Consolidated learning from the salinity ingress prevention program in Gujarat India

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Abstract
The socio-economic and environmental problems caused by the groundwater salinization in the coastal area of Saurashtra were acknowledged already in the late 1970s. Since then, the government, NGOs and the local people tried to stop, reverse and cope with groundwater salinization in a joint program. This study looks at the effects of this long-term program and consolidates learning by taking a groundwater resources management approach. For 3 river basins, a groundwater flow and solutes transport model is developed to estimate the effects of various existing and proposed measures and scenarios. The study illustrates the importance of using a groundwater resources management approach to design and optimize effective and efficient measures to counter groundwater salinization.

Introduction
Government of Gujarat (GoG) has shown awareness of the problem of salinity right from the early 1970s, when the groundwater in the coastal areas of Saurashtra and Kutch showed alarmingly rising salinity content. Two governmental High Level Committees (HLCs) examined the problem of salinity. The HLCs observed that ecological balance in the region was disturbed due to over withdrawal of groundwater as compared to its recharge. This had led to seawater intrusion, which increased the salinity of land and water in this coastal area. The salinity caused many problems like paucity of drinking water, reduction in areas under cultivation, reduction of yield, migration of people from the region and health hazards for people and cattle. The HLCs developed a 3-tier programme based on:

1) groundwater demand management techniques by means of awareness raising, implementation of water saving measures and policy instruments
2) artificial recharge of the coastal aquifers with fresh surplus runoff in various types of engineered measures
3) salinity control techniques stopping ingress of seawater through mouths of river or creeks with the aid of tidal regulators, bandharas linked by spreading channels to create a continuous pressure wall and static barriers for salinity control.

The Irrigation Department of GoG took up full responsibility and has set up the SIPC (Salinity Ingress Prevention and Control) Project to implement those recommendations, which fell within the purview of their activities. Other departments have shown less involvement. The result is that there has been a focus on the engineering approach part of the programme while the groundwater demand management approach merely has been neglected. Moreover, the number of engineered structures built and the area covered have been less than planned.

Apart from the governmental efforts, various NGOs are active in the salinity affected areas of Saurashtra and Kutch. Their work is supplementary to the GoG as they take a people-oriented and community participatory approach and focus on salinity adaptation and development of overall community resilience.

Research objectives

This study focuses on the Kodinar area where the governmental and NGOs' efforts to stop groundwater salinity have been extensive. Positive results of the implemented programme 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). 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. However, the research to check the impact of the various implemented measures has hardly been based on an integrated groundwater resources management approach.

The recommendations of the HLCs which were made in the late 1970s are still being implemented up to today. In this study a groundwater resources management approach is taken to check whether these recommendations are still valid in the first decade of the new millennium. A groundwater flow and solutes transport model is developed to check the impact of various land and water use scenarios in the Kodinar area for the next 50 years.

Study area description

Our area of interest measures 31 by 42 km^2 and covers most of the Somat, Singoda and Sangavadi river basins (Figure 1). 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 (administrative subdivision often comprising a town and neighboring villages) and parts of Sutrapada, Talala and Una talukas. A total population of 216,015 (census 2001 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 assumed to be related to this industry.

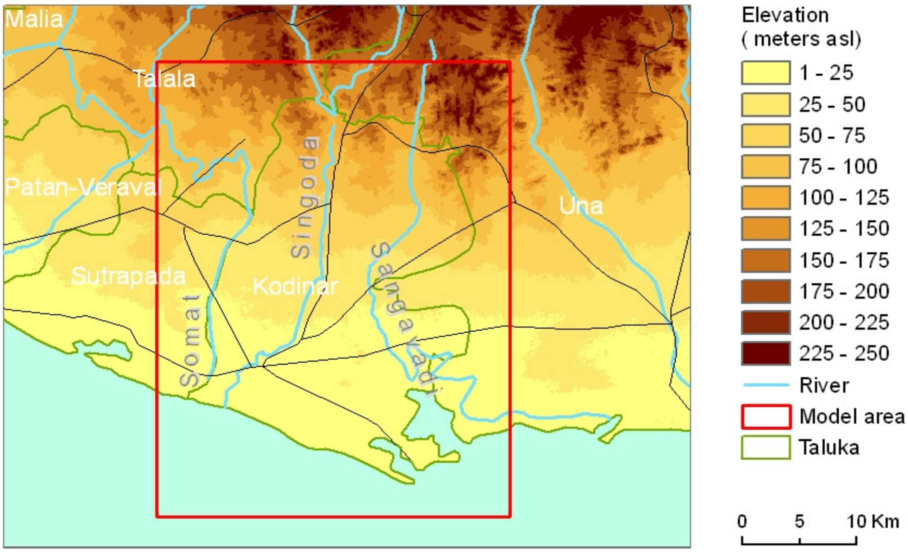

Figure 1. Model area with altitude distribution and the Somat, Singoda and Sangavadi river basins

Geology and hydrogeology

Data and information on the (hydro)geology in the model domain is relatively scarce, only partly accessible and sometimes inconsistent. Data from pumping tests and local (hydro-) geological surveys (Geoconsult 2009; GoG 2000), expertise and knowledge from groundwater experts that have worked in the area are combined with literature data (Pujari and Soni 2008; Rushton and Rao 1988) and expert judgment to make best guess estimates of the hydrogeological characteristics and properties like layer thicknesses, hydraulic conductivity (K), storativity (S), specific yield (sy) and porosity (n) in the model area.

