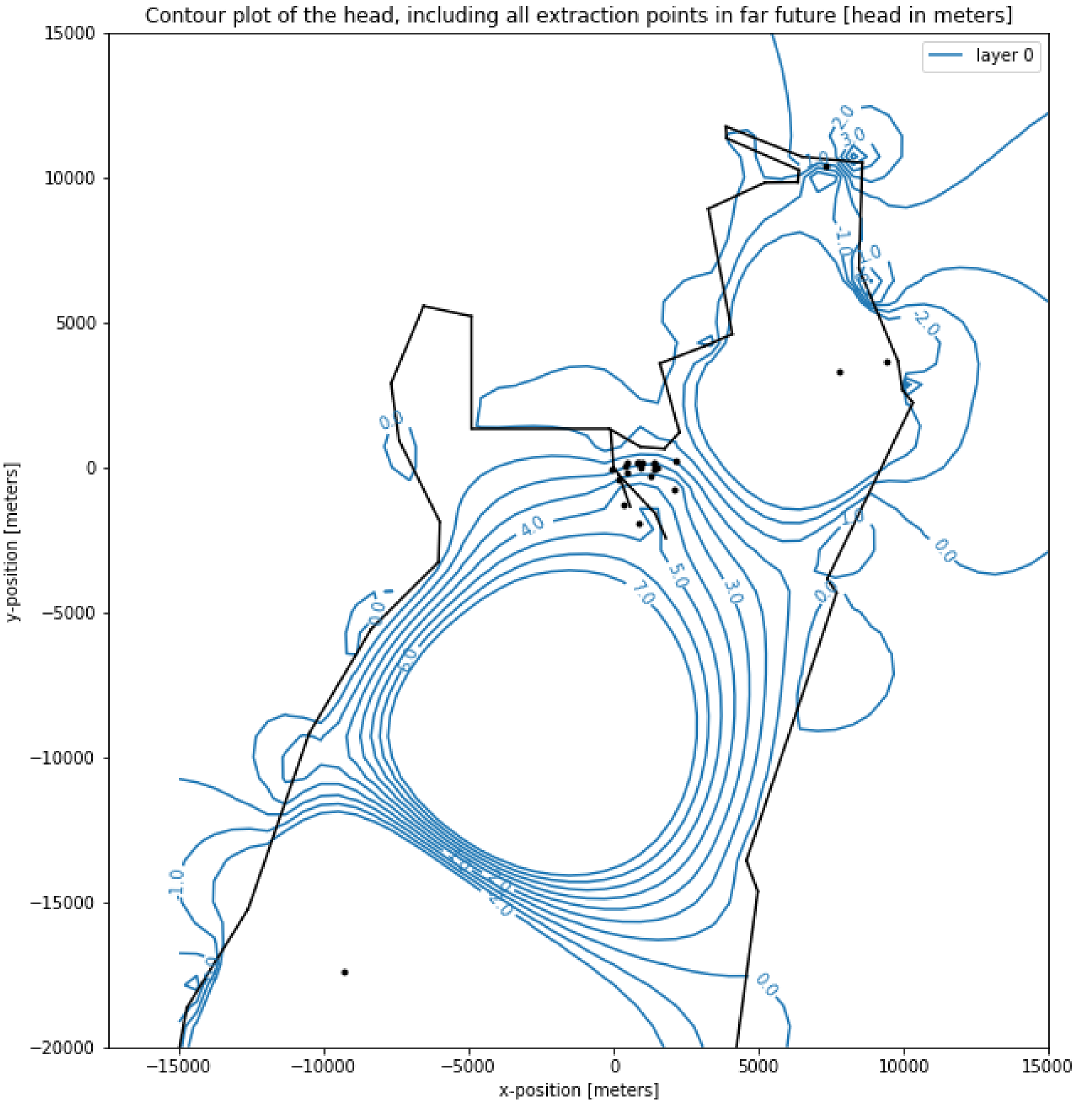

```
In [62]: #in far future
         #in 2025
         ml = ModelMaq(kaq=1, z=[0,-50])
         c = Constant(ml, xr=-5000, yr=-40000, hr=0)
         N = CircAreaSink(ml, xc=-3324.3, yc=-10000, R=1000, N=0.002)

         h = HeadLineSinkString(ml, xy=[(X_S[14],Y_S[14]), (X_S[15],Y_S[15])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[15],Y_S[15]), (X_S[16],Y_S[16])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[16],Y_S[16]), (X_S[17],Y_S[17])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[17],Y_S[17]), (X_S[18],Y_S[18])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[18],Y_S[18]), (X_S[19],Y_S[19])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[19],Y_S[19]), (X_S[20],Y_S[20])], hls=0)
         h = HeadLineSinkString(ml, xy=[(X_S[20],Y_S[20]), (X_S[21],Y_S[21])], hls=0)
```

```
h = HeadLineSinkString(ml, xy=[(X_S[21],Y_S[21]), (X_S[22],Y_S[22])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[22],Y_S[22]), (X_S[23],Y_S[23])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[23],Y_S[23]), (X_S[24],Y_S[24])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[24],Y_S[24]), (X_S[25],Y_S[25])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[25],Y_S[25]), (X_S[26],Y_S[26])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[26],Y_S[26]), (X_S[27],Y_S[27])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[27],Y_S[27]), (X_S[28],Y_S[28])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[28],Y_S[28]), (X_S[29],Y_S[29])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[29],Y_S[29]), (X_S[30],Y_S[30])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[30],Y_S[30]), (X_S[31],Y_S[31])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[31],Y_S[31]), (X_S[32],Y_S[32])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[32],Y_S[32]), (X_S[33],Y_S[33])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