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Consolidate Learning from the Salinity Ingress Prevention Measures undertaken in the Coastal Area of Gujarat

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PARTNERS VOOR WATER Bundeling van krachten
ARCADIS Infrastructure, environment, buildings
Deltares Enabling Delta Life
TU Delft Delft University of Technology
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IRAP INSTITUTE FOR RESOURCE ANALYSIS AND POLICY

Table of contents

Acknowledgements

The performed study about the effectiveness of the various measures against seawater intrusion is vital for the sustainable development of the region of Saurashtra in Gujarat. Saline groundwater causes socio-economic and environmental problems and may form a health hazard for the people in the affected areas in Gujarat. I hope that this study acts as an incentive for the people of Gujarat to raise awareness and to set up an integrated groundwater management approach program in order to control the salinity ingress. Many thanks to Alka Palrecha who was responsible for all the logistics as well as setting up workshops and supporting the contacts of stakeholders and experts. Also, I would like to thank the people of the Ambuja Cement Foundation at Kodinar who helped me during my stay there. Without the patience and energy of Frank van Weert, this study could not have been a success; thanks for your editorial remarks. Gualbert Oude Essink and Marta Fanèca Sanchez are responsible for building the 3D-groundwater solute transport model. Without their dedication and help there would not be any results. Thanks to Tom Pieterse for his visit in India and his efforts for the analysis of the coastal area of Saurashtra. Finally, many thanks to Arjan ter Harmsel who has made it possible to start up the project.

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Jeroen Posthumus *(his contribution to this study forms his thesis research in order to obtain a MSc-degree in Earth Sciences at the Utrecht University, The Netherlands)*

This study is conducted by a consortium of Dutch and Indian organizations concerned with groundwater salinization and coastal aquifer management. The Dutch partners acknowledge that without the local knowledge and network of the Indian partners this study could not have materialized. The unlimited support and coordination by the people of the ACF head office and the Kodinar field office is greatly acknowledged. The knowledge brought into the study by Mr Kumar of IRAP is much appreciated. The sharing of data and the information given by various organizations like the Ambuja Cement Limited and CSPC is acknowledged. The people's contribution to discussions during the various workshops and work review is acknowledged.

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Summary

The increasing salinity of land and water resources in the coastal areas of Saurashtra is a matter of grave concern for the Government in Gujarat. Salinization of groundwater causes socio-economic and environmental problems. Although already recognized by the Recharge Committee and the High-level Committees I and II in the early 1970s, still much work has to be done. However, the Salinity Ingress Prevention and Control along with some NGOs have constructed artificial recharge structures to arrest the salinity ingress. A joint effort by Deltares, IGRAC, Arcadis and the Ambuja Cement Foundation made it possible to perform a study for the salinity ingress problem. This study has got the objective to investigate the effectiveness of these artificial recharge structures to control the salinity ingress in the Kodinar region by developing a density driven groundwater solute transport model. Furthermore a qualitative analysis was carried out to investigate the salinization in the entire coastal area of Saurashtra by use of a simple groundwater balance approach.

The model predicts for the reference scenario (stagnant situation) that the coastal region becomes fresher due to a positive groundwater balance based on the fact that only average years in terms of precipitation were used. As a consequence the seawater front does not seem to be moving towards inland although the model constraint that the cell dimensions are not adequate could also cause this. Incorporating dry years into the model could show other results and would level out the positive groundwater balance to zero. There is also up-coning in the upper areas where basalt is present. A low permeability combined with drainage cause this. Although the model results are not satisfactory for the reference case, the comparison between the various scenarios was very useful. It can be concluded that the use of artificial recharge structures along with drip irrigation are beneficial. The future outlook that the region becomes drier, the sea level rises and the fact that there is an increase in population have got strong negative implications for the salinity ingress problem.

Assessment of the qualitative analysis of the coastal area of Saurashtra does not lead to valid conclusions as there was no correlation between the groundwater balance and the fraction saline area. This was caused by the fact that river fluxes could not be determined. However, the region of Kodinar and Talaja are gravely affected by salinity although the amount of storage of artificial recharge structures is very high. There is a lot of agricultural activity in these areas perhaps due to these artificial recharge structures. Probably in dry years the level of agricultural activity is maintained. This leads to a strong negative impact on the groundwater balance. It may therefore be concluded that the additional groundwater obtained from artificial recharge structures could act as a perverse incentive to use this water for additional agricultural activity making these areas very sensitive to salinization whenever a dry year occurs.

In order to obtain reliable model results it is recommended that TDS-concentration and water table measurements should be measured in observation wells and more frequent to obtain an idea how the groundwater system works. More pump tests should be conducted to obtain more accurate hydraulic parameters of the soil. Additionally infiltration measurements and water heights of the river should be taken in order to determine a more reliable flux from checkdams, rivers and percolation tanks. It is recommended that water saving techniques like drip irrigation should be developed. Also additional artificial recharge structures are needed to control the salinity ingress problem. But most importantly, But most importantly, installation of a groundwater management approach program is recommended by integrating the various stakeholders, experts and the government into an organization which is responsible for the

salinity ingress problem and the availability of fresh groundwater as a sustainable natural resource. Only by doing this the salinity ingress problem can be controlled efficiently.

1 Introduction

1.1 Background and problem description

The rise of the agricultural production, population growth and the economic prosperity in the region of coastal area of Saurashtra, Gujarat, has put pressure on the available natural resources. One of the natural resources is fresh water, including both surface water and groundwater. Depletion of this natural resource causes not only socio-economic problems but also environmental problems. Since the early 1970s the Government of Gujarat showed concern for the salinization of the coastal groundwater aquifers. A survey was carried out by the State Government in collaboration with the Physical Research Laboratory and the Central Ground Water Board. The survey observed that the salinity of the groundwater had become worse due to subsurface seawater intrusion and vertical percolation of saline water along the surface waters.

The salinity problem was investigated further by the Recharge Committee in 1972, the High level Committee-1 in 1975 and the High Level Committee-2 in 1978. The major cause of the depletion of groundwater and the salinity ingress is thought to be the over-drafting of groundwater for agriculture. Recommendations were made to deal with salinity ingress problem. Despite many efforts, these recommendations have been implemented only partially. The Salinity Ingress Prevention and Control (SIPC of the Irrigation department in the Narmada Water Resources, Water Supply and Kalpsar Department) has managed to construct engineering works in order to control the salinity ingress and to improve fresh water availability by constructing artificial recharge structures. Also, on the community level, various NGOs like ACF, AKRSP(I) and VRTI have made efforts to control salinity and to protect the livelihoods of the people of Saurashtra. The NGOs' efforts with respect to salinity ingress preventions in Gujarat are coordinated from the Coastal Salinity Prevention Cell (CSPC). There is regular cooperation and coordination between CSPC and the GoG. Figure 1-1 displays the several stakeholders of the "salinity ingress" problem.

Financed by Partners for Water, a study can be set up to investigate the salinity ingress problems in the coastal area of Saurashtra. A joint effort between IRAP, CSPC, ACF and the Dutch partners Arcadis, Deltares, IGRAC and the Delft University of Technology has been made to perform this study.

This study first of all focuses on the Kodinar area where the governmental and NGOs' efforts to stop groundwater salinity have been extensive. Positive results of the implemented program have been observed here. However, it is also observed that the benefits decline substantially when there is a drought (and there are frequent droughts in this area). Despite the efforts of the various NGOs, committees and other institutions, the number of non-white talukas, i.e. the talukas with unsafe level of groundwater abstraction, has increased from 5 in 1984 to 21 in 1997 in the coastal region of Saurashtra. Moreover, it is assumed that the salinity situation will become more critical in future through an increasing water demand and effects of climate change like sea level rise.

Secondly this study focuses on the whole coastal stretch of Saurashtra that appeared to be prone to salinization. In the talukas other than Kodinar, the amount of effort to deal with salinization has been less. Still, it is intended to install measures in these talukas as was recommended by the HLCs in the 1970-ies. The recommendations were only based on an integrated groundwater resources management approach. They are still considered valid after more than 25 years despite the changes in land and water use (some revisions to the recommendations were made based on new insights).

So there is scope for up scaling of the Kodinar salinity activities for the wider Saurashtra coastal stretch and for other Indian coastal parts that suffer from groundwater salinization. It is considered essential to consolidate learning from the Kodinar case in order to make this up scaling as effective and efficient as possible.

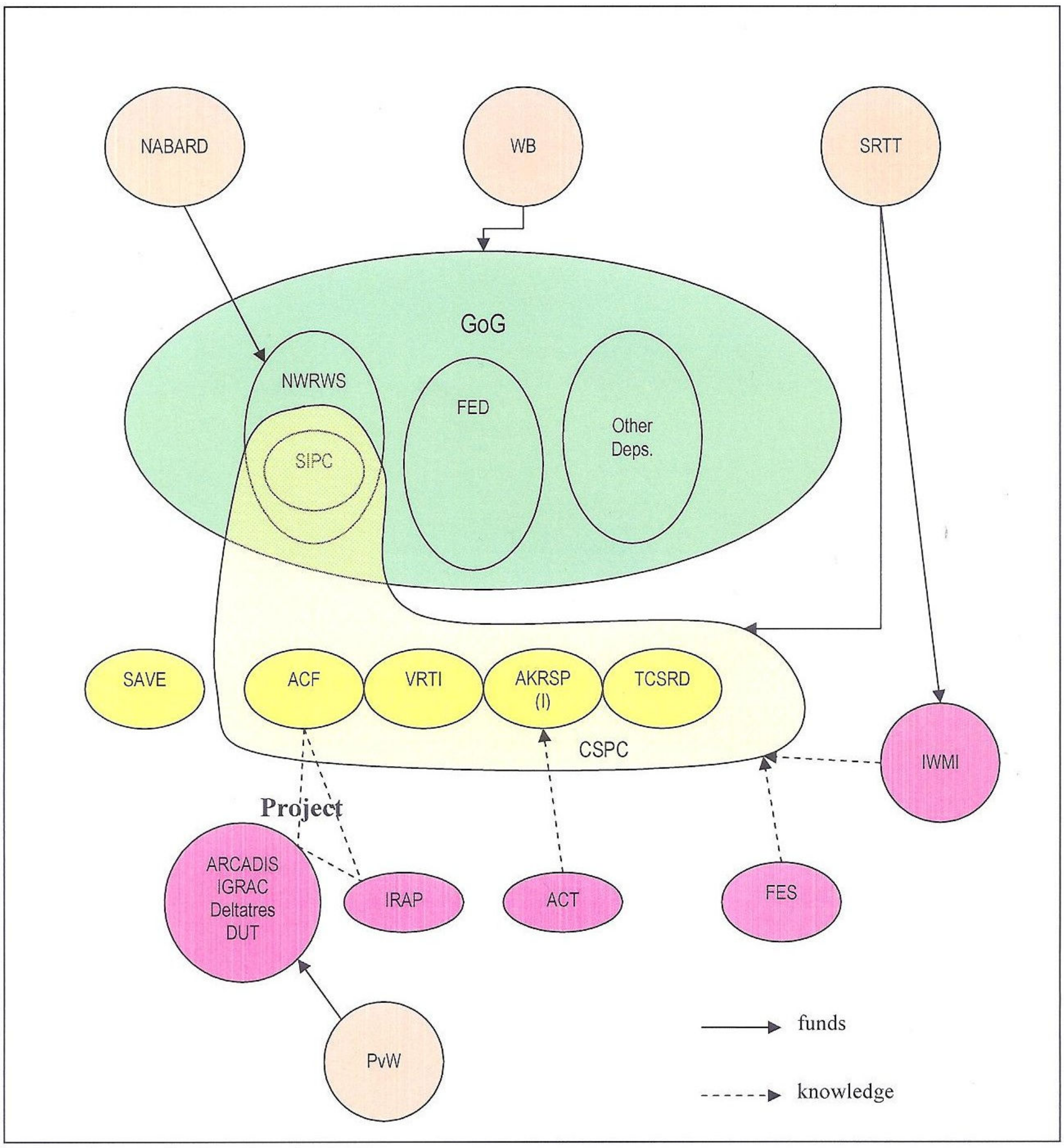

Figure 1-1: Organisational chart of the stakeholders for the salinity ingress problem

An overview of the various abbreviations of the stakeholders in Figure 1-1 can be found at the Appendix 12.1. Section 1.2 outlines the objectives and research goals for this study.

1.2 Overall project objective

The overall goal of this study is to consolidate learning form the efforts taken in the Kodinar area to deal with groundwater salinization in order to develop recommendations for effective and efficient up-scaling to other parts of Saurashtra and India.

1.3 Objective of 3D-model for Kodinar area

The objectives of the study for the Kodinar area are:

1. To determine the extent that various existing recharge and barrier interventions in the Kodinar area help to balance of groundwater withdrawal with recharge and to arrest salinity ingress?
2. To determine to what extent various demand side and other non-conventional interventions in the Kodinar area may balance groundwater withdrawal with recharge and arrest salinity ingress?
3. Furthermore following future outlooks for the region of Kodinar and the impact on the salinity situation will be investigated:
    - Population growth and therefore more abstraction in the coming 50 years
    - Increased agricultural production
    - Development industrial activity
    - Climate change and drought in the coming 50 years

These objectives are met by quantifying, identifying and analyzing the situation with the help of a groundwater flow and solute transport model.

1.4 Objective qualitative analysis of coastal area of Saurashtra

Obviously not every catchment can be modeled by a groundwater solute transport model as there is lack of information and as this is to labor intensive. The entire coastal area of Saurashtra will be examined by a simple groundwater balance approach. The goal of this qualitative analysis is to develop a simple tool to make a qualitative assessment of the salinity ingress. This will be done by looking at the following parameters:

- Natural recharge
- Abstraction
- Artificial recharge
- Fraction saline area

1.5 Consortium Partners

The consortium partners in this research project are (see also Figure 1-1):

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1.6 Report overview

This report describes the necessary parts needed to build a groundwater mass transport model, to qualitatively assess the coastal area regarding salt ingress so that conclusions and recommendations can be formulated. Section 2 describes the various governing equations regarding groundwater flow, density driven groundwater flow and mass transport. Section 3 illustrates the geology and determines the hydraulic parameters of the model area. All the fluxes that influence the Kodinar area groundwater system are determined in section 4. Section 5 outlines the model set-up. The scenarios that were used in the model are discussed in section 6 followed by section 7 that contains the results and discussions. The Saurashtra-wide qualitative basin assessment is performed in section 8. Finally the conclusions and recommendations are made in sections 9 and 10.

2 Groundwater flow and Solutes transport: Governing equations

2.1 Governing groundwater flow equations

This study focuses on the behavior of groundwater flow and solutes transport in coastal aquifers prone to salinization. The mathematical expression for groundwater flow in a porous media can be described as:

$$S_s \frac{\partial h}{\partial t} = -\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right] - W$$

Equation 1 : Expression for groundwater flow

Where S_s is the specific storage (L^{-1}),h the hydraulic head (L), q the Darcy specific discharge ($L\ T^{-1}$) and W is a source or sink term (T^{-1}). Examples of sources of sources and sinks are natural recharge, artificial recharge and abstraction.

The Darcy specific discharge can be given as:

$$q_x = -\frac{\kappa_x}{\mu}\frac{\partial p}{\partial x} \quad , \quad q_y = -\frac{\kappa_y}{\mu}\frac{\partial p}{\partial y} \quad , \quad q_z = -\frac{\kappa_z}{\mu}\left(\frac{\partial p}{\partial z} + \rho g\right)$$

Equation 2: Darcy specific discharge in the x, y and z-direction

Where, κ_x, κ_y, κ_z are the intrinsic permeabilities (L^2) of the porous media in x, y and z-directions, μ is the viscosity of the groundwater ($M\ L^{-1}\ T^{-1}$), p is the pressure ($M\ L^{-1}\ T^{-2}$), g is the gravity constant ($L\ T^{-2}$), ρ is the density of the groundwater ($M\ L^{-3}$). The hydraulic head is the defined as:

$$h = \frac{p}{\rho g} + z$$

Equation 3: Definition of the hydraulic head

Where, h is the hydraulic head (L), z is the elevation head (L). If ρ is constant the hydraulic conductivities in the x, y and z-direction are defined as:

$$K_x = \frac{\kappa_x \rho g}{\mu} \quad , \quad K_y = \frac{\kappa_y \rho g}{\mu} \quad , \quad K_z = \frac{\kappa_z \rho g}{\mu}$$

Equation 4 : Definition hydraulic conductivities

And when the term ρg is constant then the combination of Equation 2 , Equation 3 and Equation 4 becomes:

$$q_x = K_x \frac{\partial h}{\partial x} \quad , \quad q_y = K_y \frac{\partial h}{\partial y} \quad , \quad q_z = K_z \frac{\partial h}{\partial z}$$

Equation 5 : Specific discharge

2.2 Groundwater salinization

There are numerous conversion formulas relating density to chloride concentration, salinity, temperature and pressure. The following relation describes the density as a function of chloride concentration (Sorey, 1978; Holzbecher, 1998):

$$\rho(C) = \rho_f \left(1 + \alpha \frac{C}{C_s}\right)$$

Equation 6 : Relation between chloride concentration and density

Where, ρ(C) is the density of the groundwater (M L^{-3}), ρ_f is the reference density which is usually the density of fresh groundwater at mean subsoil temperature (M L^{-3}), $\alpha = (\rho_s - \rho_f)/\rho_f$ is the relative density difference (-), C is the chloride concentration or the so-called chlorinity (mg Cl^- /l) and C_s is the reference chloride concentration (mg Cl^- /l). Often seawater is used as a reference. The following values for the different parameters are used: ρ_f = 1,000 kg/m^3; ρ_s = 1025 kg/m^3; thus α = 0.025; C_s = 19,300 mg Cl^-/l; and TDS = 34,500 mg/l.

Also, density of the groundwater is a function of temperature (Hassanizadeh, 1997):

$$\rho(T, p, \omega) = \rho_f \, e^{-\alpha(T - T_0) + \beta(p - p_0) + \gamma\omega}$$

Equation 7: Relation density and temperature, pressure and activity coefficient

Where, α is the expansion coefficient 2×10^{-4} K^{-1}, β is the compressibility = 4.45×10^{-10} m s^2 kg^{-1}, γ is the activity coefficient = 0.7, ω is the mass fraction.But as the temperature difference of the groundwater is small with respect to the reference (298 K) the effect of this relation can be neglected. The dynamic viscosity is also a function of concentration but only for very high concentrations.

The following definition for the fresh hydraulic heads is given:

$$h_f = \frac{p}{\rho_f \, g} + z$$

Equation 8: Definition of fresh hydraulic head

Where, h_f is the fresh hydraulic head (L) and ρ_f is the reference density (M L^{-3}). In order to take into account groundwater density differences in the Darcy specific discharge Equation 2 and Equation 8 can be combined to:

$$q_z = -\frac{\kappa_z \, \rho_f \, g}{\mu} \left(\frac{\partial h_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right)$$

Equation 9 : Vertical specific discharge for density differences in groundwater

Viscosity differences may be neglected if density differences are small (Verruijt, 1980; Bear and Verruijt, 1987). As such Equation 9 can be written as:

$$q_z \quad = \quad -K_z \left(\frac{\partial h_f}{\partial z} + \frac{\rho - \rho_f}{\rho_f} \right)$$

Equation 10 : Vertical specific discharge for varying densities of groundwater

The density used in equation 10 is obtained from equation 6.

Groundwater flow due to hydraulic head differences and density differences are not the only processes that take place in the soil. Due to the fact that the soil is a porous medium and that there are concentration differences there is also hydrodynamic dispersion and diffusion.
The following equation describes the dispersion and diffusion processes in the soil:

$$R\frac{\partial C}{\partial t} \quad = \quad D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - \frac{\partial v_x C}{\partial x} - \frac{\partial v_y C}{\partial y} - \frac{\partial v_z C}{\partial z} - \lambda C + W$$

Equation 11: Advection-dispersion equation for solute transport

In which R is the retardation factor (-) for equilibrium sorption. This is the interaction between the solute and soil which could have the consequence that the solute is travelling with a lower speed than the groundwater. $D_{x,y,z}$ is the hydrodynamic dispersion in the x,y,z-direction (L^2 T). This is the phenomenon that describes the dispersion of the solute in the soil due to the fact that there are different flow paths that cause the solute to travel in all directions due to turtuosity. And λ is the decay factor (L^{-1}). Decay is the process that describes the decay of a solute due to microbiological activity. Note that for salts as chlorine there is no decay. Again W (L^3 T^{-1}) is the term for the various sources and sinks. This could mean removal of solutes by abstraction and infiltration of salt water. Since there is no retardation of the solute Equation 11 becomes:

$$\frac{\partial C}{\partial t} \quad = \quad D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - \frac{\partial v_x C}{\partial x} - \frac{\partial v_y C}{\partial y} - \frac{\partial v_z C}{\partial z} + W$$

Equation 11 : Advection-dispersion equation for solute transport

For our study we assume that it is a porous medium while the soil consists mainly of limestone which is fracture rock. This could mean that this does not have to be a porous medium. Our soil consists of 4 types of media which are all homogeneous.

3 Geography and (hydro)geology

3.1 Geographical description

Our area of interest measures 31 by 42 km and covers most of the Somat, Singoda and Sangavadi river basins (see Figure 3-1: Digital terrain model and model area). The altitude within the area rises from the coastline to 200 meters above sea level in the hills of the Gir forest in the Northeastern part of the area. It covers the whole of Kodinar taluka and parts of Sutrapada, Talala and Una talukas. A total population of 216,015 (census 2007 data) live in the area. The domestic water supply is mainly based on a piped system with water coming from a reservoir in the Gir area. The area has predominantly an agricultural land use with a rain-fed monsoon season, a groundwater-irrigated winter season and in some locations and during wet years sometimes also a groundwater- irrigated summer season. The number of wells (mostly dug wells with a depth of some 10s of meters) in Kodinar taluka already counts up to about 20,000. Apart from agriculture, cement producing industry is present with limestone mining and some processing plants. No significant groundwater use is related to this.

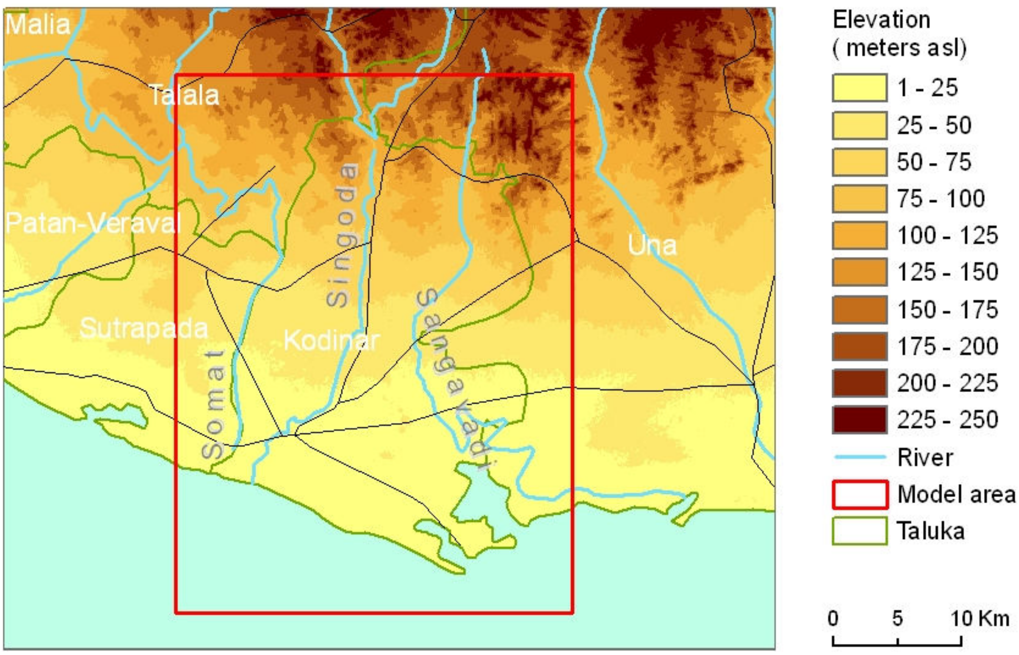

Figure 3-1: Digital terrain model and model area

3.2 (Hydro)geology

The geology of the modeled area is described by a basement formed by the Deccan Trap basalts of Cretaceous to Eocene age. The basalt is highly fractured in the top 20 or 50m, especially in the outcropping areas. The basement is overlain by the 'Gaj Formation' a Tertiary formation which includes thin alternating layers of clay, limestone, chalk and marl. Overlaying the Gaj Formation, we find the Milioltic limestone. This limestone has a primary porosity in most areas but is also karstified in many locations. The limestone is considered a very anisotropic and heterogeneous unit due to the different structures that are found in it. Conduits several meters wide and up to kilometers long form some of the most relevant anisotropic characteristics, but also fractures and dykes are randomly distributed in the limestone as well as in the underlying formations. On top of the limestone, occasional alluvial deposits consisting less than 5 meters of sand and gravel are found. These were deposited during Holocene time. They are not included in the model since they are mostly above groundwater level. in the hydrogeological profile of the model area is given in Figure 3-2.

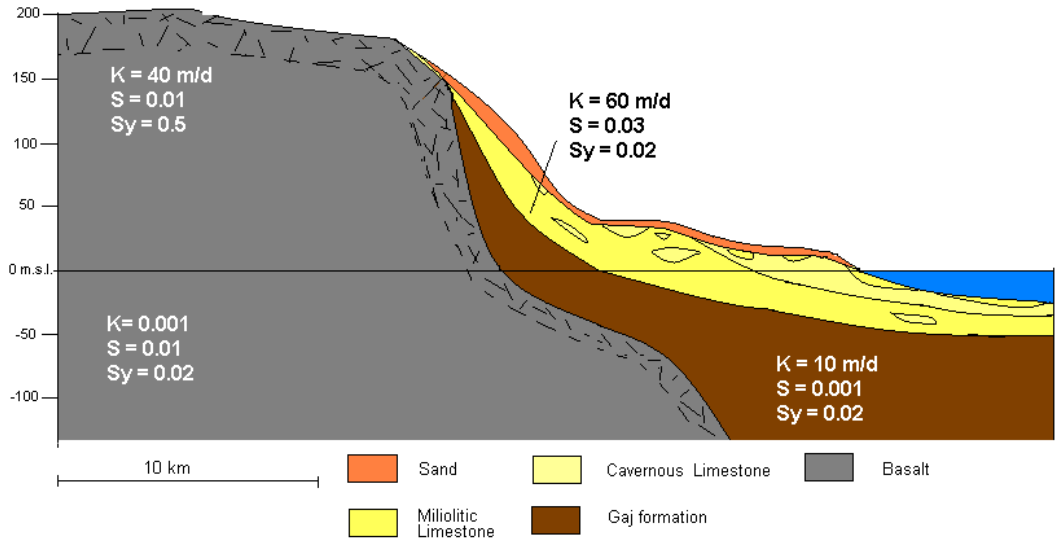

Figure 3-2: Hydrogeological profile of model area

The three materials shown in Figure 3-2 form the aquifers of the area; being the limestone the most important one. For every layer the hydrogeological parameters have been determined. The values here presented, partly come from the different existing reports about the geology of the area (Desai et al., 1978; Pareek et al., 2006), partly from reports that include several pumping tests (Geoconsult, 2009; GoG, 2000), and partly from information given by local informers. Even though there are some sources of information, some values have not been acquired with a sufficient amount of reliable data. In these cases literature was used to check the reliability of this particular value and some assumptions were made in order to determine the final value that was used in the model. Some of the assumptions that were made with the objective to decide the final input for the model are explained in the following paragraphs:

As it is described above, there are two types of Miliolitic limestone with quite different characteristics; porous and cavernous. The distribution of these two types of limestone is unknown and not possible to estimate. However, the percentage of each can be estimated taking into account to the results of a report which indicates that limestone has higher permeability close to the coast line, and lower permeability inland (Rusthon & Raghava, 1988), en partly assuming that karstified limestone is not a homogenous layer but it is randomly spread within porous limestone. As a consequence of the previous approximations, it was decided to introduce the limestone as a unique layer with parameters calculated taking the following estimations: from the coast to about 15km inland, 25% is cavernous limestone, and from 15 km inland to the hinterland part of the model, 10% is cavernous limestone. The cavernous limestone has a K_h of 600 m/d and the porous limestone a K_h of 25 m/d. The effective K_h of 60 m/d is a weighted average of the previous values. The direction and size of the cavernous limestone fractures, conduits and caves is unknown, therefore, the same hydraulic conductivity has been assumed for the horizontal and the vertical direction. The same assumption has been done in the fractured basalt. In the case of the Gaj Formation it is known that clay and marl layers are found within the formation. Therefore the vertical hydraulic conductivity has been assumed to be ten times smaller than the horizontal hydraulic conductivity.

Table 3-1: Hydrogeological values used as input for the model

Hydrogeological Unit	**Thickness (m)**	**K_h (m/day)**	**K_v (m/day)**	**S_s (1/m)**	**S_y (-)**
Miliolitic Limestone	0 -25	60	60	0.03	0.02
Gaj formation	0-100	10	0.1	0.001	0,02
Basalt	0 - 20	40	40	0.01	0.5
	0 - 115	0.001	0.001	0.01	0.02

The limestone forms an unconfined aquifer which is found until almost 20 km inland. The specific storage (S_s) of the porous limestone appears to be 0.0001 according to some pumping tests that were not published. Literature indicates that the storativity coefficient of unconfined aquifers equals the effective porosity, which at the same time can be assumed very close to the specific yield (S_y). For this reason the value that has been chosen for porous limestone is a similar value to its specific yield.

4 Sources and sinks

4.1 Introduction

In order to develop the solutes transport model, the various sources and sinks (see also chapter 1) of the hydrological system in our model domain are analyzed. The following schematic representation of the model domain (Figure 4-1) shows the various mass fluxes that form the sinks and sources:

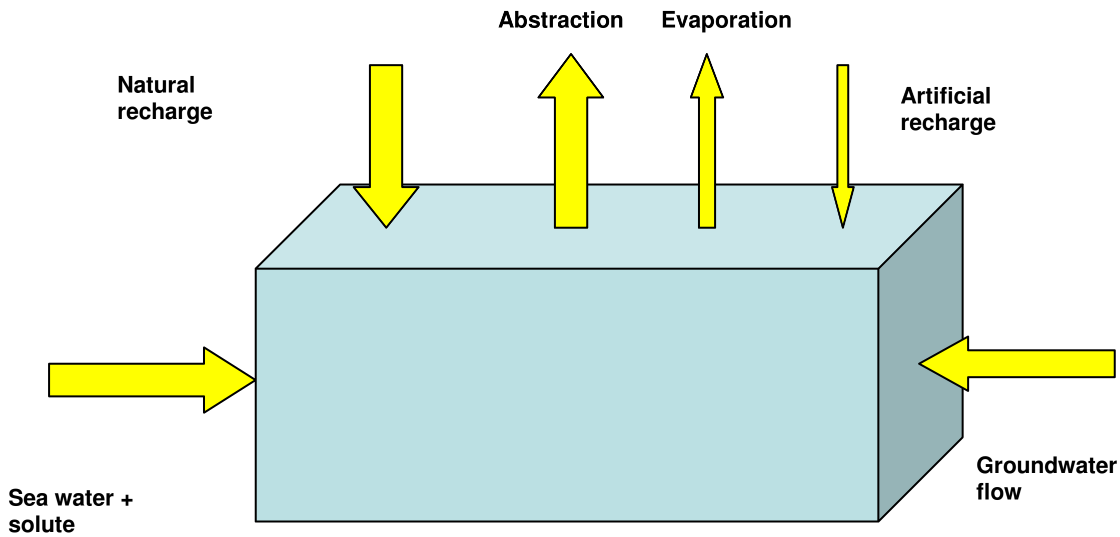

Figure 4-1: Sinks and sources of the hydrological system in the model area

Following mass fluxes are identified:
**** Sources***
- *Natural recharge (NR)*. A fraction of the precipitation infiltrates directly into the soil in the form of natural recharge.
- *Artificial recharge (AR) and rivers*. By use of human structures water will be stored so that the water can infiltrate into the soil. Also the infiltration of rivers will be taken into account here.

**** Sinks***
- *Groundwater abstraction (Q)*. The main sink of the black box model is the abstraction. Abstraction is needed for irrigation purposes.
- *Evaporation*. Both open water as evapotranspiration is considered here and is taken into account for the various sinks and sources.

There are mass fluxes on the left and right-hand sides of the model. By use of boundary conditions they are solved implicitly in the model; these boundary conditions are described in section xxx.

4.2 Natural recharge

Concepts
Precipitation that falls during the monsoon may replenish the groundwater systems since it partly infiltrates the soil and percolates to the groundwater table. The amount of precipitation actually percolating to the groundwater table is in general depending on:

- Factors determining interception of precipitation before it reaches the groundwater table like vegetation type, micro-ponding, storage as soil moisture,
- Factors determining how fast precipitation runoffs to a drainage systems like drainage density and relief,
- Factors determining the infiltration capacity like the unsaturated hydraulic conductivity of the top soils and the soil moisture content.
- The characteristics of precipitation events itself (rain density and duration).

The precipitation natural recharge relationship is considered semi-linear except for the extreme parts of the precipitation range. There is often a threshold rainfall value that needs to be exceeded before and groundwater replenishment takes place. There is also a maximal rate of natural recharge determined by the infiltration capacity of the top soils.

It is not in the scope of this study to look at these factors in detail in order to determine the natural recharge. However following general observation with respect to these factors for the modeled area can be made:

- The relief is gently sloping in the Gir Forest and more flat in the coastal direction in our model area.
- Vegetation cover as soon as the monsoon starts is relatively thin and there are no crops on the fields so there is little canopy interception
- The top soils (black soils) in the model area are loamy to heavy clays. At the moment the monsoons starts the soils is normally totally dry with low initial infiltration capacity. Crust-forming during the hot periods in the summer season decreases the infiltration capacity even further. Crack formation in the clay and field tillage enhances the infiltration capacity of the soil.
- The total rainfall falling during the monsoon varies in this area from 200 to 1,200 mm/year. The rain pattern during is often in short duration high density spells.

Literature data
In the literature, various efforts are made to estimate the natural recharge during the monsoon period in Gujarat and the wider environment. Rangarajan and Athavale (2000) estimated threshold rainfall values to generate natural recharge of 220 and 355mm for respectively sediments and basalt formations. Various studies with natural recharge measurements collected or performed by them indicate that 4.1 to 19.7% of the precipitation eventually becomes natural recharge in India. Sharda et al. (2006) estimated the natural recharge to be 7.3 and 9.7% of the precipitation for the years 2003 and 2004 in the Kheda district in NorthEastern Gujarat. Also they found a threshold rainfall value of about 200 mm to be able to generate natural recharge. The natural recharge as percent of the precipitation is maximal in the precipitation-range from 600 to 800 mm. If precipitation exceeds this range, the percent-wise volume of precipitation that becomes natural recharge decreases again. IRMA &UNICEF (2001) stats that Saurashtra has an utilizable annual recharge of 4.54E9 m^3 and a precipitation of 36,5 km^3. This means that about 12% of the precipitation results in actual groundwater replenishment.

This last number corresponds very well on expert judgment guesses of geologists and hydrogeologist who have worked in the area extensively for many decades (8-10% and 10-12% of precipitation becomes natural recharge in basalt and limestone respectively; personal communication with Mr. Sharma and Mr Bhatnagar)

Water table fluctuation method
In this study, we estimated the natural recharge coastal talukas in Saurashtra using the water table fluctuation method. This method is based on the principle in groundwater level in an aquifer is reaching the aquifer. This method is well suited to determine seasonal groundwater storage and natural recharge estimates for the unconfined hardrock (limestones and basalts) aquifers under a monsoon regime (Maréchal et al., 2006).

Table 4-1 : Natural annual recharge and precipitation per coastal taluka in Saurashtra

Taluka	1993	1994	1995	1996	1997	1998	1999	average
				Natural annual recharge (mm)				
Bhavnagar	48	56	44	24	44	34	10	*37*
Gogha	50	149	38	31	38	75	33	*59*
Kodinar	105		139		139	101		*121*
Mahura	65	91	53	58	53	58	16	*56*
Malia Katina	59	223	100	198	100	191	37	*130*
Mangrol	18	150	61	153	61	142	41	*89*
Rajula	47	49	14	15	14	71	14	*32*
Shihor	46	66	29	15	29	100		*48*
Sutrapada	87	158	70	216	70	94	26	*103*
Talaja	105	157	134	61	134	127	36	*108*
Una	58	148	90	64	90	60	76	*84*
average	*62*	*125*	*70*	*83*	*70*	*96*	*32*	*77*
				Annual precipitation (mm)				
Bhavnagar	416	754	533	637	563	770	423	*585*
Gogha	448	635	506	558	671	653	510	*569*
Kodinar	500	1144	732	889	537	1130	411	*763*
Mahura	622	796	275	384	551	761	309	*528*
Malia Katina	400	1228	708	891	718	947	416	*758*
Mangrol	233	1262	698	545	552	918	235	*635*
Rajula	684	826	325	429	670	637	232	*543*
Shihor	420	729	565	478	540	700	423	*551*
Sutrapada	444	671	497	1266	825	1309	452	*781*
Talaja	570	1633	801	1019	779	1062	499	*909*
Una	626	904	839	808	782	671	446	*725*
average	*488*	*962*	*589*	*719*	*653*	*869*	*396*	*668*
				Natural recharge as percent of precipitation (%)				
Bhavnagar	11	7	8	4	8	4	2	*7*
Gogha	11	23	7	6	6	11	7	*10*
Kodinar	21		19		26	9		*19*
Mahura	10	11	19	15	10	8	5	*11*
Malia Katina	15	18	14	22	14	20	9	*16*
Mangrol	8	12	9	28	11	15	17	*14*
Rajula	7	6	4	3	2	11	6	*6*
Shihor	11	9	5	3	5	14	0	*7*
Sutrapada	20	24	14	17	9	7	6	*14*
Talaja	18	10	17	6	17	12	7	*12*
Una	9	16	11	8	11	9	17	*12*
average	*13*	*14*	*12*	*11*	*11*	*11*	*8*	*11*

During the monsoon, it is assumed that aquifer's water balance simplifies to one incoming flux from the natural recharge. There is little evaporation loss since groundwater tables are initially deep and evaporation rates are small. Groundwater abstraction is negligible since agriculture (the main groundwater using sector) is predominantly rain-fed during monsoon.

In this study we used about 1,850 measurements of groundwater table changes over the monsoon in coastal talukas of Saurashtra for the years 1993 to 1999. Only those measurements were used that have a groundwater table increase during the monsoon. The exact locations of the measurements were unknown during the study and hence it is not known whether the observed groundwater table increases were a result of only natural recharge processes or also because of other recharge processes coming from rivers, check dams and or percolation tanks.

The increases in groundwater table must be multiplied with the specific yield of the aquifer to calculate the natural recharge. We used an overall specific yield value of 0.02 (-) derived from various pumping tests results and literature sources for the limestone aquifer in coastal aquifer.

Table 4-1 gives the natural recharge fluxes and measured precipitation (both in mm/yr) for various coastal talukas over the period 1993-1999. The highest natural recharge averaged over the talukas is 125 mm in 1993. This is the year with the highest averages precipitation (962mm). The talukas with the highest natural recharge values over the period 1993-1999 are Kodinar, Malia Katina, Sutrapada and Talaja. Partly, this can be explained by higher received volumes of precipitation in these talukas. However, when one looks at the percent-wise volume of precipitation becoming natural recharge the talukas Kodinar, Mangrol, Malia Katina and Sutrapada score highest. The number of realized artificial recharge structures in these talukas is relatively high. We assume that the increase in groundwater table observed in the wells over the monsoon period is the result of both natural and artificial recharge processes. The averaged natural recharge (both over all talukas and the measured time period) as percent from the precipitation is 11%. This number corresponds well with the data found in the literature and from expert judgment.

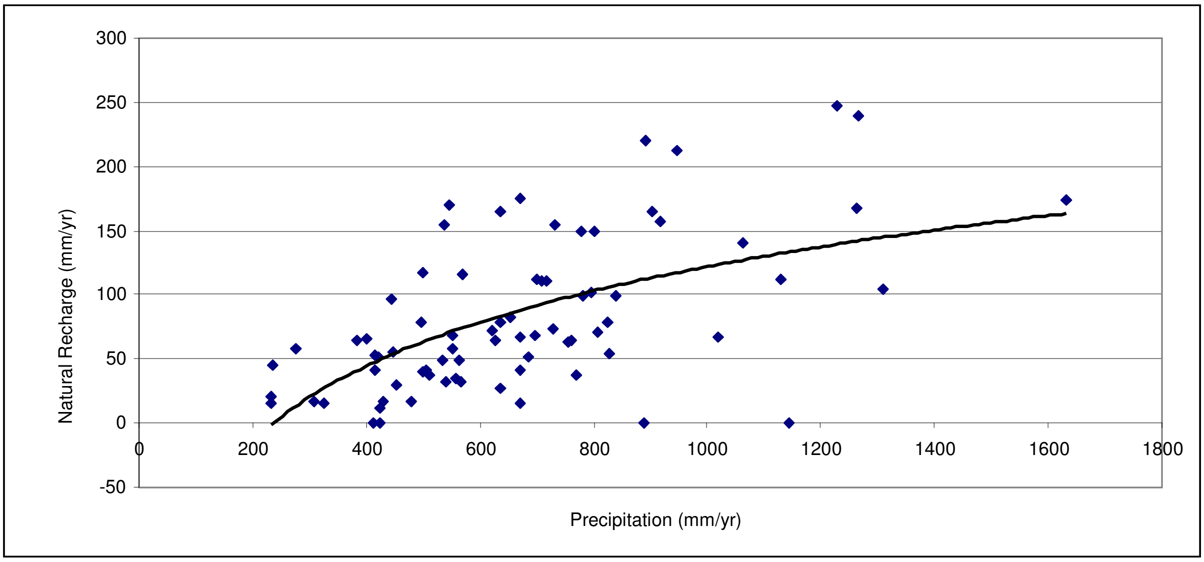

Figure 4-2 : Relation between natural recharge and precipitation in Saurashtra coastal talukas

Figure 4-2 gives the natural recharge values as a function of annual precipitation value based on the measurements in Table 4-1. Based on this figure we assume the following generalized natural recharge fluxes for coastal talukas with predominantly limestone aquifers in Saurashtra are as given in Table 4-2.