[33],Y_S[33]), (X_S[34],Y_S[34])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[34],Y_S[34]), (X_S[35],Y_S[35])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[35],Y_S[35]), (X_S[36],Y_S[36])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[36],Y_S[36]), (X_S[37],Y_S[37])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[37],Y_S[37]), (X_S[38],Y_S[38])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[38],Y_S[38]), (X_S[39],Y_S[39])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[39],Y_S[39]), (X_S[40],Y_S[40])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[40],Y_S[40]), (X_S[0],Y_S[0])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[0],Y_S[0]), (X_S[1],Y_S[1])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[1],Y_S[1]), (X_S[2],Y_S[2])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[2],Y_S[2]), (X_S[3],Y_S[3])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[3],Y_S[3]), (X_S[4],Y_S[4])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[4],Y_S[4]), (X_S[5],Y_S[5])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[5],Y_S[5]), (X_S[6],Y_S[6])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[6],Y_S[6]), (X_S[7],Y_S[7])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[7],Y_S[7]), (X_S[8],Y_S[8])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[8],Y_S[8]), (X_S[9],Y_S[9])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[9],Y_S[9]), (X_S[10],Y_S[10])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[10],Y_S[10]), (X_S[11],Y_S[11])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[11],Y_S[11]), (X_S[12],Y_S[12])], hls=0)
h = HeadLineSinkString(ml, xy=[(X_S[12],Y_S[12]), (X_S[13],Y_S[13])], hls=0)

b1 = HeadWell(ml, X_B[0], Y_B[0], hw=h_b[0])
b2 = HeadWell(ml, X_B[1], Y_B[1], hw=h_b[1])
b3 = HeadWell(ml, X_B[2], Y_B[2], hw=h_b[2])
b4 = HeadWell(ml, X_B[3], Y_B[3], hw=h_b[3])
b5 = HeadWell(ml, X_B[4], Y_B[4], hw=h_b[4])
b6 = HeadWell(ml, X_B[5], Y_B[5], hw=h_b[5])
b7 = HeadWell(ml, X_B[6], Y_B[6], hw=h_b[6])

w1 = Well(ml, xw=X[0], yw=Y[0], Qw=Q_w[0],  rw=0.55/2)
w2 = Well(ml, xw=X[1], yw=Y[1], Qw=Q_w[1],rw=0.55/2)
w3 = Well(ml, xw=X[2], yw=Y[2], Qw=Q_w[2],rw=0.61/2)
w4 = Well(ml, xw=X[3], yw=Y[3], Qw=Q_w[3],rw=1.4/2)
w5 = Well(ml, xw=X[4], yw=Y[4], Qw=Q_w[4],rw=0.7/2)
w6 = Well(ml, xw=X[5], yw=Y[5], Qw=Q_w[5],rw=0.55/2)
```

```
w7 = Well(ml, xw=X[6], yw=Y[6], Qw=Q_w[6], rw=1.06/2)
w8 = Well(ml, xw=X[7], yw=Y[7], Qw=Q_w[7],rw=1.00/2)
w9 = Well(ml, xw=X[8], yw=Y[8], Qw=Q_w[8], rw=0.60/2)
w10 = Well(ml, xw=X[9], yw=Y[9], Qw=Q_w[9], rw=0.59/2)
w11 = Well(ml, xw=X[10], yw=Y[10], Qw=Q_w[10], rw=0.55/2)
w12 = Well(ml, xw=X[11], yw=Y[11], Qw=Q_w[11], rw=0.60/2)

#left side river
h41 = HeadLineSinkString(ml, xy=[(X_R[0],1300), (X_R[1],Y_R[1])], hls=[0, -1.67])
h42 = HeadLineSinkString(ml, xy=[(X_R[1],Y_R[1]), (X_R[2],Y_R[2])], hls=[-1.67, 6.02])
h43 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[3],Y_R[3])], hls=[6.02, 2.76])

#right side river
h44 = HeadLineSinkString(ml, xy=[(X_R[2],Y_R[2]), (X_R[4],Y_R[4])], hls=[6.02, 4.44])
h45 = HeadLineSinkString(ml, xy=[(X_R[4],Y_R[4]), (X_R[5],Y_R[5])], hls=[4.44, 6.12])

w = Well(ml, X_BW[0], Y_BW[0], Qw=2500, rw=1.00/2)
w = Well(ml, X_BW[1], Y_BW[1], Qw=3000, rw=1.00/2)
w = Well(ml, X_BW[2], Y_BW[2], Qw=7000, rw=1.00/2)
w = Well(ml, X_BW[3], Y_BW[3], Qw=9000, rw=1.00/2)

ml.solve(silent=True)
```

```
In [63]: ml.contour([-15000,15000,-20000,15000], ngr=50, levels=np.arange(-2,8,1),labels=True,
decimals=1, figsize=(10,20))
plt.title("Contour plot of the head, including all extraction points in far future")
plt.xlabel("x-position [meters]")
plt.ylabel("y-position [meters]")
plt.axis('scaled')
plt.ylim(-20000,15000)

print (ml.head(X_B[0], Y_B[0]))
print (ml.head(X_B[1], Y_B[1]))
```

```
[ 4.54006575]
[ 5.39001915]
```