Table 4-2: Natural recharge fluxes for coastal talukas with predominantly limestone aquifers in Saurashtra

	Precipitation range (mm/yr)	**Natural recharge (mm/yr)**	**Natural recharge as percent of precipitation (%)**
dry year	200 - 600	45	11
normal year	600 - 1,000	100	13
wet year	1,000 - 1,400	140	13

4.3 Artificial Recharge and Rivers

Introduction
The following artificial recharge techniques are being used in the Kodinar taluka in Gujarat:

- Percolation tanks
- Percolation tanks with recharge wells
- Checkdams
- Bhandaras
- Interlinking channels

The section introduction outlines the origin of these structures.

A percolation tank is usually a lower part of a village area that has been flooded during the monsoon. Precipitation runs off to the lower parts of the village area and fills up the percolation tank. The water then infiltrates into the ground, replenishing the groundwater system. By using a recharge well the water will infiltrate into the aquifer more rapidly and more efficiently as the bottom of the percolation tank is often silted and therefore clogged. Sometimes the percolation tanks are dug out or there are walls or dykes constructed along the perimeter.

There are 3 main river systems in the Kodinar taluka: Singoda, Somat and Sangavadi. As the intensity of the precipitation during the monsoon months is very high, the three main river systems are filled in a short time in such a way that there is too little time for the water to infiltrate as most of the water will flow directly into the sea. By building checkdams along the main river systems, the water is retained so that the water can infiltrate. In that way much more water is recharged into the groundwater system.

By digging interlinking channels from the 3 main river systems, the water from the rivers is rerouted, allowing more water to be recharged into the groundwater system. Also, some of the interlinking channels are rerouted to percolation tanks or well systems to benefit from the excessive river water. Other interlinking channels are connected with so-called bhandaras. These bhandaras are large fresh water basins near the coast of Saurashtra created by blocking the river estuaries with tidal regulators and dams.

Figure 4-3: Example of a percolation tank

Figure 4-4: Example of checkdam in Singoda River near Kodinar

Figure 4-5: Sodam bhandara

Quantifying the artificial recharge and river fluxes
Since there is lack of data or other information about infiltration rates from percolation tanks, checkdams and rivers, a flux quantification approach is needed that is simple and conceptually right.

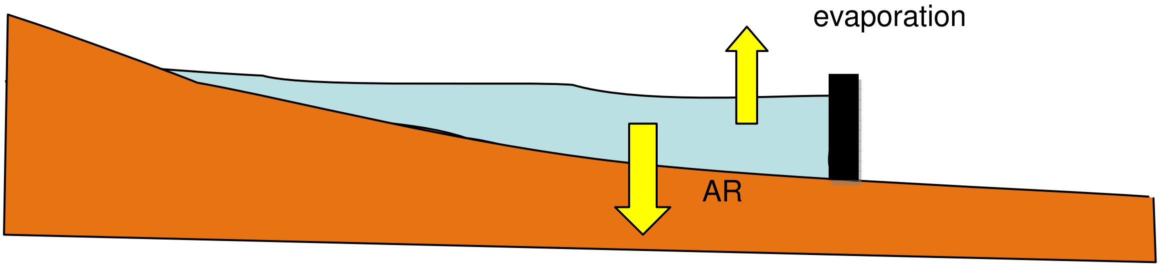

Figure 4-6: Schematic representation of a checkdam

Figure 4-6 shows the schematic checkdam concept. When the reservoir behind the dam has been filled with river runoff, water in that reservoir will evaporate and infiltrate. If the residence time of the water and the initial water depth behind the checkdam are known, we can calculate the infiltration flux by abstracting the evaporation flux.

Figure 4-7 shows the schematic representation of a percolation tank with a recharge well.

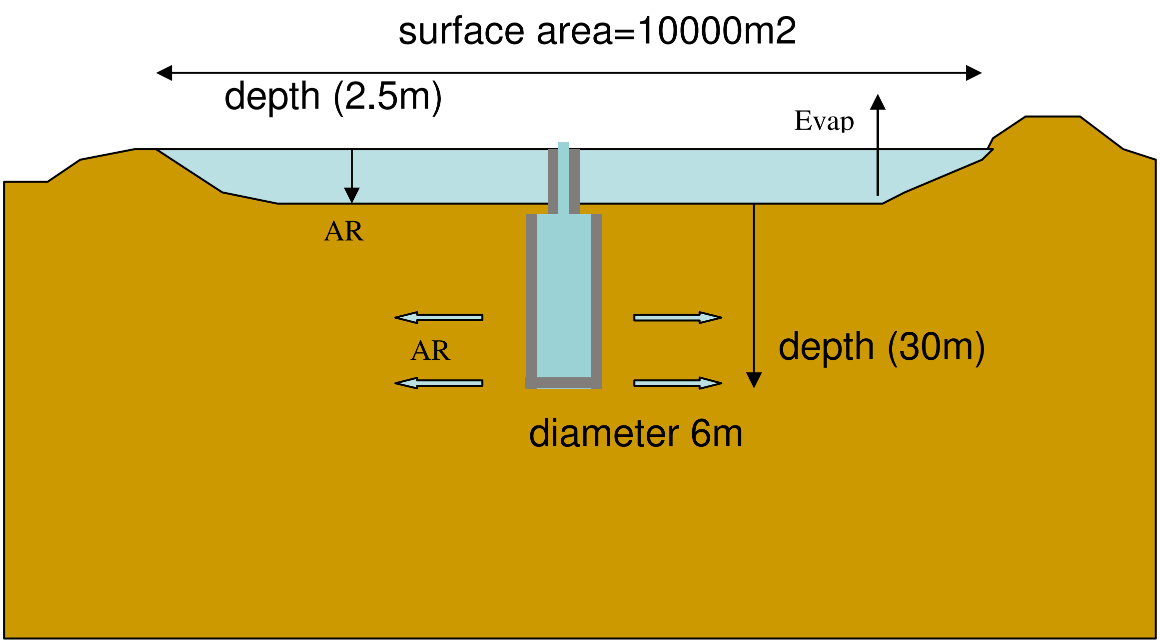

Figure 4-7: Schematic representation of a percolation tank with recharge well

The Ambuja Cement Foundation has collected information about the artificial recharge structures in the Kodinar taluka. The storage values of the various artificial recharge structures are known. The surface areas can be estimated by dividing it with the depth 2.5 m. There are no records known of the dimensions of the percolation tanks and checkdams. This value is an approximate value and was used after several interviews; however these heights have not been measured.

By multiplying the surface area with the evaporation rate, the total amount of evaporated water can be calculated. It has been pointed out by several interviews with the people from the Ambuja Cement Foundation that the various structures are filled 4 times for a normal year in terms of precipitation throughout the monsoon period. To spread these fillings over the monsoon period, the duration for each filling is now known. The filling data are shown in the appendix. The infiltration rate will then be:

$$I_{flux} = \frac{N_{fillings} \times \left(\dfrac{Storage_{structure} - \dfrac{E_{flux} \times A_{surface}}{12}}{30} \right)}{A_{surface}}$$

Equation 12: Determination of the infiltration flux of an AR structure

With I_{flux} the infiltration rate in m/day and E_{flux} the evaporation rate in m/year. $N_{fillings}$ is the number of fillings (-), $storage_{structure}$ is the capacity of the artificial recharge structure (m^3) and $A_{surface}$ is the surface area of the water in the structure (m^2).

With,

$$A_{surface} = \frac{Storage_{structure} \times f_{structure}}{Depth_{structure}}$$

Equation 13 : Determination of the surface area of an AR structure

$F_{structure}$ is the correction factor for the geometry of the structure; the value is 1 for a percolation tank and 2 for a checkdam.

Evaporation fluxes were determined by use of data from the National Institute of Hydrology located in Roorkee (http://www.nih.ernet.in/nih_rbis/india_information/evaporation.htm). Figure 4-8 shows the mean annual evaporation amount in cm. It shows that the evaporation rates in the coastal area of Saurashtra are varying from 250 to 350 cm per year. These are relatively very high values compared to the rest of India (150 to 250 cm per year).

The National Institute of Hydrology also provides monthly information. Figure 4-9 shows the monthly evaporation for the coastal area of Saurashtra. It can be seen that the evaporation peaks during the summer (400 mm). During monsoon, when the air is very humid, it declines to 200 mm. During winter when the temperature declines, the value of 200 mm is maintained as the dry air compensates for the lower temperature.

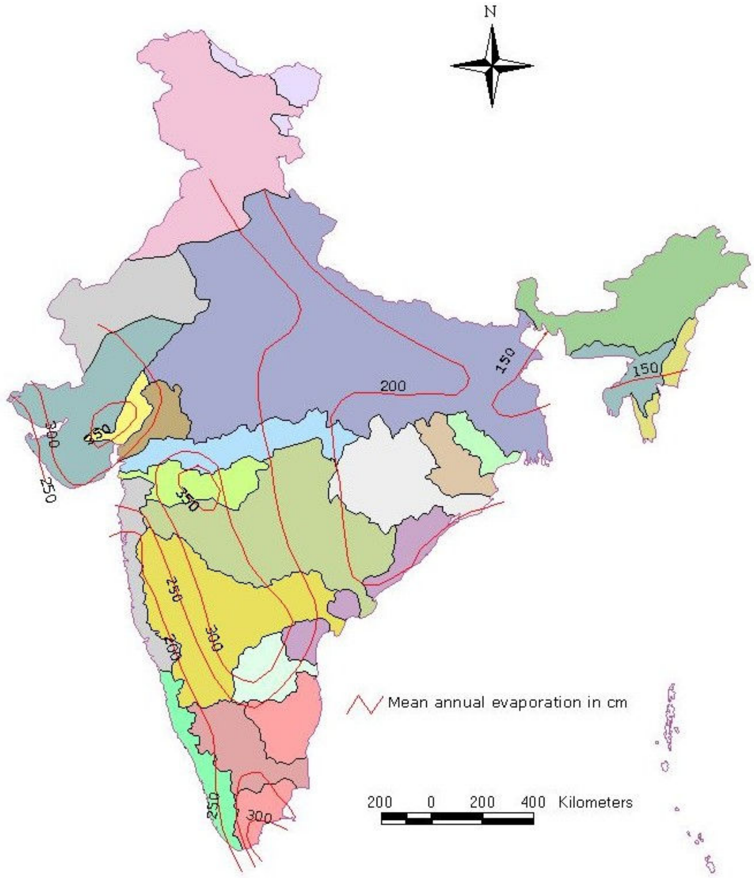

Figure 4-8 : Mean annual evaporation for the Indian subcontinent

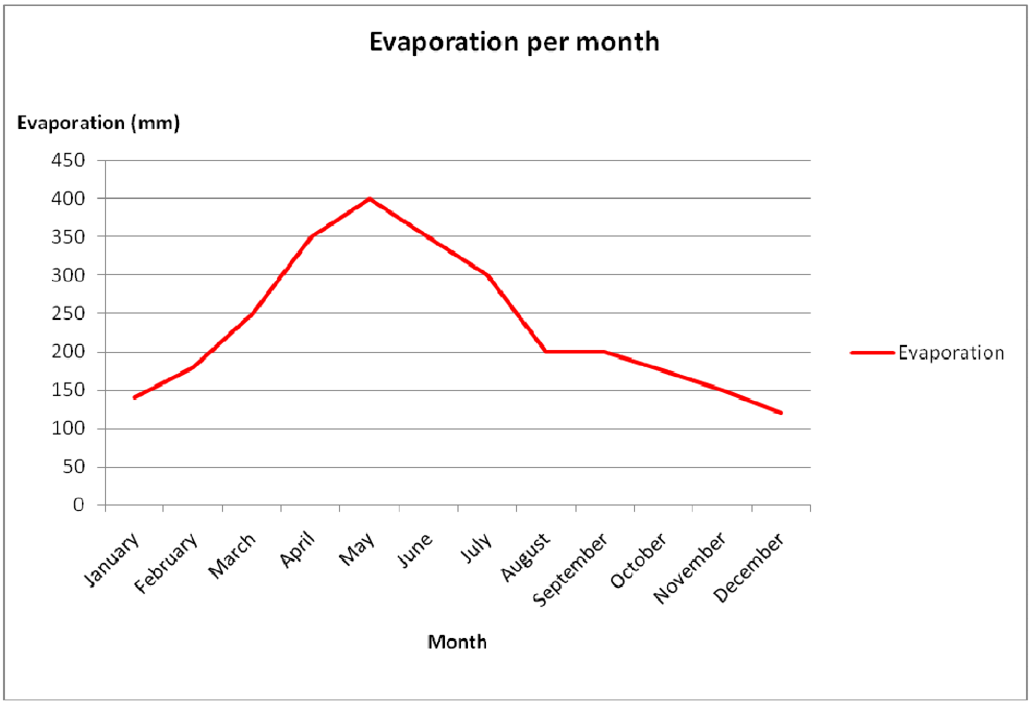

Figure 4-9 : Evaporation in mm per month for the coastal area of Saurashtra

The values in Figure 4-9 were used in Equation 12 to calculate the infiltration rates which are shown in Table 4-3.

Table 4-3: Infiltration rates for the various structures

Infiltration rates	**Main rivers [mm/day]**	**Checkdam [mm/day]**	**Percolation tank [mm/day]**
June	36	36	36
July	73	73	73
August	77	77	77
September	38	38	38
October	6	6	6
November	0	3	6
December	0	3	6
January	0	3	6
February	0	3	6
March	0	3	6
April	0	3	6
May	0	0	0

As can be seen from Table 4-3 the river fluxes are the same as the checkdam accept that the river will run empty in November. This is the best estimate that can be taken since it is unknown how much water infiltrates from the river systems. Note that from October till April the water is still infiltrating due to runoff and groundwater flow.

Several interviews with various local experts lead to the conclusion that a similar conceptualization of the bhandaras does not hold. It is observed that the water level in the bhandaras remains fairly constant throughout the year. During and after the monsoon the bhandaras are recharge with freshwater runoff from the rivers and interlinking channels. This freshwater recharge decreases to zero in the months afterwards. Constant evaporation from these large open water bodies gradually lowers the water table in the bhandaras. However saline water recharge from the underlying aquifer and the nearby sea partly replaces this lost volume of water and balances the water table. TDS-concentration slowly rises to levels of 6000 mg/l.

4.4 Groundwater abstraction

In the coastal area of Saurashtra, groundwater is abstracted mainly for agriculture use (irrigation). As the agricultural area and yield has been rising over the last two decades, the amount of groundwater being abstracted has also increased. During winter the land is irrigated for agricultural production. During monsoon only the water demanding crops are irrigated like cotton and sugarcane. Since there is groundwater scarcity there is less irrigation in summer times than in the winter times. Unfortunately, the groundwater wells are hardly being monitored and little information on groundwater abstraction is available for the model area. Therefore a different approach has been used where the groundwater abstraction is estimated from various sources of proxy information and expert judgment. Figure 4-10 shows an approximation of how to achieve the groundwater abstraction fluxes.

1. The amount of agricultural area per crop type has been described per taluka (Kodinar, Una, Sutrapada and Talala) and per year over the period 2000 till 2004 by the Agricultural Department in Gandhinagar (sees Appendix 12.3, Table 12-4).

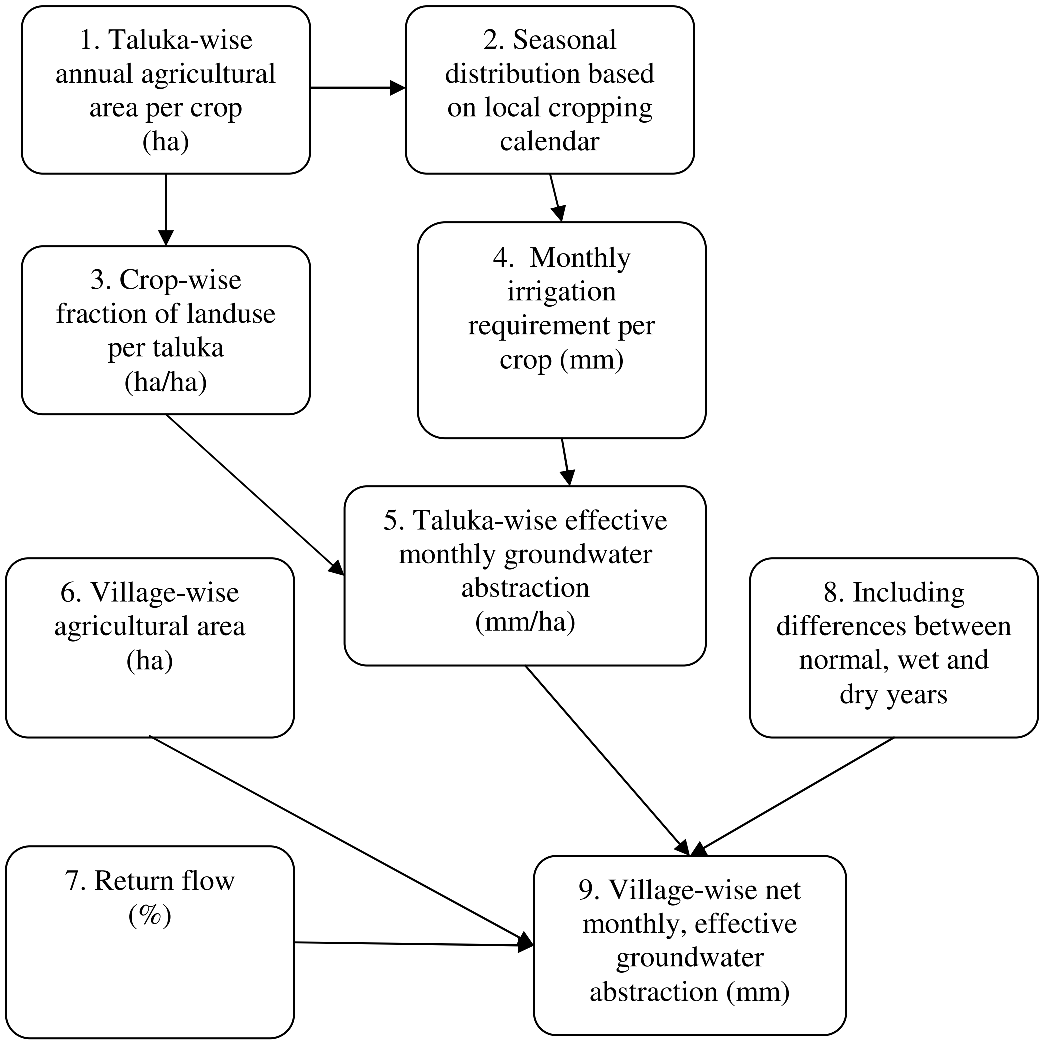

Figure 4-10: Flow sheet for the determination of the abstraction flux

2. It is assumed that the agricultural area per crop type is based on the total production of one whole year (monsoon, winter and summer season). Based on several interviews with farmers and local experts for a local cropping calendar is developed for the 10 most grown crops in the area. This agricultural area per crop type is monthly-wise distributed over the three seasons (agricultural area per crop type and per season) based on the cropping calendar (see Appendix 12.3).

3. The relative crop fractions to the total agricultural area are now calculated for each taluka and per season based on steps 1 and 2 (see Appendix 12.3, Table 12-6).

4. Based on expert knowledge from local experts and farmers the monthly required columns of irrigation water per crop and per season are determined for the 10 most grown crops (based on number of irrigation of and the assumption that during each irrigation 5cm of water column is applied). See Appendix 12.3, Table 12-5.

5. Based on steps 1 to 4 the effective monthly groundwater abstraction is determined per taluka taking into account the relative fractions of the crops and the cropping calendar.

6. The GIS data base of the Coastal Salinity Prevention and Control contains Census 2001 data with the total cropped area per village. This enables a more precise geographical distribution of the groundwater abstraction fluxes of step 5. Also a factor has been introduced to match the gap between the data from the Agricultural department and the CSPC.

7. It is assumed that the type of irrigation practiced in the model area leads to a return flow component. This return flow is assumed to reach the groundwater table and actually replenishes the groundwater systems. This part of the abstracted groundwater for irrigation purpose is thus not lost from the groundwater balance. To calculate the net groundwater abstraction, the return flow component needs to be subtracted from the effective monthly groundwater abstraction in step 5. The fraction of return flow is studied by many Indian scholars and varies dependent on crop type, irrigation practice, climate and soil type (Kim et al, 2007 and Mohan et al., 2008). The return flow factor depends on various things including soil type, porosity and soil moisture. It has been agreed to apply a return flow factor of 0.3 for all crop types in all seasons in the model domain.

8. From the precipitation records it is known that the average precipitation in the Kodinar taluka is approximately 800 mm. Table 4-4 shows the precipitation in the Kodinar taluka for the years 2000 till 2003 and the corresponding agricultural areas. Since there is a correlation between the precipitation and the agricultural area in a year, we must use the right data in order to use the right abstraction fluxes. It can be seen from Figure 4-11 that although the precipitation in year 2001 is only 554 mm, the amount of agricultural area is only 2500 ha less than the agricultural area in year 2003 when there is 1205 mm of precipitation (far above the average precipitation of 800 mm). This means that all the agricultural information in the year 2001 can be used as an average year.

Table 4-4: Precipitation records and corresponding size of agricultural area

Year	Precipitation [mm]	Agricultural area [ha]
2000	336	36,280
2001	559	46,610
2002	416	36,440
2003	1,205	49,199

Figure 4-11 shows that there is a correlation between the precipitation and the size of the agricultural area. This graph can then be used to calculate the agricultural area for an average year in terms of precipitation (800 mm). Since the size of the agricultural area at the precipitation value of 559 mm does not differ much from the wet year of 1,205 mm (interpolating between these values would mean an agricultural area of 47,000 ha with a precipitation of 800 mm). It is therefore assumed that the year with the precipitation value of 559 mm is an average year so that the data for that year can be used in our model as average years have been used.

If the crop water demand and the amount of hectares per crop are known the daily abstraction flux can be determined, Equation 14:

$$Q_{Agri} = w_{column} \frac{A_{crop}}{A_{agri}} \times \frac{1}{30.5 \times 12}$$

Equation 14: Gross daily abstraction flux

A_{crop} is the agricultural area per crop type (ha), A_{agri} is the total agricultural area (ha), w_{column} is the crop water demand (m) and Q_{agri} is the gross daily abstraction flux (m/day).

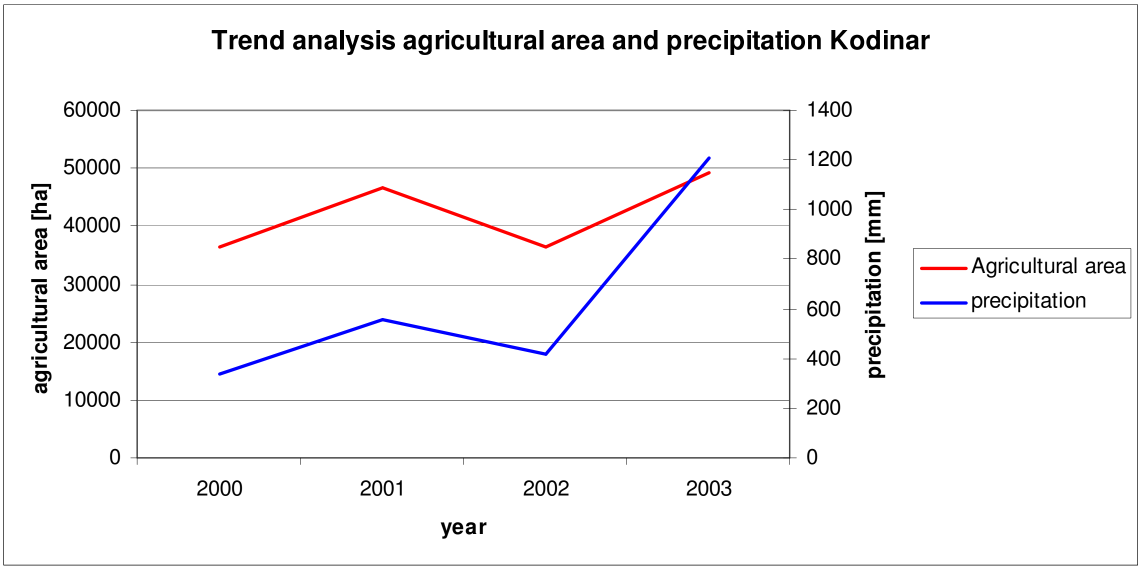

Figure 4-11: Trend analysis between precipitation and agricultural area

There are two data sets, the Census data from CSPC and the data of the agricultural department of Gandhinagar which have to be used together in order to determine the abstraction. To make these data sets consistent with each other, a correction factor has been used, f_{irr}, see Appendix 11.2, Table 12-7. Considering return flow, the net abstraction per day can now be calculated as Equation 15 shows.

$$Q = f_{irr} \times \frac{A_{TOTIRR}}{A_{TOT}} \times f_{return} \times Q_{Agri}$$

Equation 15 : Net abstraction flux corrected for each season

F_{irr} is the seasonal correction factor (-), A_{totirr} is the total agricultural area (ha) from the census data (2007), A_{tot} is the total area of a taluka taken from the census data (2007), f_{return} is the return flow factor (0.7).

For average years the abstraction fluxes are determined. Table 4-5 shows the abstraction fluxes for each month and for each taluka in the study area.

Table 4-5 : Daily abstraction fluxes for each taluka

	Kodinar	Sutrapada	Una	Talala
	mm/day	mm/day	mm/day	mm/day
June	0.5	0.4	0.4	0.5
Juli	0.5	0.4	0.4	0.5
August	0.5	0.4	0.4	0.5
September	0.5	0.4	0.4	0.5
October	5.0	4.0	4	6
November	5.0	4	4	6
December	5.0	4	4	6
January	5.0	4	4	6
February	5.0	4	3	6

March		5.0	4	3	6
April	5.0		4	3	6
May	5.0		4	3	6

4.5 Assumptions

Following assumptions and simplifications are used to fill in various information gaps in order to be able to estimate the sources and sinks fluxes:

- The measurements of the hydraulic heads are not made in observation wells but in the dug wells which are obviously used using for drinking water and irrigation purposes. One may question whether these water levels for the nearby groundwater levels are representative. It is furthermore questioned whether pumping tests that are originally designed for porous media provide reliable hydraulic characteristics for fracture media like in our model domain. The specific yield value of 0.02 derived from these pumping tests is therefore questionable and prone to error. Taken this into account, the water table fluctuation method used to determine the natural recharge and which uses both specific yield and hydraulic head data includes uncertainty.
- It is assumed that check dams fill up 4 times during a normal monsoon (and in the months afterwards). This number of fillings is based on the experiences and the opinion of local experts. Also, the assumption has been made that percolation tanks or village pond fills itself 4 times. It is not very clear how the number of fillings depend on the precipitation value. Water levels are hardly recorded in the recharge structures and hence it is difficult to estimate the total amount of water that was been stored and infiltrated. The infiltration is furthermore dependent on soil characteristics. Recharge structures get filled with fine sediment which makes infiltration difficult. These complicating and recharge limiting factors are not considered.
- For simplification reasons, we used uniform concepts and dimensions for all artificial recharge structures in the model area based on average values. This means that the effects of recharge structure that strongly deviate from these average values are over- or underestimated.
- The evaporative loss from open water bodies is directly dependent on the surface area of these water bodies. Data about artificial recharge structures did not provide any information about the surface of the storage structures. These surface areas are determined by dividing the storage volumes by 2.5 which is considered as the averaged check dam height and percolation tank depth.
- As was explained in section 4.4, the groundwater abstraction flux is derived from various sources of proxy information. Expert judgment is used to downscale data from taluka-level to village-level and from annual amounts to monthly fluxes. Each of these down-scaling exercises uses data with some level of uncertainty in it.
- The land use data that is used is not seasonally diversified. The seasonal diversification is based on expert judgment but is applied for the whole model domain without geographical differences. Also the crop water demand is assumed to be similar throughout the model.
- Despite regional surface water use regulations in place, surface water is possibly used for irrigation in the model area by means of direct lifting from check dams and bhandaras. Information about this surface water uses fails and hence is not considered. This may well lead to an overestimation of the groundwater abstraction fluxes.
- It is assumed that each village in a taluka has a similar cropping pattern. However, it is known that for example sugarcane production takes place in areas with high water availability like directly next to rivers and bhandaras. This geographical specification of cropping patterns is not taken into account.
- In the model we use also a hard flux for the river. Though these fluxes must be considered with caution it is much better to model it this way than as a normal river where the river conductance must be estimated which is much more prone to error, especially considering that

water heights of the rivers are not known. Also, the baseflow component could not be estimated.

4.6 Mass balance

Based on the quantification of the sources and sinks fluxes, a month-wise groundwater mass balance is compilated for the Kodinar taluka. Figure 4-12 displays this mass balance for a normal monsoon year.

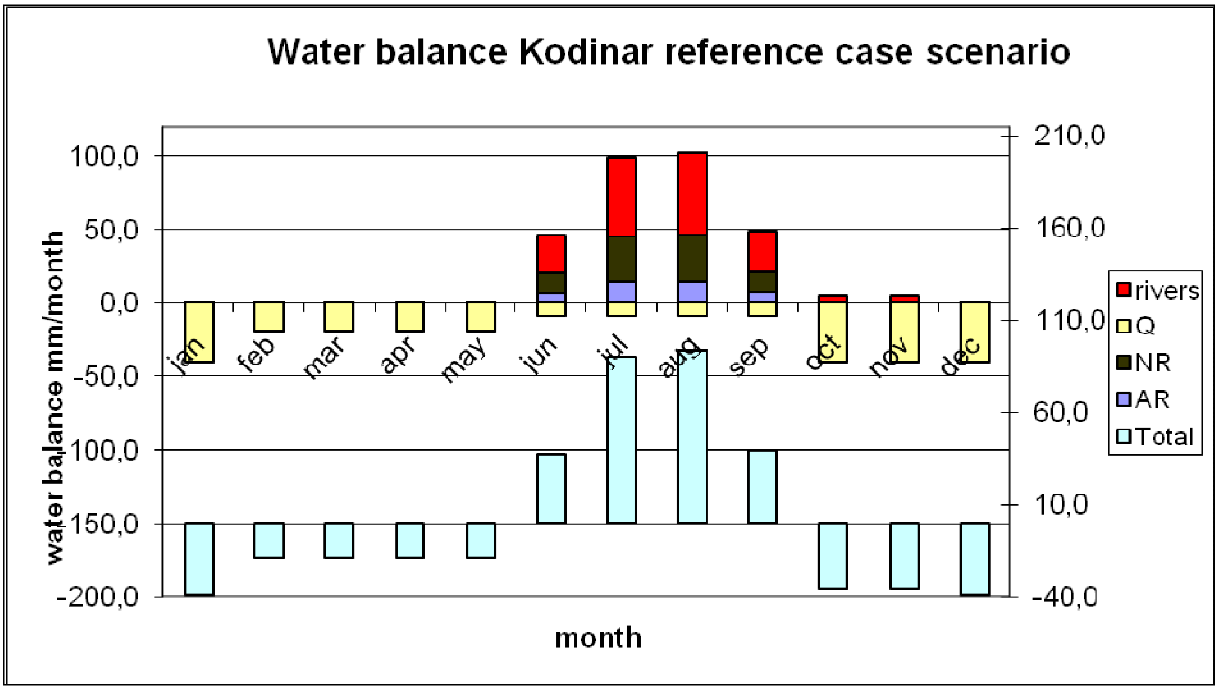

Figure 4-12: groundwater balance average year, Kodinar

The top part of Figure 4-12 contains the abstraction (Q, yellow), the natural recharge (NR, black), the artificial recharge (AR, purple) and the river fluxes (rivers, red). The lower part of Figure 4-12 displays the total monthly groundwater balance (cyan). The groundwater recharge during and directly afterwards the monsoon period is clearly visible. During these months there is a positive total groundwater balance. During the other months in the year there is a negative total groundwater balance. By summarizing all the monthly total groundwater balances, the total accumulated annual groundwater balance for Kodinar taluka in a normal year can be calculated. This accumulated groundwater balance has got the value of 40 mm/yr. This would result in a groundwater table rise of approximately 1 m as the effective porosity is 0.02. Note that the rivers contribute a large portion of the balance while these fluxes must be interpreted with caution since data needed for their quantification is merely lacking. The fact that the water table rises 1 m is considered to be quite reasonable and realistic.

For a dry year where, the picture is quite different (Figure 4-13).The recharge fluxes are much smaller since they are directly dependent on the amount of precipitation. In this case, groundwater abstraction is assumed to be 70 % of the normal year value. This is based on local expert judgment and based on comparisons of agricultural yield/precipitation ratios for a number of years. Here, the total accumulated annual groundwater balance for Kodinar taluka is -110 mm. This would mean a decline of the groundwater table by more than 5 m during a dry year.

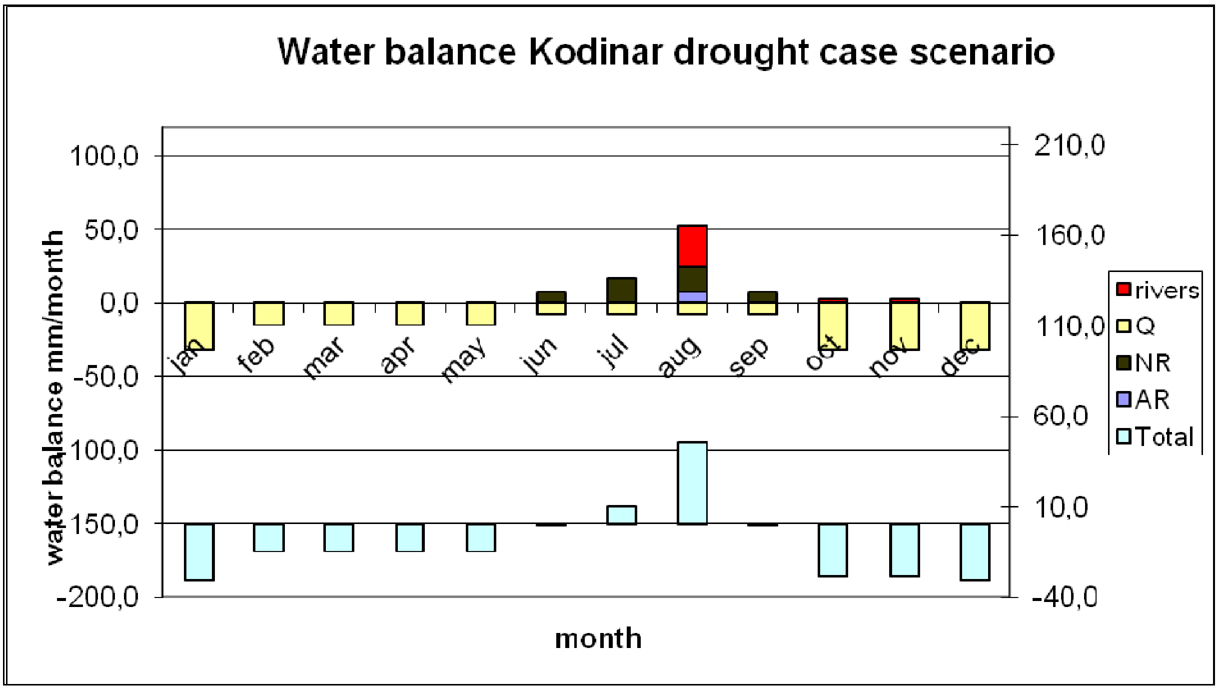

Figure 4-13 : Groundwater balance for a dry year, Kodinar

The accumulated annual total groundwater balance for Kodinar taluka in a wet year is estimated to be 55 mm/yr. When taking into account the frequency of occurrences of normal, dry and wet year in the model area over the period 1993-2008, a total groundwater balance of - 15 mm/yr is estimated.

5 Numerical model and experimental set-up

5.1 Introduction

In order to investigate the behavior of the salinization processes in the model area and to estimate the effects of the artificial recharge structures, land and water use behavior and other possible measures, a numerical 3-D transient groundwater flow and solutes transport model is developed.

A numerical computer model is a useful tool to quantify salinization processes. It numerically solves the differential Equation 1 and Equation 11. The numerical solution gives estimates of the hydraulic heads and groundwater TDS-concentrations in the model domain. From this solution also derived variables like groundwater fluxes and mass fluxes can be calculated. Since this model is a 3-D model it produces this information for the whole model domain. So, heads and TDS-concentrations are calculated for all the hydrogeological formations mentioned in section 3.2. This model is a transient model meaning it takes into account temporal changes. Hydraulic heads and TDS-concentrations can be calculated for the current situation but also for future situations.

Solving time-dependent differential equations for a certain model domain is only possible when boundary conditions are given for the domain boundaries and initial conditions for the whole model domain. These boundary conditions and initial conditions are explained in sections 5.3.

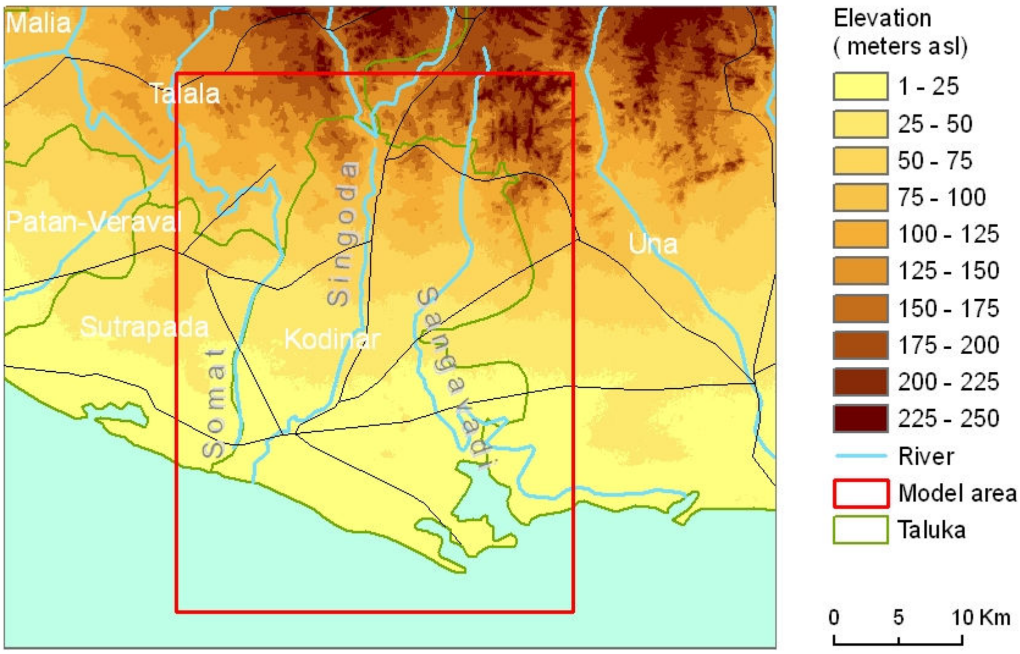

Figure 5-1 : Model area of the Kodinar taluka

5.2 Model set-up

The model has been set-up from a practical point of view. Not only should the model cover the whole taluka but the model boundaries must also picked in a logical way such that there are no-flow boundaries at the Eastern and Western side. The grid size is a limiting factor because the running time of a model with more than 200 rows and columns is too long. This results in a cell resolution of 200 m by 200 m which is acceptable. The model area (red box) is shown in Figure 5-1. Note that the model area covers a large area surrounding Kodinar taluka. This has been done to make sure that there is a gradual transition from the boundaries at the edges of the model area. In Table 5-1 model specifications are displayed.

Table 5-1: Model dimensions

Type	Dimensions
length	42 km
width	31 km
Rows	210
columns	155
Cell resolution	200 * 200 m
layers	41

The grid cell resolution largely determines the numerical accuracy of the model solutions. In this study, a grid cell resolution of 200 by 200 m is chosen. This is assumed to be detailed enough to simulate rivers, checkdams and ponds fluxes accurately and to study effects of salinization on a river basin scale. The surface level geometry of the model has been determined by a digital elevation model from the CGIAR consortium for spatial information (http://srtm.csi.cgiar.org/) with a resolution of 90 by 90 m. The number of layers is large because numerical stability of the model must be ensured, resulting in layer depth of 5 m for the bulk of the model.