Contour plot of the head, including all extraction points in far future [head in meters]
layer 0
x-position [meters]
y-position [meters]
15000
10000
5000
0
−5000
−10000
−15000
−20000
−15000
−10000
−5000
0
5000
10000
15000
4.0
5.0
7.0
3.0
6.0
0.0
1.0
-1.0
-2.0
2.0

6. ESUDER Case-days

Photos of Case-days

Figure 22: ESUDER – Case-days

List of participants

Name	E-Mail
Paulina Adolfo	paulinaadolfo15@gmail.com
Silvia Mbula	silvialickstipmiguel@gmail.com
Fernando Seneta	seneta195@gmail.com
Andre Castene	andrecmopageriua@gmail.com
Elcio Rosse	tropadalinha07@gmail.com
Jacinto Matsinhe	jacintoeliasmatsinhe@gmail.com
Cristoveo Come	cristovaocome@gmail.com
Dario Lourenco	dario.lourenco@gmail.com
Salvador Mulhanga	salvador.12mulhanga@gmail.com
Claudio Simbine	simbineclaudio@gmail.com
Aldimiro Jorge	aldimirosamuel@gmail.com
Belquissa de Almeida	belquissealmeida@yahoo.com

Assignment Case Days

Water Quality Assignment – Esudar University

Groundwater is used for multiple functions in the area of Machavenga. The people are not connected to a water connection and rely on the water from the wells. Some of these wells, have different functions for water usage. Management and control of water in rural areas is of great importance. For every function, different parameters are more relevant than others.

1. Which functions can water from wells fulfill in rural areas? Do you have an idea which parameters are of importance for these functions? Which function do you think has the highest water quality standard and which the lowest?

2. Relatively, groundwater is of good quality and could sometimes directly be used for the described functions above. However, sometimes this groundwater could be polluted by anthropogenic industrial, agricultural or domestic activities. Moreover, water quality parameters can also change by natural processes.
   Which kind of processes can you imagine that might affect the functions of water? What kind of change in parameters would you expect?

3. Now it is time to start measuring, because measuring is knowing ('meten is weten' in Dutch). Note down the values of the parameters measured.

4. What are the most interesting measured values? Can you give an explanation why this value is so interesting?

   December is the start of the rain season. Imagine it will rain the coming 5 days and 5mm each day. What will be the new measured values? Assume no abstraction is taking place.

Rainwater composition	
Parameter	**Concentration [mg/L]**
Nitrate	0,1
Dissolved Oxygen	4,0
Phosphate	0

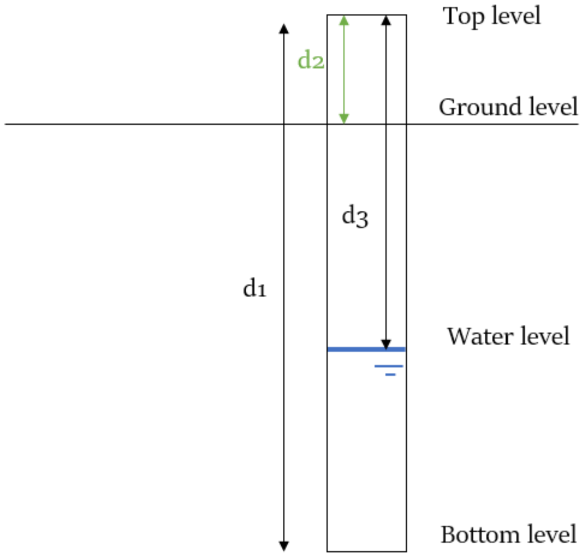
5. What do you expect the new measured values would be? For some answers, you can calculate. For some answers, you can estimate.
6. What do you expect if there is no rain, but hot, dry and sunny days. What will the concentrations be in this case?

Geohydrological Assignment – Esudar University

Welcome to the geohydrological part of the day! The goal of this assignment is to get insight into the direction of groundwater flow with the use of three wells.

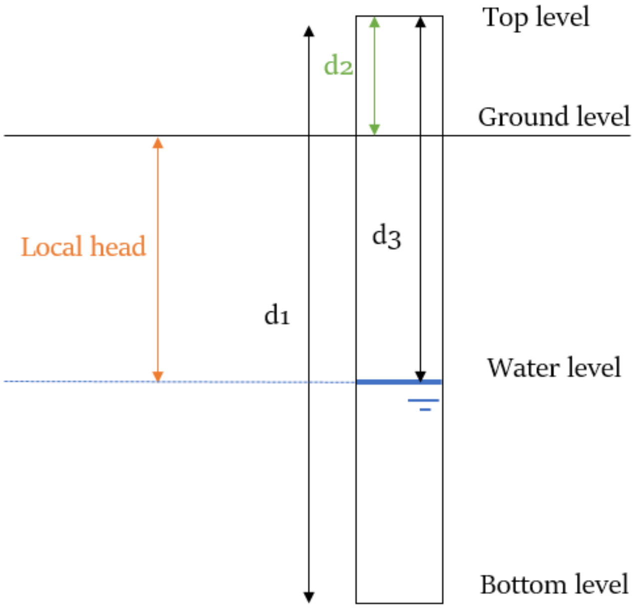
Question 1: Perform the level measurements at each well