5.3 Boundary conditions

Top boundary

At the top of the model, source and sink fluxes have been put in like natural recharge, artificial recharge, rivers and groundwater abstraction. More about the top fluxes of the model can be found in 12.4. These fluxes are specified a flow boundary conditions (with a month-wise variation in its strengths).

The flux data needs to be linked to grid cells which have got the dimension of 200 by 200 m. The natural recharge serves as a blanket throughout the top of the model and varies only in time. Each percolation tank is represented by one grid cell which has a surface area of 4 hectares. The surface area of each percolation tank has been determined by dividing the storage volume by a depth of 2.5 m. This leads to an average surface area for percolation tanks of approximately one hectare. In order to input the right flux, the amount of water that actually infiltrates must be divided by 4 in order to get one hectare of surface for each percolation tank.

The average slope of the model surface in North-South direction (the overall direction of the rivers in the model area) is such that every 400 m in the North direction the top rises 2.5 meters. Taking this into account each checkdam has been represented by 2 grid cells which have an accumulated length of 400 meters.

All source fluxes have a specified input TDS-concentration. The TDS-concentration of the infiltrating precipitation is assumed to be 10 mg/l. The TDS-concentration of the infiltrating runoff in checkdams and tanks/ponds is assumed to be 600 and 100 mg/l.

Bottom Boundary
It is assumed that there is no flow through the bottom of the model. The cells at the bottom are specified as inactive, as if there is an impermeable layer. In reality there is a Deccan trap formation consisting of basalt below the Miliolitic limestone and Gaj formations. The basalt is almost impermeable (in any case when relatively compared wit the limestone formations) and that is why the choice for a no-flow boundary condition is considered appropriate.

Lateral boundaries
The lateral sides of the model are are defined as no-flow boundaries. The overall groundwater flow direction is parallel to the lateral model boundarties. Hence no-flow is assumed to occur over these lateral boundaries. Moreover, the location of the lateral boundaries is more or less on the river basin divides. It is assumed that there is neither surface water flow nor groundwater flow over these divides.

Cross Boundaries
The Southern cross boundary of the model is bounded by the sea. This boundary condition is defined as a general head boundary (at mean sea level) and a constant mass boundary with a seawater concentration of 35.000 mg/l.

The Northern cross model boundary has general head conditions varying with time (see Table 5-2). The time variation takes into account the seasonal rising and falling of the groundwater table.

Table 5-2: Boundary conditions hydraulic head at the North side of the model

Month	Constant hydraulic head (m)
June	0.9 * surface level -17
July	0.9 * surface level -15
August	0.9 * surface level -13.5
September	0.9 * surface level -12.5
October	0.9 * surface level -12
November	0.9 * surface level -13
December	0.9 * surface level -14
January	0.9 * surface level -14.5
February	0.9 * surface level -15
March	0.9 * surface level -15.5
April	0.9 * surface level -16
May	0.9 * surface level -16.5

This relationship between the hydraulic head and surface level is based on 1,850 hydraulic head measurements over the Saurashta coast. At the Northern cross boundary a mass boundary condition is defined. The concentration increases from 100 to 7500 mg/l TDS along the 41 layers. A concuctance of 1000 has been used.

More detailed description of the boundary conditions can be found at the Appendix 12.4.

5.4 Time horizon

Before any the model or any scenarios can be run, the initial hydraulic heads of the groundwater system and the initial salt distribution must be created. The initial hydraulic heads are modelled by giving them a value of 6 m below surface level of the digital elevation model. In a similar way, the initial salt distribution has been put in based on expert judgment on saline intrusion wedges and estimated on the scarce TDS observation in the shallow wells. With these initial hydraulic head and TDS-distributions, the model is run in a trial mode. The trial model automatically runs to more appropriate hydraulic head and TDS-distributions which are used as initial conditions to run the mode in a scenario mode. Figure 5-2 shows the initial TDS-distribution used to tune the scenarios.

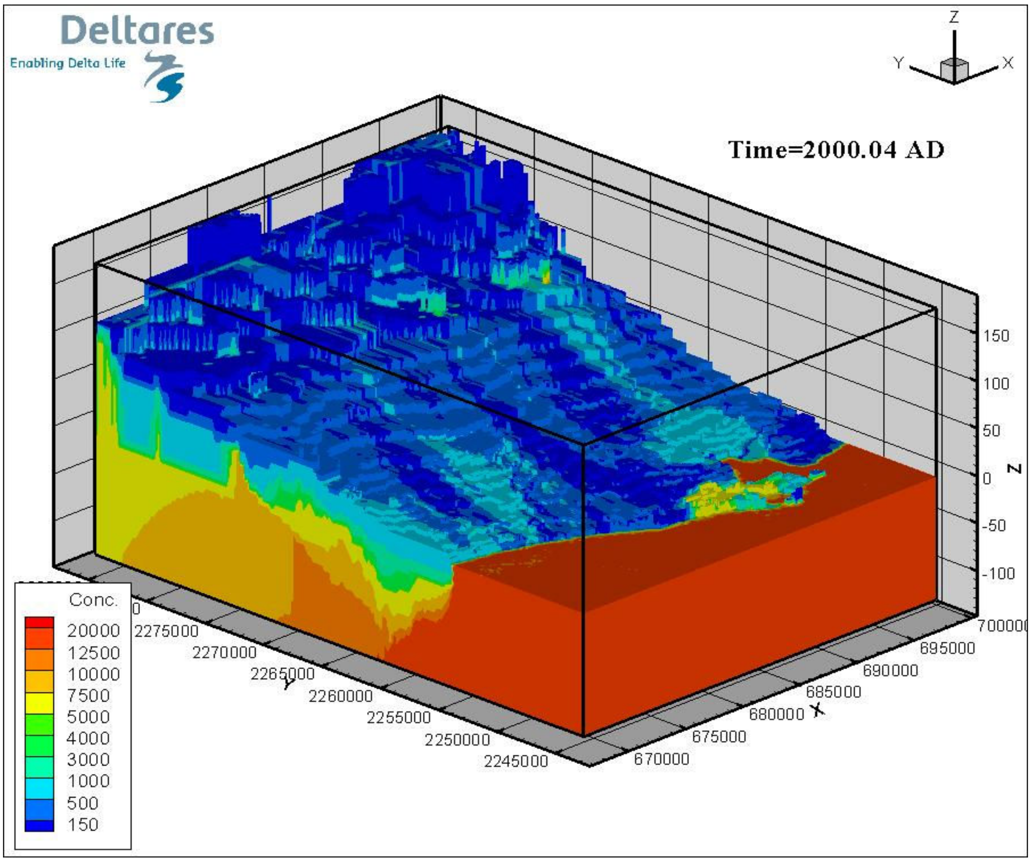

Figure 5-2 : Initial TDS-distribution in mg/l

Groundwater system dynamics and particularly salinization phenomena are slow processes. It may takes years or decades to notice significant changes in such systems or phenomena. In this study a modeling time of 50 years has been chosen, starting from the year 2000 as there is data originating from that date and ending at 2050.

The time variation in model input is on a monthly base. This means that per month, different input values for precipitation, evaporation, groundwater uses etc. are specified. It is assumed that this is detailed enough to include the time-dependent processes that are significant in the model area.

5.5 PMWIN & MOCDENS3D

As a modeling environment PMWIN has been used. This modeling software is a shell around MODFLOW (McDonald and Harbaugh, 1988) and uses these codes for groundwater flow in a porous medium. For density driven flow the three-dimensional solutes transport computer code MOC3D (Konikow et al., 1996) was adapted for density differences and is called MOCDENS3D (Oude Essink, 1998). Now it is possible to model transient groundwater flow and solutes transport in three-dimensional hydrological systems where non-uniform density distributions occur. MOCDENS3D uses the equations in section 2 to model the density driven flow.

6 Scenarios for Kodinar area

6.1 Introduction and objective

The groundwater flow and solutes transport model as described in the earlier sections is primarily developed to study the salinity ingress prevention programme as implemented in the Kodinar area. It is obvious to use this model to look more specifically at the effects of the various implemented measures such as the checkdams, percolation tanks and bhandaras. However, this tool can also be used to study the potential effects of measures that can be implemented in future. For example, in the original recommendations of the HLCs it was foreseen to implement groundwater demand management approaches. These have not been carried out. The tool can be used to estimate the effects on salinization when they still are being implemented in future,

Besides the already implemented or possibly to be implemented measures, various other large-scale processes are taking place that drive salinization in this area. Examples of such processes are climate change and economic growth. Moreover, the government of Gujarat has ambitions to develop the coastal zone of Gujarat which may have significant effects on land and water use. It is desirable to analyze possible effects on salinization of these future outlooks.

6.2 Scenarios

A workshop was organized to have a brainstorm session about the future outlooks. Table 6-1 shows the scenarios which are developed.

Table 6-1 : Various scenarios used in the 3D-model

Development	**Groundwater abstraction)**	**Recharge (artificial and natural)**
1. Reference case	Stagnant	Stagnant
2. Reference case without artificial recharge	Stagnant	No artificial recharge , natural recharge is stagnant
3. Business as usual Increase in population Increase in abstraction	Increase Q with 1 % per year till 2025, Increase Q with 7 % from 2025 till 2050	Stagnant
4. Business to the max	Increase agricultural area during the summer	Stagnant
5. Reference case Plus development industrial zone	Stagnant + 5 MCM/year industrial abstraction	Stagnant
6. Drought scenario	Decrease in Q from 2025 till 2050 with 22 %	Less natural recharge, less artificial recharge
7. Reference case + Drip irrigation	Decrease in Q by approx 30 %	Stagnant

1. *Reference case*. This is the basic model set-up. The sinks and sources of the model have been described in the previous sections. This model will be compared with all the other models to look at the sensitivity of changes. This is also not a realistic outlook as all the sinks and sources are

constant. The amount of people in the region will grow rapidly as the health situation is improving.

2. *No artificial recharge*. This scenario is used to see what the effects are of using artificial recharge structures. The artificial structures are left out. If the change is significantly, it is wise to keep on building these structures in future.
3. *Business as usual*. Here, the growth of the amount of people causes more abstraction of groundwater for agricultural and domestic purposes. According to the IWMI report (Amarasinghe et al., 2007) the amount of people will grow 25 % in till 2025 and after that 7 % in the next 25 years till 2050. As a consequence the amount of abstraction is increased similarly. So Abstraction rates will increase 1 % per year till 2025 and 7 % in the next 25 years.
4. *Business to the max*. Here, the objective is to look at effects of a rise in abstraction. The farmers irrigate their lands during the summer at the same pace as if it was winter, an abundance of water with no interest to look at the consequences.
5. *Development industrial zone*. Here, it is investigated the effects of increasing industrial activity using 5 mcm per year at the coastal region.
6. *Drought scenario, climate change*. Due to climate change the sea level is rising. The sea level rises 0.5 cm per year. This could have an effect on the salt water intrusion. Also, the Saurashtra area could get drier. The natural recharge will decrease linearly with the decrease of the average annual precipitation from 800 mm in 2000 to 400 mm in the year 2050. From the year 2025 till 2050 there will be 22 % less abstraction.
7. *Drip irrigation*. The majority of the farmers use flood irrigation to irrigate their lands. In this scenario all farmers change their irrigation method into drip irrigation. By doing this approximately 30 % water is saved.

6.3 Translation of scenarios into model input

In order to simulate these scenarios the model input is changed:

- As has been stated earlier in scenario 1 the basic input has been used as has been described in the previous sections.
- In scenario 2 the artificial recharge structures have been left out by changing the input code for the model.
- In scenario 3 the abstraction rises 1% each year so this would mean: abstraction is (1 + 0.01*t)*Q; t in years and Q is the abstraction.
- In scenario 4 the abstraction during the summer has been changed. This means that the size of the agricultural area is the same of that in the winter and which means that irrigation in summer is doubled. So the value of f_{irr} of the winter is used (see also appendix 11.2, Table 12-7). This factor is used to make the two data sets consistent(Census 2001 and Agricultural Department of Gandhinagar)
- In scenario 5 an additional 5 million m^3/year is being abstracted near the coast.
- In scenario 6 the sea level rises 0.5 cm/year. The general opinion is that the sea level rises 50 cm in the coming 100 years. There is less natural recharge each year as the precipitation will decrease from 800 mm to 400 mm in 2050. According to Figure 4-11 the total irrigated area decreases significantly from 46,000 ha to 36,000 ha when the precipitation is lower than 521 mm. This means that from the year 2025, when there is a precipitation value of 600 mm, the abstraction rates decrease with 22 % (36,000/46,000) as the irrigated area is decreased from 46,000 ha to 36,000 ha. Due to the drought there is less precipitation, as a result there is less groundwater to irrigate which results in less farming land.
- In scenario 7 the return flow is reduced from 70 % to 90 %, but the abstraction is lowered to 50 % (Mohan et al., 2007 and Kim et al., 2008). In this way approximately 30 % of the groundwater is saved.

The model results based on these scenarios are shown in section 7.

7 Model results and discussion

7.1 Introduction

This section outlines the results of the 3D density driven groundwater solute transport model. First, the results of the reference case are discussed in section 7.2. Both the initial hydraulic head distribution as well as the initial TDS-distribution has been reviewed. Then it is investigated whether the concentration of an observation well fluctuates throughout the year. After that, cross sections which display the concentration profiles between the year 2005 and the year 2055 are discussed. Also length profiles which display the concentration profiles between the year 2005 and 2055 are compared. In Section 7.4 the results of the various scenarios are investigated. Fresh water volume and the average concentration of the observation wells are compared with each other during 50 years, followed up by a discussion.

7.2 Results of the reference case scenario

Figure 7-1 displays the concentration of an observation well. The concentration is displayed along the y-axis and the x-axis displays the time in years. Figure 7-1 Shows that there is fluctuation of the TDS-concentration inside the observation well, although the concentration fluctuates between 4,100 and 4,200 mg/l TDS, this is not a large amplitude when taken into account that the system ranges from 0 to 35,000 mg/l TDS. Since groundwater with values higher than 150 mg/l chlorine[1] are not potable, this observation well is obviously very saline.

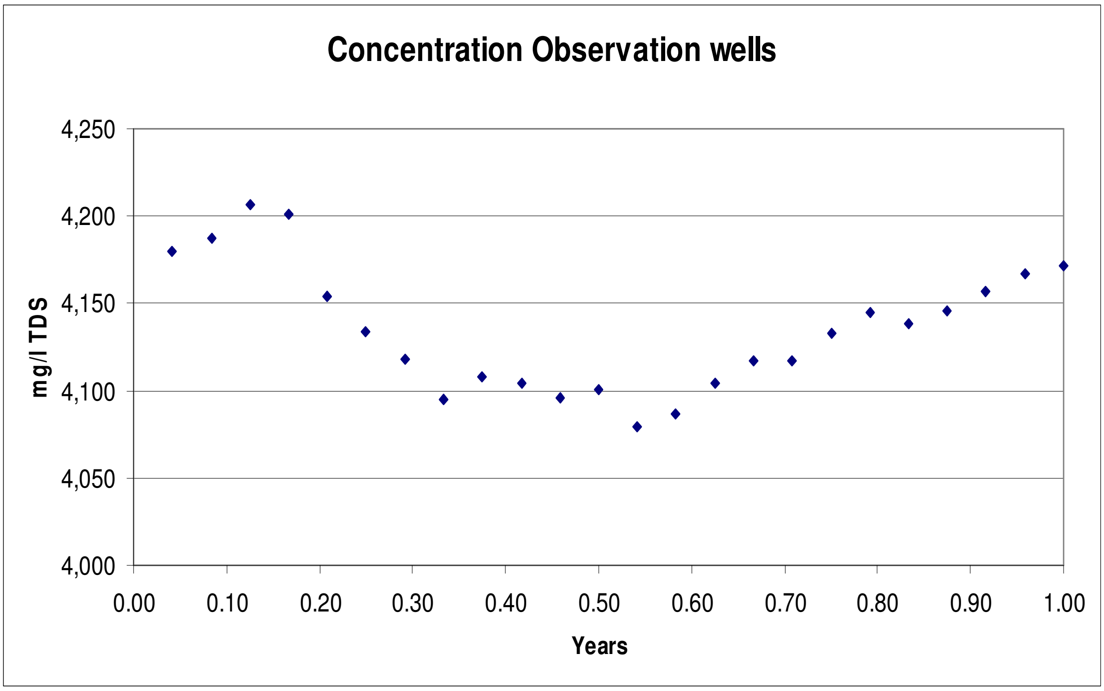

Figure 7-1 : Seasonal variation of the concentration in a observation well

[1] According to the European Commission and the World Health Organisation

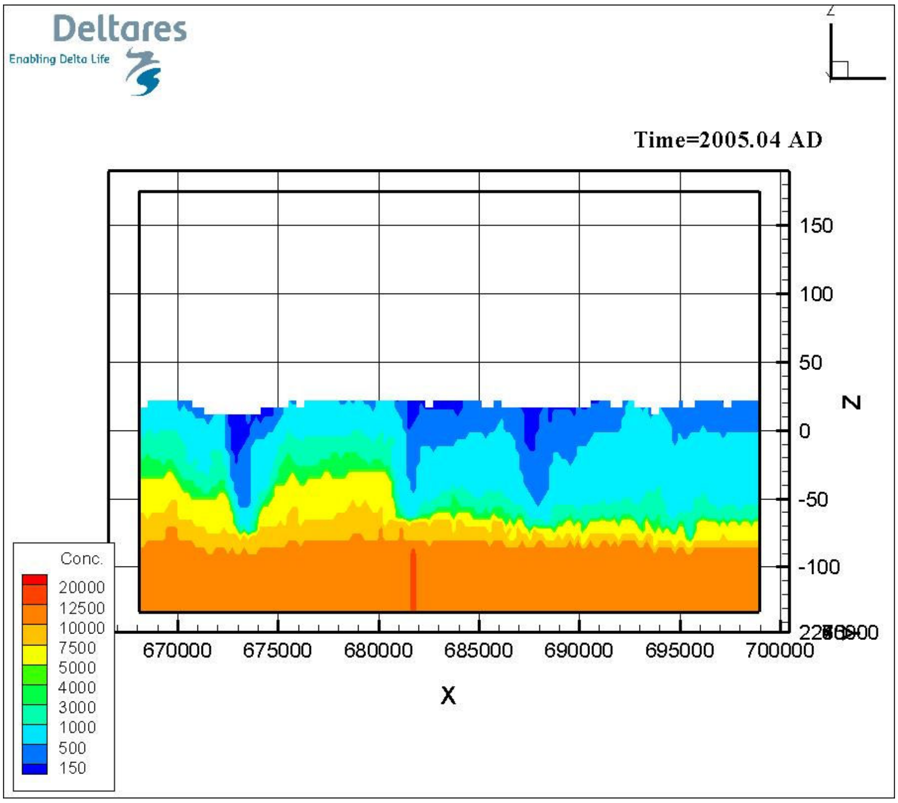

Figure 7-2 : Calculated TDS-concentration in 2005 for the reference case at cross section y = 2,260,000

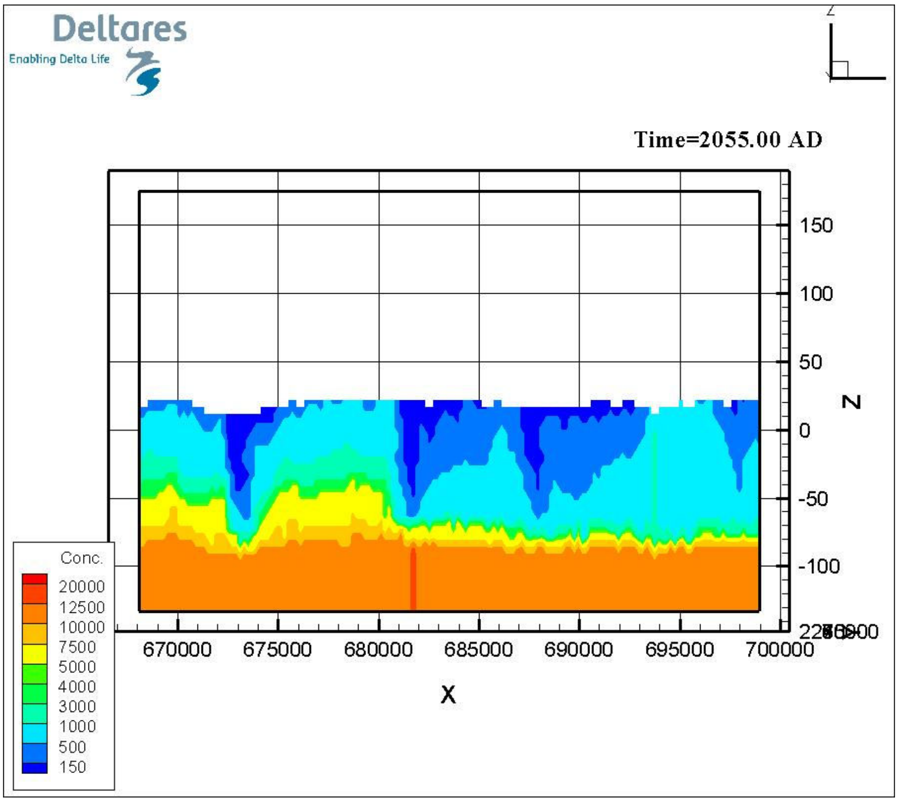

Figure 7-3 : Calculated TDS-concentration in 2055 for the reference case at cross section y = 2,260,000

Figure 7-2 and Figure 7-3 show the total dissolved salt concentration of a cross section of the model of the groundwater system in 2005 and 2055. The location of the cross section is at y = 2,260,000.

The red color indicates high (> 20,000 mg/l TDS) concentrations whereas the blue color represents low concentrations (< 150 mg/l TDS). Figure 7-2 and Figure 7-3 show that the water becomes fresher after 50 years and that the dark blue areas indicate the location of the rivers and checkdams where replenishment of groundwater occurs.

Figure 7-4 and Figure 7-6 show the total dissolved salt concentration of the groundwater system in 2005 and 2055. The position in the x-direction of the length profile is at x= 687,000.
Again the red color indicates high TDS-concentrations (> 20,000 mg/l) and the dark blue color represents TDS-concentrations of 150 mg/l and less. It can be observed in the length profiles that the groundwater becomes fresher near the shallow parts of the coastal area.

Furthermore, it can be observed in the length profiles that the groundwater becomes more saline in the hinterland part of the model area. A comment is made on this in section 7.3.

7.3 Discussion results of the reference case scenario

Figure 7-2 and Figure 7-3 show that at the cross section the groundwater becomes fresher. It is explained by the fact that the groundwater balance is 40 mm/yr. Dry years have not been taken into account (-120 mm/yr, see section 4.6). When dry years would have been included in the reference scenario a different picture would be obtained.

It can be observed in the length profiles that the groundwater becomes fresher in the shallow parts of the coastal area. This expected since the reference case is based on the assumption that over the next 50 years normal monsoon years prevail.

Furthermore, it can be observed in the length profiles that the groundwater becomes more saline in the hinterland part of the model area. The salinization process taking place in this part is up-coning of saline groundwater that is assumed to exist in the deeper parts of the basalt aquifer. The hydraulic characteristics of the basalt aquifer inhibit sufficient groundwater recharge. However, groundwater abstraction is taking place resulting in a negative groundwater balance for this part of the model domain.

Often salinization is seen as sea water intrusion in the form of a landward movement o a sharp fresh saline groundwater interface. This cannot be observed in the model results. The first comment on this is that salinization often appears in much more complex shapes of mixing fresh, brackish and saline groundwater. Vertical movements of saline groundwater is often more important than lateral ones. Secondly, the horizontal cell dimensions of 200 meters is 40 times larger than the cell thickness of 5 m. Due to this irregular pancake-like cell shape the horizontal solutes transport is possibly underestimated while the vertical movements are and overestimated.

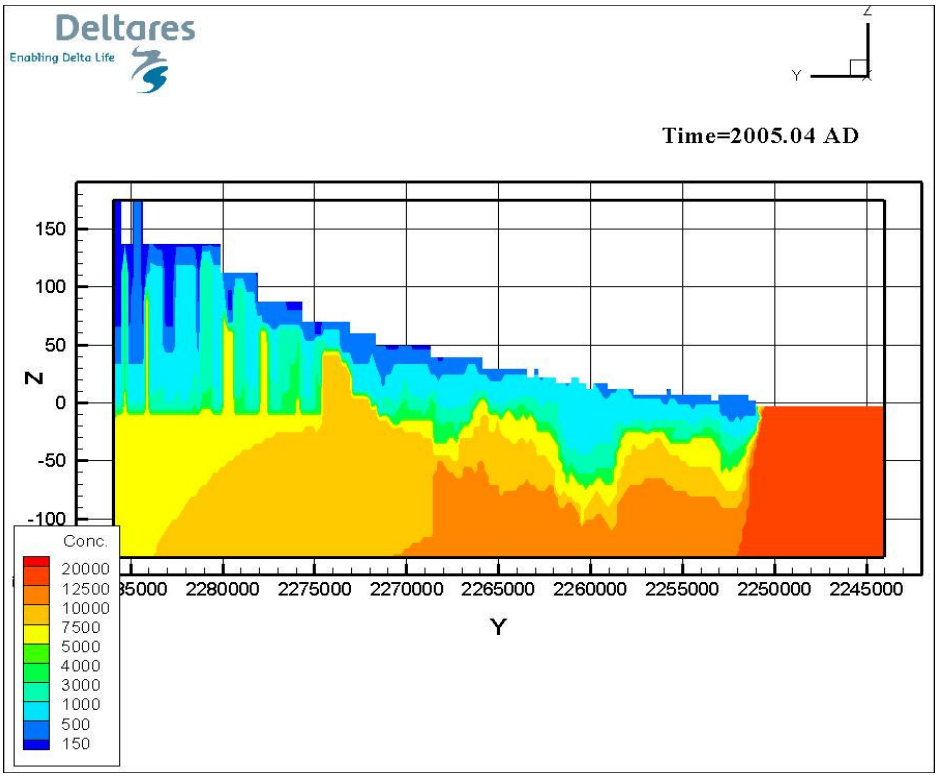

Figure 7-4 : Calculated TDS-concentration in 2005 , reference case scenario in length profile at x=687,000

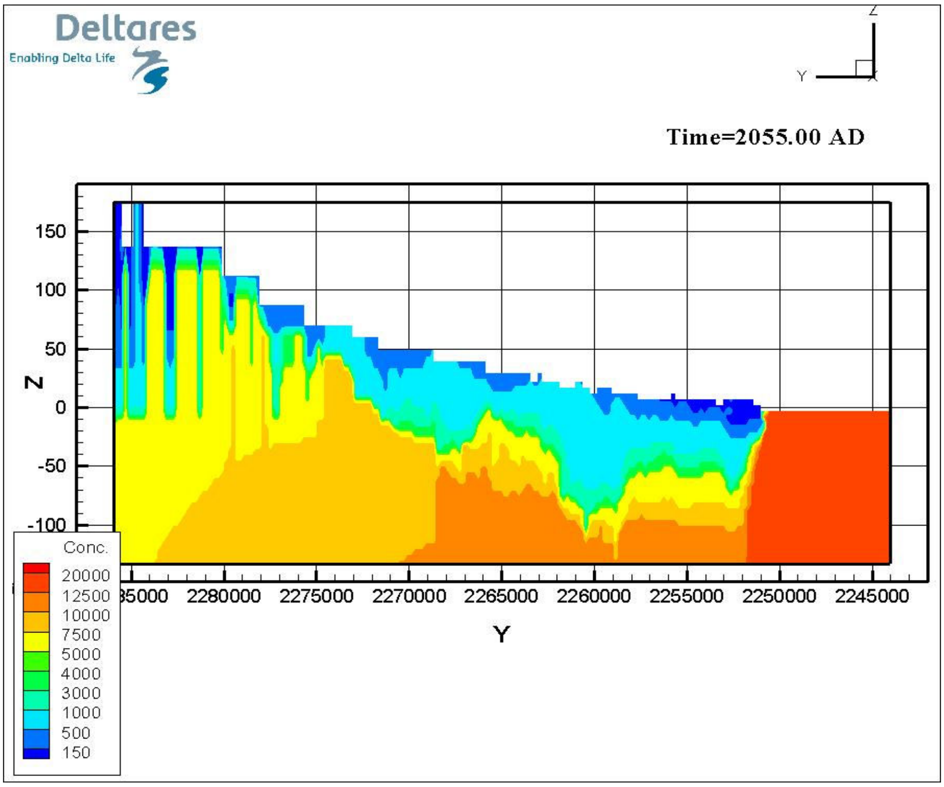

Figure 7-5: Calculated TDS-concentration in 2055 reference case scenario in length profile at x= 687,000

7.4 Results and discussion of the scenarios

As has been stated in section 6 scenarios have been defined that describe possible future outlooks of the coastal area of Saurashtra. The groundwater model is used to simulate these scenarios. In this section, results from these scenarios are compared with the reference scenario.

In the previous section, Figure 7-2 and Figure 7.4 showed decreasing groundwater concentrations over the next 50 years. However, the cross section may not be representative for the whole model area. To check the scenario effects for the whole model domain, it is checked how the fresh groundwater volume changes in the 50 meters shallow West part of the aquifers. Fresh groundwater is defined as water with a concentration less than or equal to 2,000 mg/l. The changes in fresh groundwater volumes are displayed in Table 7-1 and in Figure 7-6.

Table 7-1 : Changes in fresh groundwater volumes in 50 m thick shallow aquifer for the various scenarios

Scenario	Initial fresh water volume (m^3)	Fresh water volume	Change in fresh water	Change in % fresh water
Reference case	7 E09	6.5 E09	-5.6 E08	-9
No artificial recharge	7 E09	6.1 E09	-1.0 E09	-16
Business as usual	7 E09	6.4 E09	-6.1 E08	-9
Business to the max	7 E09	6.4 E09	-6.1 E08	-10
Industrial zone	7 E09	6.5 E09	-5.5 E08	-8
Drip irrigation	7 E09	6.2 E09	-8.3 E08	-13
Drought	7 E09	6.5 E09	-5.1 E08	-8

What can be seen is that the drip irrigation scenario is relatively the best and that leaving out the artificial recharge is the worst situation just like the drought scenario. This is in contradiction with the findings in section 7.2 where the situation gets better. This can be explained by the fact that there is up-coning of salt groundwater in the upper area which is responsible for the decrease of the amount of fresh water. This means that the use of artificial recharge structures and drip irrigation should be encouraged to deal with the salt intrusion.

Figure 7-7 shows the average concentration, which are in line with the results in Figure 7-6.

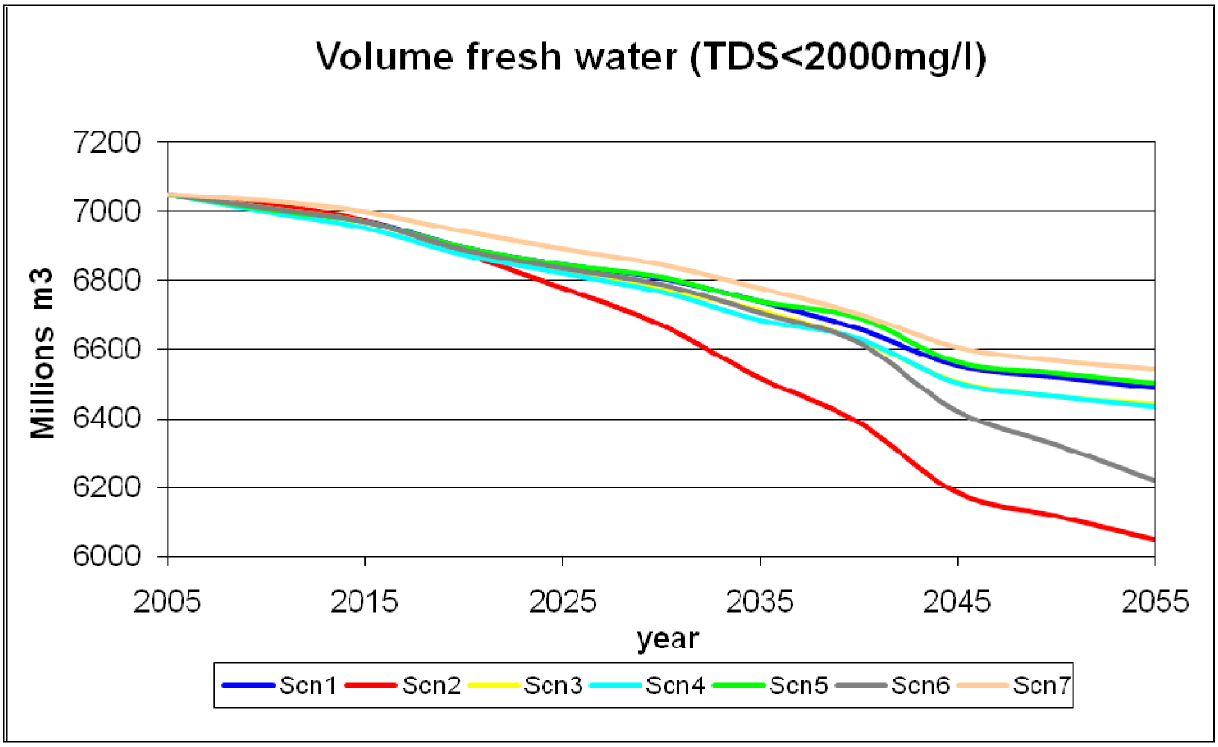

Figure 7-6: Change in fresh groundwater volume in 50 m thick shallow aquifer slab from 2005 till 2055

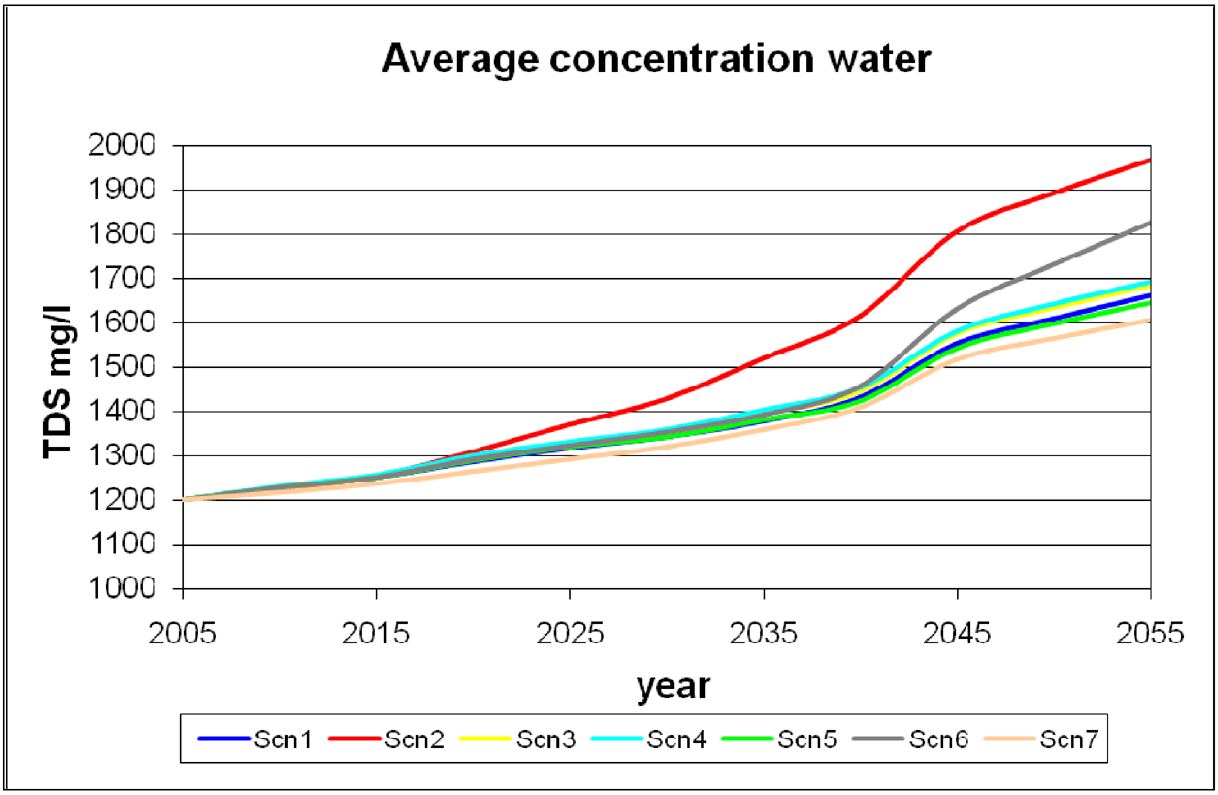

Figure 7-7 : Average concentration of the groundwater from 2005 till 2055

8 Qualitative analysis coastal area Saurashtra

8.1 Introduction

Based on the results of the 3D-groundwater model conclusions can be made about the groundwater salinization situation in the Kodinar region. The groundwater model forms a tool to consolidate learning from the Kodinar area. The model input is site specific in terms of sources and sinks and the geological situation and therefore the hydrogeological parameters. This means that the model outcome cannot be directly used to assess groundwater salinization in other coastal sites in Saurashtra or other places in India. The overall goal of this study is to consolidate learning from the efforts taken in the Kodinar area to deal with groundwater salinization in order to develop recommendations for effective and efficient up-scaling to other parts of Saurashtra and India. Comparing the other salinization affected areas of Saurashtra with the Kodinar area provides a means to upscale the lessons learnt from Kodinar.

The next sections outline the concept and the qualitative analysis of the groundwater water balance in the coastal area of Saurashtra.

8.2 Methodology

As a starting point the data for the whole coast of Saurashtra has been examined to set up a methodology for the analysis. The data that were available include:

- Precipitation records (taluka wise)
- Land use data (taluka wise)
- Storage capacities of artificial recharge structures (catchment wise)
- Hydraulic heads and total dissolved salt data for some areas (village wise)
- Data about affected areas regarding salt intrusion (catchment wise)

Note that these are the main sources and sinks for the groundwater system accept for the contribution to the groundwater system from the rivers. There is no information available about the contribution to the groundwater system from the rivers like storage capacities, water heights or infiltration rates. In this study, it is assumed that the amount of water that contributes to the groundwater system from the rivers is the same for the whole area of Saurashtra. As most of the accessed data are sorted and organized per taluka, the analysis has been set up taluka wise. This means by the previous statement that the amount of water that infiltrates from the river system per hectare in a taluka is the same for every taluka.

The natural recharge has been estimated to be 10% of the precipitation as explained in section 5.4. The methodology used to calculate the amount of groundwater that is used for irrigation is the same as in section 5.3. This means that the amount of water that has been abstracted is the averaged water demand per crop area multiplied with the agricultural area. During the monsoon there is auxiliary irrigation. Expert judgment estimates this to be 100 mm. The artificial recharge structures are modeled in this analysis by saying that each structure is filled 4 times for a precipitation of more than 600 mm. Thus the methodology to calculate the natural recharge, abstraction and the artificial recharge is only valid for medium wet to wet years. So what about dry years?

For dry years the abstraction rates are decreased by 22 % (see 6.3, scenario 6) and the contribution of the artificial recharge structures is decreased. For normal years the structures are filled 4 times. Now, for dry years the structures are filled up only 1 time. As there is an average precipitation which incorporates dry years, the contribution of the natural recharge does not need to change. After the amount of dry years has been determined the several contributions are corrected.

The TDS data have been used just as an indicator for some areas to show whether there is a connection between the findings of the analysis and these data. The way the groundwater has been measured in terms of TDS concentrations is doubtful (see conclusions). However, it can be of value to look at a decrease or increase in TDS concentration per year at a certain village. By determining the slope of this in- or decrease in TDS concentration in the years ’91-’00, this can be seen as a measure for the groundwater balance. Figure 8-1 shows the TDS concentration slope versus the total groundwater balance. Clearly, there is not a correlation.

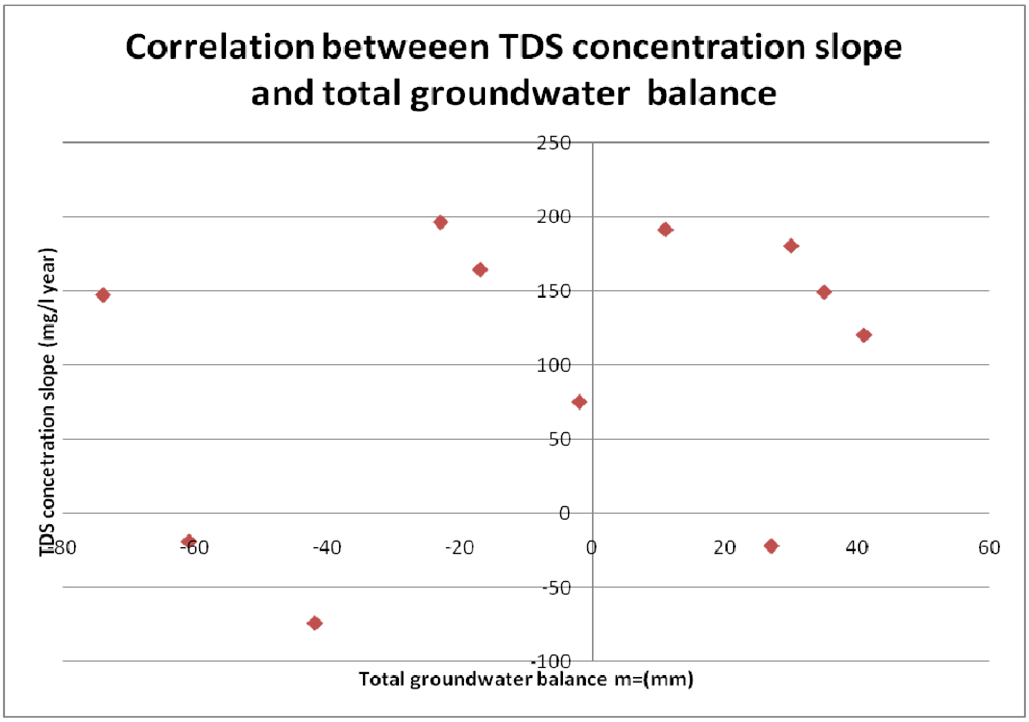

Figure 8-1 : Trend between the TDS concentration slope and the groundwater balance

Dams and major irrigation structures have been included by this analysis. Each dam or major irrigation structure has got an amount of benefitted area per taluka. The amount of benefitted area per artificial recharge structure has been determined by the Government of Gujarat. The amount of benefitted area can be seen as additional surface water for irrigation. Subtracting the amount of benefitted area from the total agricultural area will lead to a better and a corrected abstraction flux.