For these measurements we provide you the following tool:



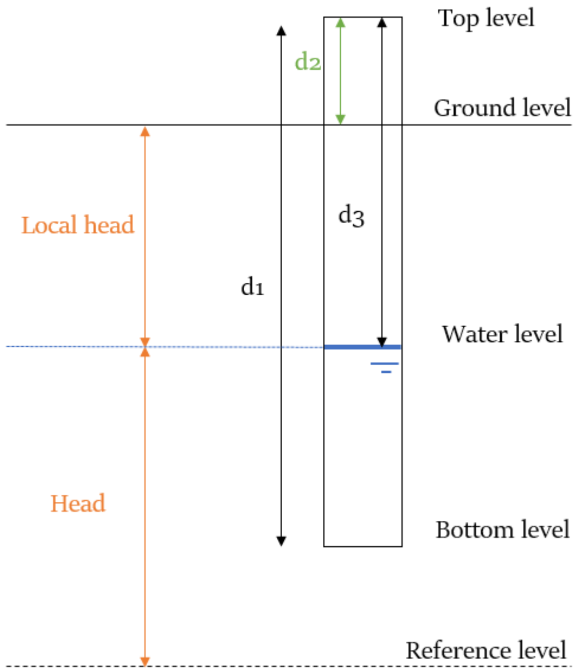
Measurements	Well 1	Well 2	Well 3
Bottom level to top level [m]			
Water level to top level [m]			
Ground level to top level [m]			
Diameter [m]			

Question 2: Calculate the local heads of the wells



	Well 1	Well 2	Well 3
Local head [m]			