Similarly the amount of affected area per catchment has been determined by the Government. The fraction of salinization affected area (affected area divided by total surface area of talukas) is assumed to be a measure for the severity of groundwater salinization in that taluka. By plotting the groundwater balance versus the fraction affected area a trend could be established. This is shown in Figure 8-4.

By adding up the various fluxes, the total groundwater balance per taluka can be determined. Additionally the fraction of saline area per taluka and the TDS concentration slope can be determined.

8.3 Results

Figure 8-2 displays the results of the qualitative analysis of the coastal talukas in Saurashtra. The figure shows the various sources and sinks (AR = artificial recharge, Q = groundwater abtraction, NR = natural recharge, TDS = total dissolved salt concentration slope in groundwater) of the groundwater system for the different talukas. Table 12-8, in the appendix, displays the sources and sinks of the groundwater system of each taluka.

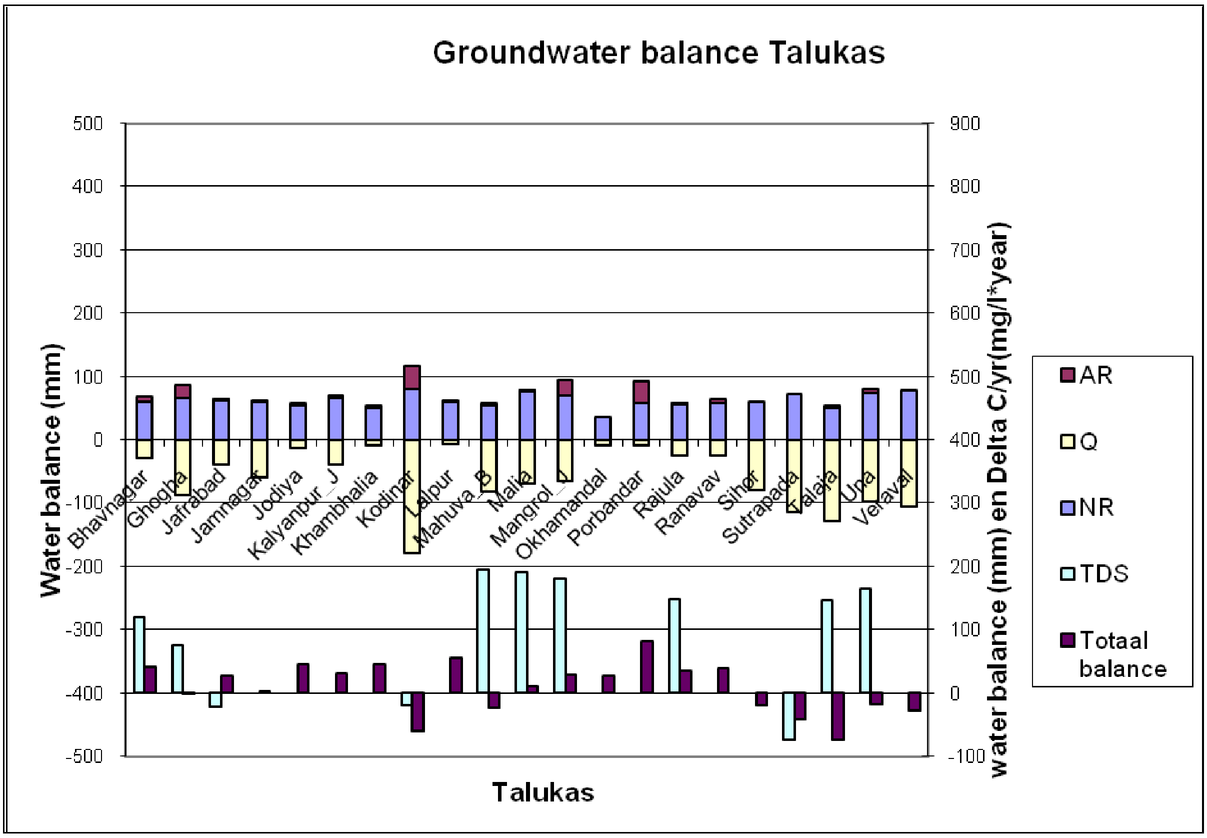

Figure 8-2 : Natural recharge (NR), abstraction (Q), artificial recharge (AR), the total groundwater balance and the TDS slope

Another way to show the results of the analysis is to look at the total groundwater balance and the fraction saline area per taluka (Figure 8-3).

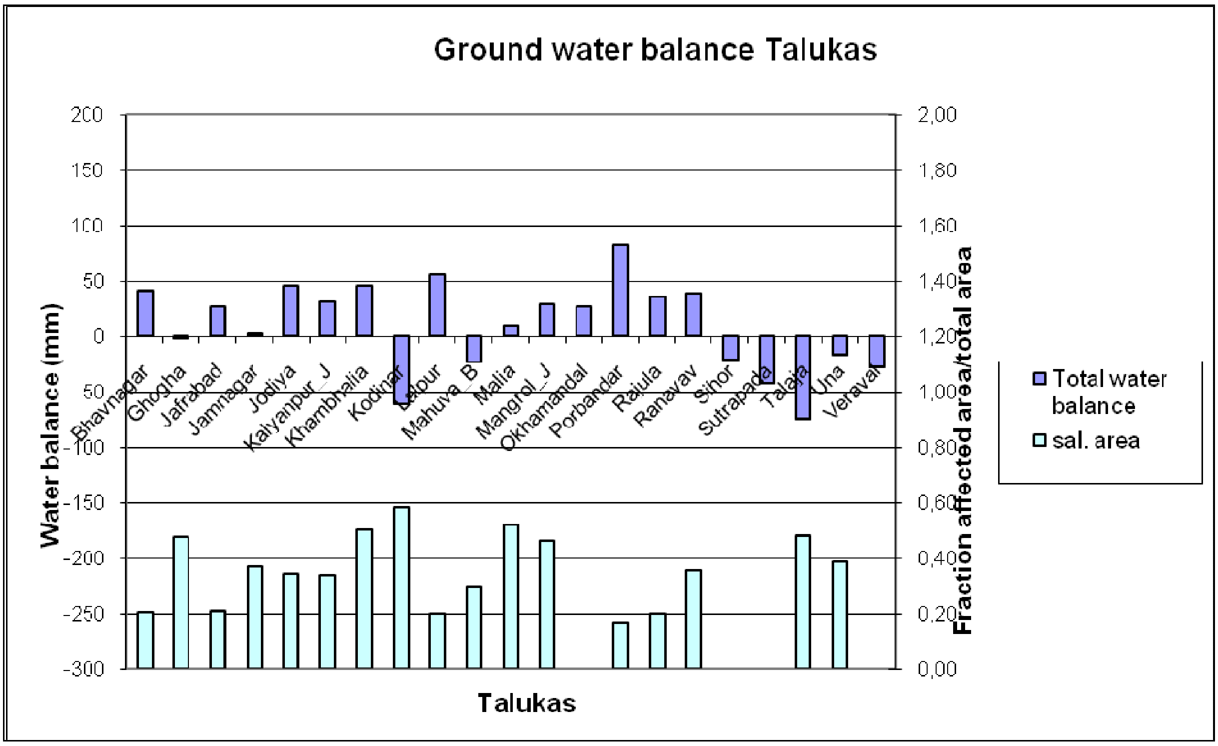

Figure 8-3 : Total groundwater balance and the fraction saline area

No conclusions or relations can be determined by looking at Figure 8-3. Plotting the fraction saline area against the total groundwater balance is therefore needed to make any conclusions if possible. Figure 8-4 illustrates this.

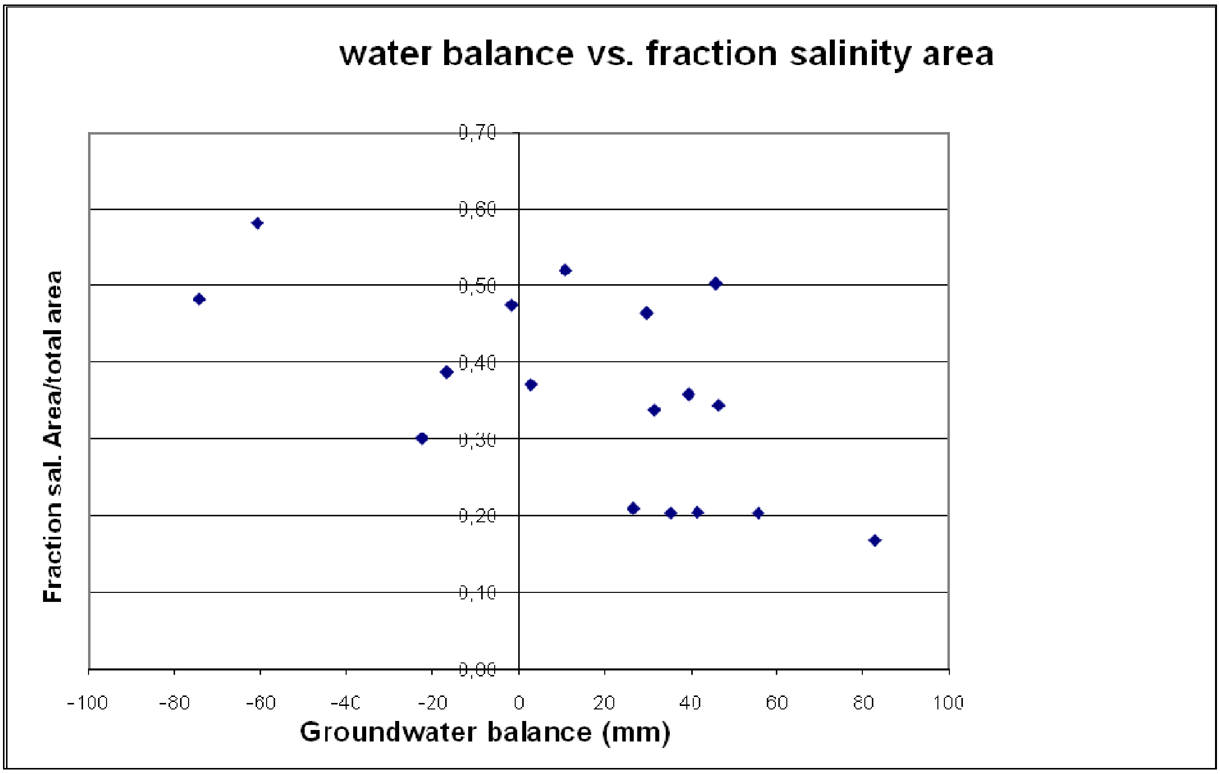

Figure 8-4 : relation between the accumulated groundwater balance and the fraction saline area

Figure 8-4 Shows some relation between the fraction saline area and the total groundwater balance. But if the two points on the left and the right point are left out, there does not seem to be any correlation.

Plotting the results in a map may provide a relation geographically. Figure 8-5 shows the total groundwater balance per taluka. The green colors represent positive total groundwater balances and the red and orange negative total groundwater balances.

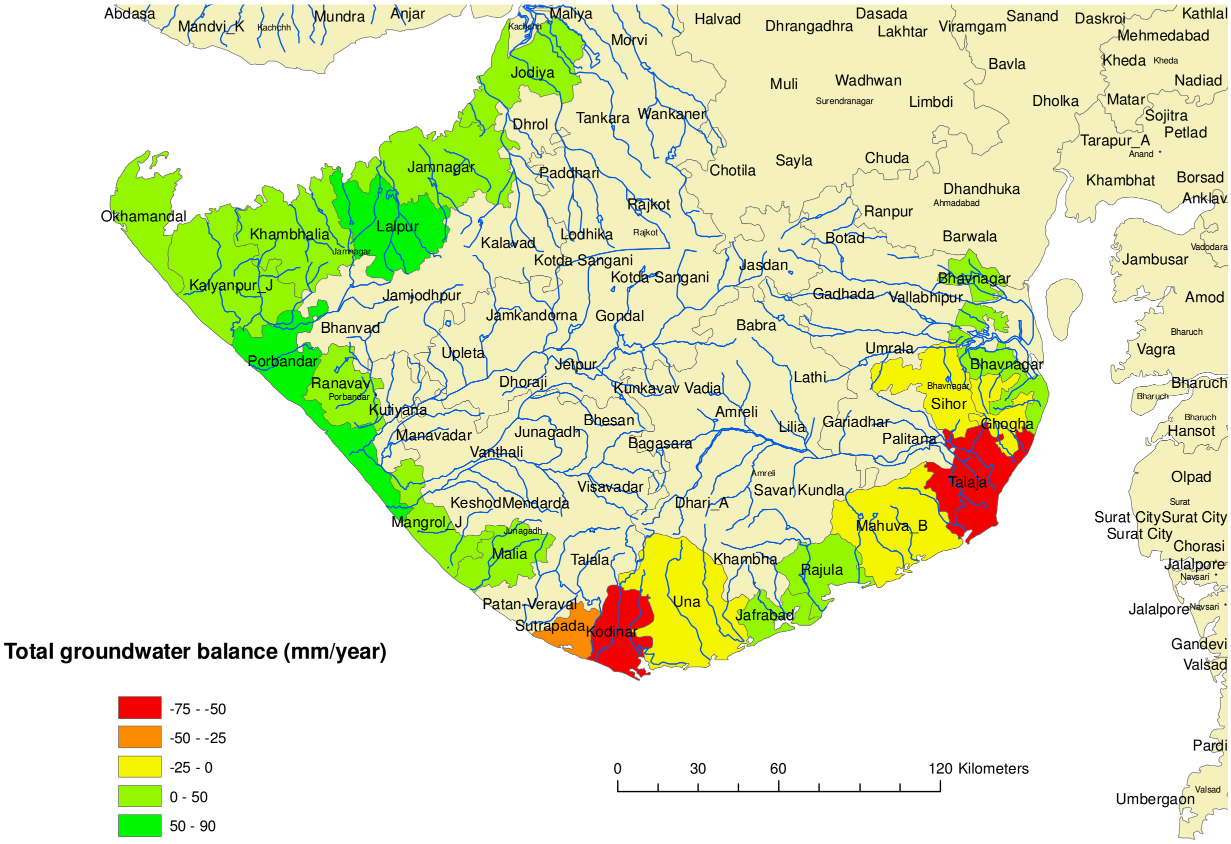

Figure 8-5 : Total groundwater balance per taluka

An illustration of the fraction saline area has been displayed in Figure 8-6. Similarly the green colors represent talukas with low fractions of saline areas and the red colors represent talukas with high fractions of saline areas.

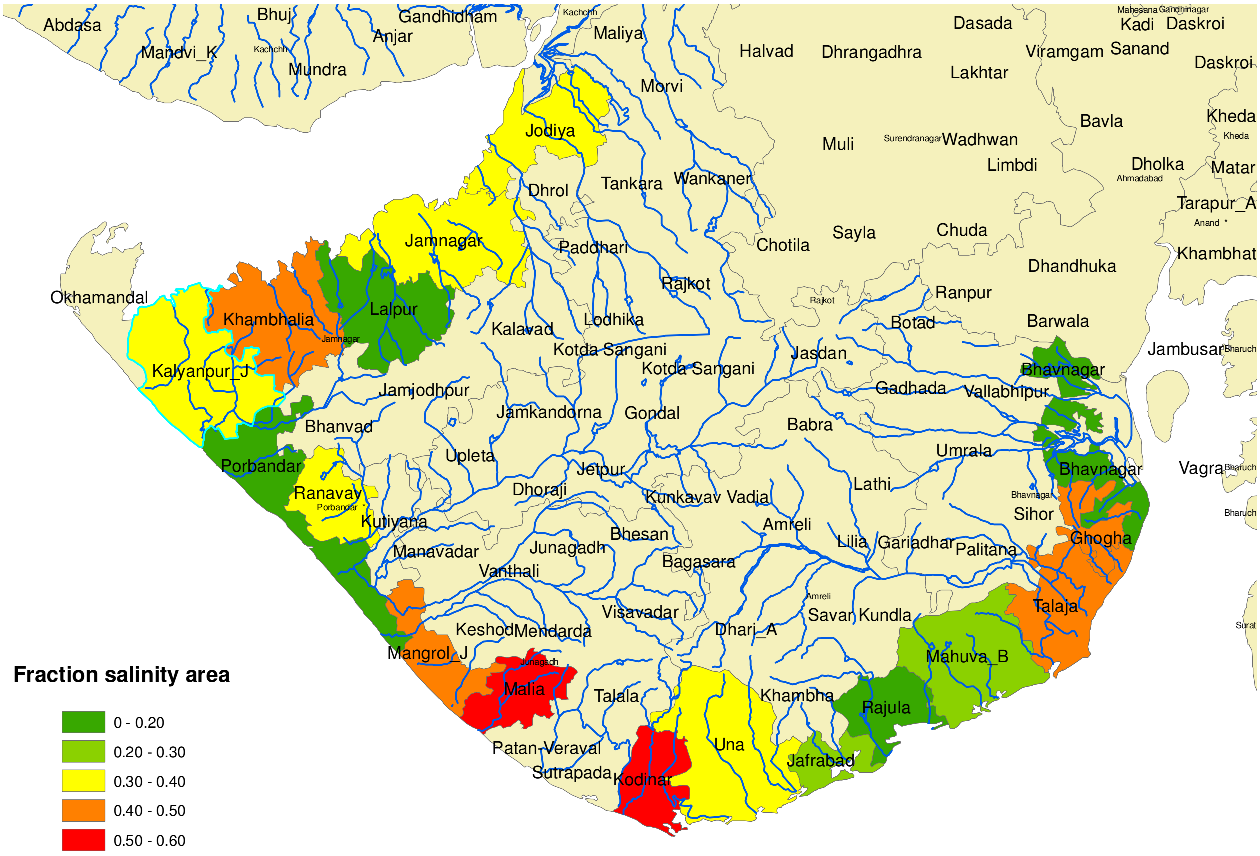

Figure 8-6 : Fraction saline area per taluka

8.4 Analysis and discussion

No conclusions can be made from Figure 8-2 as there does not seem to be any relation between the TDS concentration slope and the total groundwater balance. Additionally one should use caution when interpreting Figure 8-2 as the estimation of the fluxes is doubtful. Also the river fluxes are left out of the study which does not create a realistic view of the situation.

As can be seen from Figure 8-4 there appears to be some relation between the groundwater balance and the fraction of saline area but this must be interpreted with care. The lack of data such as river data, irrigation schemes of dams and major irrigation structures, accurate salinity information explains the poor relation between the fraction saline area and the total groundwater balance and should be incorporated. Now it is assumed that all the artificial recharge structures have been built instantly as the variable time has not been incorporated. How the situation has evolved the last 10 years is missing, so the benefits of artificial recharge could not be visible at all.

Comparison between Figure 8-5 and Figure 8-6 does not provide any clarification. Only talukas Kodinar and Talaja have negative groundwater balances and high fractions of saline areas as was expected. This can be addressed to high abstraction fluxes.

Figure 8-5 and Figure 8-6 show that the situation in Kodinar and Talaja is concerning, though there are a lot of artificial recharge structures in the Kodinar area. These two areas have a high agricultural activity probably due to these structures in normal and wet years. But when there is a dry year and the agricultural activity is maintained, it causes a strong negative groundwater balance in that year. This means that these areas are more sensitive to salinization. Thus, great caution should be taken when there is extra water available due to artificial recharge structures. The fact that there is additional groundwater availability could act as a perverse incentive and therefore can cause an unintended consequence: namely over-withdrawal of groundwater during dry years. Therefore the people of Saurashtra should be aware of this so that it would not turn out into a moral hazard by underestimating the underlying risk of withdrawing extra groundwater for agricultural activities. Thus, additional groundwater availability should be used to stop the salt ingress not for extra agricultural activity.

9 Conclusions

The conclusions sections have been divided into 3 parts:

- Kodinar 3D-groundwater solute transport model
- Qualitative analysis coastal area of Saurashtra
- Process conclusions

Kodinar 3D-groundwater solute transport model.

- The model predicts for the reference case that the groundwater becomes fresher near the coast. This is because there is positive groundwater balance for the entire surface area of + 40 mm/year. Taken porosity into account the water table increases significantly each year (by 1 m each year). This is obviously not very realistic. Note that there is a dry year every 4 years at which there is a groundwater balance of -120 mm/year. When incorporated into the model this should compensate for the rise of the groundwater table and the fact that the coastal area becomes fresher.

- The fact that there is a positive groundwater balance is probably the reason that the seawater front does not seem to be moving towards inland as was expected.

- The parts in the hinterland of the model predict a strong salinization due to low infiltration (low permeabilities) and high abstraction. This causes the up coning of relatively salt water.

- The model predicts negative effects when the artificial recharge structures are left out. This means that the artificial recharge structures are beneficial for the groundwater system and the salinity ingress problem.

- Water saving techniques like drip irrigation are also beneficial. This is the most favorable scenario.

- Climate change phenomena like sea level rise and droughts and the growth of population in the coming 50 years should raise awareness to control the salinity ingress more intensely as they have a strong negative impact in terms of salinization in the Kodinar region.

Qualitative analysis coastal area of Saurashtra.

- As has been shown in Figure 8-4 the relation between the fraction saline area and the groundwater balance is very weak. No conclusions can be made as the mass balances approach misses an important parameter: the river fluxes. It has been assumed that the river fluxes are by default the same which is of course not true.

- The people of Saurashtra should be aware of the moral hazard that additional groundwater availability due to artificial recharge would not act as a perverse incentive to use the additional obtained groundwater for agricultural activities. Thus, additional obtained groundwater due to artificial recharge should be used to control the salt ingress problem.

Process conclusions

- It can be concluded that the 3D-groundwater solute transport model is an important management tool to raise awareness and to control the salinity ingress further, although it must be interpreted with caution as the model partly relies on anecdotal and proxy information.

10 Recommendations

10.1 Improve monitoring of (ground)water levels and TDS

n order to fully understand the salinization processes taking place in the coastal aquifers of Saurashtra it is recommended to improve its monitoring. Currently, monitoring of groundwater table and TDS levels takes place in about 1,850 (most dug) wells on a bi-annual base (pre- and post monsoon measurements). The dynamics of some of the processes take place on a higher pace (like the recharge from all storage structures).

To be able to understand these dynamics a higher monitoring frequency (monthly) is required. Also the geographical scale of the underground processes is often not covered with the existing spatial density of observations. In areas where there are large spatial differences to be assumed (near to features that input or extract groundwater in large volumes) the monitoring data should be increased (e.g. place observation wells in a line perpendicular to some of the check dams length at a space interval of hundreds of meters). The distribution of the observation locations should not be based on administrative criteria as is the case presently (Moench et al., 2003) but on aquifer and river basin characteristics.

Only data for the shallow part of the coastal aquifers exists (since it is mainly monitored from the dug wells). Groundwater salinity levels in the deeper parts of the aquifers are not known. Part of the salinity in the shallow parts may be explained from upcoming of deep saline groundwater. This needs to be verified and hence a number of deep wells should be installed in each river basin in the coastal area and in the hinterland. TDS and groundwater table measurements are currently being taken in dug-wells instead of observation wells. Ideally observations are not conducted in wells that are being pumped or recharged since it affects the measurements. This results in a under- or overestimation of the measurements since the dug wells are used for irrigation purposes. Instead drilled tube well-like observations wells or piezometers should be installed and used for that purpose.

Additionally the water tables and TDS contents in recharge structures (check dams, percolation ponds), rivers, interlinking channels and bhandaras need to be monitored in order to quantify their fluxes. Furthermore infiltration capacity tests need to be carried out in order to estimate the river, percolation tank and checkdam fluxes more accurately.

Bottom line is that the monitoring system in place should serve the purpose of checking trends, sudden changes and effects of distinct measures or large-scale and widespread approaches like land use changes. The monitoring system modalities should fit the Gujarati institutional settings, capacities and resources. It must be noted that designing an effective and efficient monitoring system is a project in itself.

10.2 Update & refine groundwater model

The model is based on relatively scarce data, information derived from proxy data, expert judgment and assumptions based on oral history. At this stage the model is already a useful tool. However, because of the limited quantity and quality of model input, model results should be interpreted with caution. A number of opportunities for model improvement are given here:

- The initial TDS-distribution used in the model is poor since it is based on a limited number of measurements and no information for the deeper parts exists. When additional data becomes available through advanced monitoring the initial TDS-distribution can be improved

- The recharge fluxes from surface water bodies (check dams, rivers) are based on relatively simple concepts. In case data on water level changes in these bodies becomes available we are able to develop more sophisticated concepts of the recharge processes.
- A uniform hydrogeological 2-D profile is laterally extrapolated to create a 3-D model. The hydrogeological geometry used in the model can be improved by taking into account geographical differences in the known geology. Pumping test results in karstified and fractured limestone and basalts should be interpreted carefully since these were developed for porous media aquifers (Moench et al., 2003). Additional pumping tests should be carried out to improve the geographical differences in the hydraulic properties of the soil. Now these hydraulic properties are based on a limited number of experiments.
- The occurrence of karst features and fractures in these aquifers possibly enable conduit-like groundwater flow as well. At this stage the coastal aquifer system is modeled using a porous medium concept. It is assumed that at this large scale and for our purposes this is an acceptable approach. More advance modeling approaches like dual porosity systems could be applied to include these processes. However, it should be noted that even more data is needed to develop such models
- At this stage the reference scenario is based on a 50-year repetition of normal monsoon years. This gives a rather optimistic view on the groundwater balance. In a next step the reference case will include drought years and wet years as well.

Possibly next projects or model uses in the area will provide the opportunity to implement these improvements.

10.3 Integrated groundwater resources management approach

The salinity ingress prevention scheme in Saurashtra is basically carried out by the SIPC, of the Irrigation Department and by a number of NGOs. SIPC’s strength is in the design and engineering of infrastructural works like tidal regulators and checkdams, percolation tanks. By doing this they meet one the recommendations from the HLC, i.e. stopping salinity ingress in the tidal inlets and creeks and increasing groundwater replenishments by collecting and infiltrating runoff. SIPC’s approach to the salinization problem can be described as an *engineering approach*. The NGO approach to salinization is much more *people-oriented*. They frame salinization as one of the problems people and communities at grass-root level have to face in order to improve their livelihood. They have a focus on coping and adaptation and partly also on water harvesting, storage and artificial recharge.

The *integrated groundwater resources management* approach used in this study is complementary to the engineering approach and the people-oriented approach. It uses a constant and frequent monitoring of the groundwater system status to develop and implement groundwater management plans. Though that there is a focus on the groundwater system, links with other water systems, ecology, land and water use are explicitly taken into account. The monitoring includes the status of the systems, trends like salinization and also assessing the effects of implemented measures (like artificial recharge) or policy instruments (like pricing). Monitoring and groundwater resources modelling tools are often and ideally used conjunctively as decision-support tools. The groundwater management plans include both hardware measures (civil engineered structures) as soft measures like regulations, awareness raising, financial instruments. Groundwater management plans are regularly adjusted to the latest system status information and hence have a cyclic, adaptive character.

We propose a salinization prevention approach that is based on an integration of the three above mentioned approaches. We feel that this combination of approaches is needed to be able to implement the complete list of recommendations of the HLCs. Moreover, we feel that this combined approach is needed to update and improve the HLC’s recommendations which are merely based upon information and research form the 1970-ies.

It has been shown that water saving techniques like drip irrigation are beneficial for the water availability and to control salinity ingress as was already assumed in the recommendations of the HLCs. Efforts should be taken to change the irrigation behavior of farmers. Using the *integrated groundwater resources management* approach and applying tools like the groundwater model presented in this report my help to convince and motivate farmers to change their farming practices. Furthermore, based on this study it is advised to raise the amount of artificial recharge structures but keep in mind the downstream effects as there is only a limited amount of water available for instance during dry years. Again using tools such as the groundwater model may support an optimal recharge design.

We suggest that activities are needed to enable this integrated approach to combat salinization:

- Development of sufficient knowledge and expertise on hydrology, hydrogeology, and natural resources management in those Governmental departments and NGO that deal with salinization. This basically means hiring those expert people or training of already employed staff. In this respect it is noteworthy to mention that Deltares is running a barefoot hydrologists programme with the NGO Gram Vikas in Orissa. In this programme, some staff of this NGO are trained to become barefoot hydrologist. It is assumed to enable them to make the right choices and decisions in their catchment management programmes, to communicate with governmental officials, researchers and consultants when it comes to technical groundwater management issues. This programme is appreciated and may be repeated with Gujarati NGOs.
- Increased cooperation between the various governmental departments that deal with water and land management in the salinity ingress prevention programme (as was originally recommended by the HLC.
- Increased coordination of governmental and NGOs'salinity ingress prevention activities. CSPC is currently successfully performing this coordinating role. Enlargement of their capacity would enable this increased coordination.

10.4 Data access for all

There is already a large amount of data on groundwater systems available. However, in this project it was found that most of this data is not easily accessible, non-consistent and non-verified and often non-complete (with gaps in monitoring frequency and density). Also duplication of monitoring activities takes place because of a lack of understanding and coordination between different organisations. We strongly recommend a situation where there is data access for all those stakeholders (from individual farmers to governmental agencies that perform strategic water resources planning) that somehow might benefit from using the data. Ideally all data is:

- uniformly collected, stored and analyzed based upon internationally (or at least locally) accepted standards
- checked and verified to exclude and eliminate outliers or mistakes by means of simple analysis
- stored in a digital form in a central computerized database
  put in the public domain ideally without any use restriction and at affordable costs (ideally for free for the end users)
- easily accessible via a website or via regular updates send by email, in reports and on CDs
- analyzed by an expert organisation to derive information (maps, trends) which is also put in the public domain.

Summarized the way forward (the consolidated learning) in managing salinization according to this study is in

- the use of frequent monitoring and groundwater models as a decision support system tools
- taking a regional approach based on river basins/and or aquifers where the various water subsystems are linked

- having a central role for CSPC that combines engineering approach, people-centered approach and the integrated groundwater resources management approach
- organizing regular combined meetings of several NGOs and the various relevant departments of the Government of Gujarat.

10.5 Study how to balance water in basalt aquifer to stop salinization

This study showed effects of salinization in the hinterland. Since measurements in the hinterland are scarce it is hard to check whether the model predictions are actually true. In order to verify, this part of the coastal zone needs to be monitored more closely. In case the model predictions correspond with measurement more efforts should be put in trying to balance groundwater recharge with groundwater abstraction in this area. It is known that recharging the basalt aquifer is much more difficult than recharging the limestone aquifers. What other solutions are possible for this area..

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12 Appendix

12.1 Organizational chart

The following list displays the explanations of the abbreviations of the stakeholders and partners mentioned in the introduction:

ACF	:	Ambuja cement Foundation
ACT	:	Arid Communities and Technologies
AKRSP	:	Aga Khan Rural Support Programme
CBO	:	Civil based organization
CSPC	:	Coastal Salinity Prevention Cell
DUT	:	Delt University of Technology
EIA	:	Environmental impact Assessment
FED	:	Forest and Environmental Department
FES	:	Foundation for ecological systems
GoG	:	Government of Gujarat
HLC-I & II	:	High Level committee I and II
ICZP	:	Integrated Coastal Plan
IGRAC	:	International Groundwater Resources Assessment centre
IRAP	:	Institute for Resources Analysis and policy
IWMI	:	International Water management Institute
IWRM	:	Integrated Water resources Management
KVY	:	Kharsh Vistarotthan Yojana
MAR	:	Managed Aquifer Recharge
NABARD	:	National bank for Agriculture and Rural
NGO	:	Non-Governmental organization
NRM	:	Natural Resources Management
NWRWS	:	Narmada Water Resources, Water Supply and Kalpsar Department
RWH	:	Rainwater harvesting
SAVE	:	Saline Area Vitalization Enterprise
SIPC	:	Salinity Ingress Prevention and Control
SRRT	:	Sir Rathan Tata Terust
TCSRD	:	Tata Chemicals Society for Rural Development
VRTI	:	Vivekanand Research Training Institute
WB	:	Worldbank
WUA	:	Water User Association

12.2 Number of fillings and evaporation data

The various artificial recharge structures are shown below in Table 12-1:

Table 12-1: Various recharge structures

Artificial recharge structures
Percolation Tank
Checkdam
Bhandara
Spreading channel

The following table shows the filling data for the checkdams and percolation tanks:

Table 12-2 : Number of fillings for recharge structures

Fillings	Number	Month
	0.5	June
	1	July
	1	August
	0.5	September
	1	Oktober

As has been displayed in section 4.2, the precipitation starts normally the 15th of June and ends at the end of September. Most of the precipitation will fall during July and August resulting in one filling for these months. As it will take time for the water to reach the river system as groundwater flow and runoff the number of fillings for October is one. Note that this filling scheme only holds for a normal year in terms of precipitation which is 800 mm.

The following table displays the monthly evaporation data:

Table 12-3 : evaporation data for each month

Evaporation	[mm/month]	[m/year]
January	140	1.68
February	180	2.16
March	250	3.00
April	350	4.20
May	400	4.80
June	350	4.20
July	300	3.60
August	200	2.40
September	200	2.40
October	175	2.10
November	150	1.80
December	120	1.44
average	235	2.27

12.3 Abstraction data

The following table shows the amount of hectares per crop per taluka in the year 2001:

Table 12-4 : Land use (ha)

village	Paddy	Jowar	Bajara	Wheat	Moong	Udid	Tur	Gram	S'cane	Cotton	Sesamum	G'nut	Castor	Mustard	Cumin	sum
Sutrapada	*0*	*25*	*1150*	*4000*	*100*	*50*	*0*	*50*	*300*	*150*	*150*	*18160*	*10*	*20*	*10*	*24175*
Kodinar	*0*	*200*	*8500*	*7000*	*350*	*450*	*60*	*300*	*4000*	*3000*	*250*	*22000*	*250*	*250*	*0*	*46610*
Una	*0*	*20*	*7500*	*4150*	*450*	*350*	*300*	*350*	*130*	*11020*	*530*	*38750*	*0*	*50*	*1150*	*64750*
Talala	*0*	*0*	*400*	*4500*	*100*	*600*	*1300*	*560*	*3500*	*505*	*180*	*16500*	*200*	*20*	*25*	*28390*

Every crop needs a certain amount of water column. The table below shows the irrigation demand per crop per season in mm water column.

Table 12-5 : Irrigation demand per crop in Kodinar area

cropping season	Paddy	Jowar	Bajara	Wheat	Moong	Udid	Tur	Gram	S'cane	Cotton	Sesamum	G'nut	Castor	Mustard	Cumin
Monsoon		50	50	50	50	50	100	50	100	50	50	50	50	50	50
Winter		300	350	500	300	300	600	300	1075	550	300	400	500	300	300
Summer		300	350	500	300	300	600	300	1075		300	400		300	300

Not every crop is grown in every season. The following table shows the fraction per season for each crop:

Table 12-6 : fraction of the agricultural area per crop that is grown in each season in Kodinar area

cropping season	Paddy	Jowar	Bajara	Wheat	Moong	Udid	Tur	Gram	S'cane	Cotton	Sesamum	G'nut	Castor	Mustard	Cumin
monsoon	1	0.5	0.8		0.25	1	1		1	1	0	0.8	1		
Winter		0.3	0	1				1	1	1			1	1	1
Summer		0.2	0.2		0.75	1			1		1	0.2	0		
Sum	1	1	1	1	1	2	1	1	3	2	1	1	2	1	1

In order to calculate the total water demand for a certain village, the so called total irrigation area in the GIS files is used to calculate this. Since these data do not fully comply with the data available from the Agricultural Department in Gandhinagar, the data is recalculated with a factor to meet with these inconsistencies:

Table 12-7 : correction factor for the agricultural area: f_{irr}

Taluka	winter	summer	monsoon
Sutrapada	0.58	0.42	1.97
Kodinar	0.61	0.39	1.39
Una	0.62	0.38	1.53
Talala	0.62	0.38	1.53

12.4 Boundary conditions

1. Boundary

There are 2 groups:

a. Ground: they are calculated in this package
b. Surface boundaries: they are calculated partly in this package and partly in the well-recharge package

a. <u>Ground</u>

Inside this group we find 3 subgroups

<u>MOUNTAIN BOUNDARY:</u>

- Surface
    - Ghb=2
    - where: first row and cells which are just under the air (mountain boundary surface)
    - **head=0.9*maaiveld – x**; x goes from 12,5 and 17 and it changes with the month

- Deep
    - Ghb=2
    - Where: first row and cells which are one layer lover than the cells that are just under the air (mountain boundary deep)
    - **Head= head of the layer above + delta correction**
        - Delta correction= alfa times (half the concentration of the cell + half the concentration of the cell above) divided by 35.000 and times the mean of the cell size in respect z.

<u>SEA BOUNDARY</u>

- Surface
    - Ghb=1
    - Where: first layer with ibound=2, which means cells in the sea just below sea level
    - **Head: msl*(slr*(time-1)/12)+delta correction = delta correction**
        - Delta correction= alfa times (half the concentration of the cell + half the concentration of the cell above) divided by 35.000 and times the mean of the cell size in respect z.

- Deep
    - Ghb=3
    - Where: last row and cells that are below the cells that are just below the sea level
    - **Head: head of the layer above + delta correction**
        - Delta correction= alfa times the mean of concentrations of that cell and the cell above divided by 35.000

<u>REST MODEL AREA</u>

- Ghb=0

- These cells don't have a **head,** which means that MODFLOW will calculate it.
- In the sides of the model (so E and W) there is a no flow boundary.
- The bottom of the model is also considered a no flow boundary.

b. <u>Surface</u>

<u>BHANDARAS</u>

There are three types of bhandaras:

- Bhandara 1
  - **Head: original head times de factor that is valid for the month of the stress period that is being calculated**

- Bhandara 2
  - **Head: original head times de factor that is valid for the month of the stress period that is being calculated**

- Bhandara 3
  - **Head: original head times de factor that is valid for the month of the stress period that is being calculated**

<u>CHANNELS</u>

- **Head: (maaiveld – 2) times 1**

<u>MINE</u>

- **Head: (maaiveld – 5) times 1**

2. Concentration

- Groundwater: The concentration increases from 100 to 35000mg/l TDS along the 41 layers.

  There is a trial to make the wedge and distribute the concentrations in the wedge. The wedge is now a straight line which starts at the coast and goes inside approximately

  Options:
  - Improve the wedge
  - Leave the wedge as it is now

- Bhandaras:
  - Bhandara 1: Concentration: 1100
  - Bhandara 2: Concentration: 2100
  - Bhandara 3: Concentration: 3100

- Channels: Concentration: 600
- Mines: concentration: 4500

3. Conductance

Mountain boundary = 1000
Sea boundary = 1000
Bhandara = 100
Channel = 100
Mine = 100
Drains = 100

12.5 Saurashtra wide analysis

Table 12-8 shows the various sources and sinks of the groundwater system in the coastal area in Saurashtra:

Table 12-8: Sink, sources, the groundwater balance and the fraction of salinity area

Talukas	NR (mm)	AR_nett (mm)	Abstraction (mm)	Total_balance (mm)	TDS (mg/l*yr)	fractionsal
Bhavnagar	61	8	-28	41	120	0.20
Ghogha	66	21	-88	-2	75	0.48
Jafrabad	64	1	-39	27	-22	0.21
Jamnagar	59	2	-59	3	0	0.37
Jodiya	54	5	-13	46	0	0.34
Kalyanpur_J	67	2	-38	31	0	0.34
Khambhalia	50	4	-9	46	0	0.50
Kodinar	80	37	-178	-61	-19	0.58
Lalpur	59	3	-7	56	0	0.20
Mahuva_B	55	3	-81	-23	196	0.30
Malia	78	1	-68	11	191	0.52
Mangrol_J	71	23	-64	30	180	0.47
Okhamandal	36	0	-9	27	0	0.00
Porbandar	58	34	-9	83	0	0.17
Rajula	58	1	-24	35	149	0.20
Ranavav	59	6	-25	39	0	0.36
Sihor	60	0	-80	-20	0	0.00
Sutrapada	72	0	-113	-42	-74	0.00
Talaja	51	3	-129	-74	147	0.48
Una	75	5	-97	-17	164	0.39
Patan-Veraval	80	0	-107	-27	0	0.00