Question 3: Calculate the heads relative to the given reference level

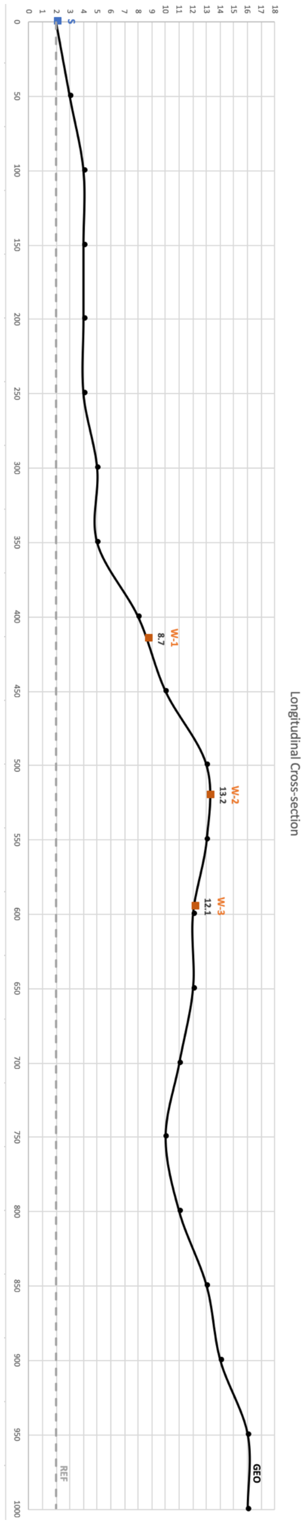


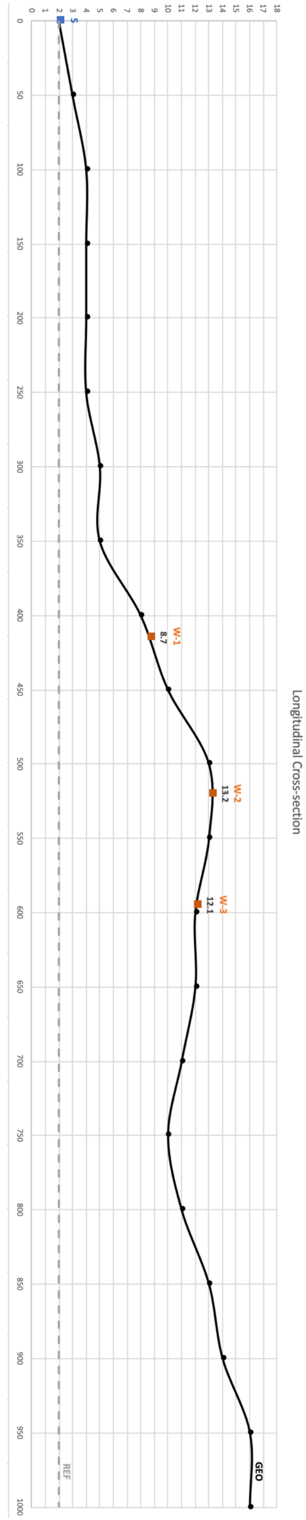
	Well 1	Well 2	Well 3
Head to reference level [m]			
Reference level (sea) [m]	2,0	2,0	2,0
Ground level (geo) [m]	8,7	13,2	12,1

Question 4: Use the following cross-section to make predictions about the flow direction

For this question a longitudinal cross-section in given on the next page

a) Draw the heads (to reference level) of each well
b) Draw the water table over the cross-section
c) Predict the flow direction(s)
d) Where would you place a latrina? Please motivate your answer.
e) Where would you place an additional well? Please motivate your answer.


Longitudinal Cross-section
S
W-1
8.7
W-2
13.2
W-3
12.1
GEO
REF


Longitudinal Cross-section
S
W-1
8.7
W-2
13.2
W-3
12.1
GEO
REF

1

Question 5: Use Darcy's Law to calculate the flow direction in the cross-section

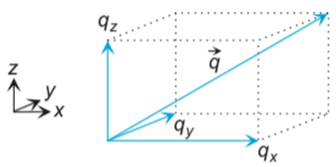
For this question some assumptions should be made in order to make a calculation:

There are three wells (W-1, W-2, W-3) in a sand aquifer as shown in the longitudinal cross-section of Question 4. The heads at them are calculated in Question 3.

The rate of recharge (R) here is estimated to be 0.004 m/day. The average horizontal hydraulic conductivity (Kx) of the sand is estimated to be 5 m/day, based on typical values of soil types (Davis, 1969).

Assume that in the area of these three wells, the vertical specific discharge (qz) equals the recharge rate (R).

Now make use of Darcy's Law: $q_s = -K_s * \frac{dh}{ds}$ in three dimensions:



$$q_x = -K_x \frac{\partial h}{\partial x}$$

$$q_y = -K_y \frac{\partial h}{\partial y}$$

$$q_z = -K_z \frac{\partial h}{\partial z}$$

$$|\vec{q}| = \sqrt{q_x^2 + q_y^2 + q_z^2}$$

a) Estimate the vertical hydraulic conductivity (Kz) using the heads at wells W-1 and W-2.
b) Estimate the horizontal specific discharge (qx) using the heads at wells W-1 and W-3.
c) Make a scaled vector sketch showing the x and z components of specific discharge, and the total specific discharge vector $\vec{q}$ (assume that there is no flow in the y direction).

Follow up – Esudar University

We have shown you a small part of our research with this assignment. Of course, this kind of research can be elaborated to larger scale with other scenarios.

- Could you think of a good idea for a follow up of this research?

- How could you use this method for other research?

- Do you think this can be done anywhere else?

- How can the water quality measurements become more accurate?

- How can the ground water model be build more accurate?

We would like to thank you for joining us this day and we hope you liked what we have shown you today. We definitely did!