The geology of the modeled area is described by a basement formed by Deccan basalts which are highly fractured in the top 20 or 50 meters, especially in the outcropping areas. This is overlain by the Gaj Formation, which includes thin layers formed by clay, limestone, chalk and marl. Overlaying the Gaj Formation we find Miliolitic limestone which has primary porosity and is heavily cavernous in some locations. Also fractures and dykes have been found in it. On top of the limestone, occasional alluvial or coastal deposits consisting of less than 5 meters of sand and gravel are found. A simplified hydrogeological profile running from the coast to the hills in the North is shown in Figure 2.

The direction, distribution and size and the level of conductance or impermeability of the caverns, fractures, and dykes are hardly known. Therefore, the various hydrogeological units are considered as homogeneous and isotropic with two exceptions. The cavern distribution is assumed higher in the coastal areas than inland. (Rusthon and Rao 1988). In this study we used following distributions: from the coast to about 15 km inland, 25% of the Miolitic limestone is cavernous, and from 15 km inland to the end of the model, 10% is cavernous. The cavernous and non-cavernous parts of the limestone have an estimated K of 600 and 25m/d. An effective K is determined based on a weighted average of the previous values. Because of the inter-layering of clay layers in the Gaj formation the vertical component of K is assumed 10 times smaller than the horizontal component.

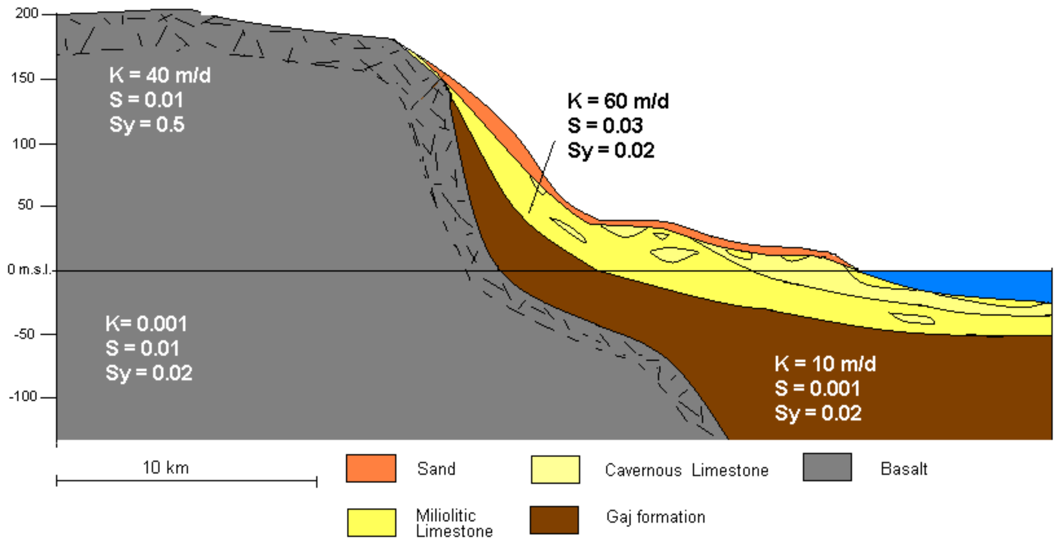

Figure 2. Hydrogeological length profile

The groundwater and solutes balance

Following fluxes determine the groundwater and solutes mass balances in the modeled domain: natural recharge, artificial recharge, groundwater abstraction, river fluxes and lateral in- and outflow.

The natural recharge is the amount of precipitation that infiltrates and eventually replenishes the groundwater reservoir. In this study, we estimated the natural recharge of coastal talukas in Saurashtra using the groundwater table fluctuation method. This method is well suited to determine seasonal groundwater storage and natural recharge estimates for unconfined hard-rock aquifers under a monsoon regime (Maréchal et al. 2006). 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. The averaged natural recharge is 10% of the precipitation. This number corresponds well with the data found in the literature (Rangarajan and Athavale 2000) and from expert judgment. The average amount of precipitation in normal, wet and dry monsoons, measures 800, 1200 and 400 mm/yr for this area. Monsoon starts half of June and ends half of September. The TDS concentration of the infiltrating precipitation is assumed to be 10 mg/l.

Surplus runoff is collected in various recharge structures like checkdams in the rivers, percolation ponds (some are improved by installing recharge wells in them). The number of checkdams and the percolation tanks/ponds in the model domain are 60 and 74. Water levels and stream flows in or out of these structures are not monitored. Hence the amount of recharge is estimated based on anecdotal information from experts working in the locally present NGOs and from farmers. They experience that these recharge structures fill up and empty 4 times during a normal and wet monsoons and 1 time during a dry monsoon. It is assumed that these volumes of stored runoff totally recharge the groundwater systems except for the evaporative loss that happens when the water ponds in these structures. The TDS concentration of the infiltrating runoff in checkdams and tanks/ponds is assumed to be 600 and 100 mg/l.

Groundwater abstraction in this part of India (like in most of India) is not metered. Hence to determine the groundwater abstraction flux, proxy information is used. In this study, this flux is determined by using census data (2001) and governmental information on agricultural production. Irrigation engineers from the Farm Science Center in Kodinar determined a regional cropping calendar with irrigation groundwater demands per crop and per season. Taluka-wise and multi-annual data on cropping areas and the regional cropping calendar form the base to produce effective irrigation demands. Village-wise information (census 2001) on irrigated areas (in total about 30,000 hectares) determines the geographical distribution of groundwater abstraction over the model domain. A return flow factor of 30% is taken into account. Groundwater abstraction reduces to 70% after dry monsoons.

Based on anecdotal information we assumed that rivers and spreading channels hold water and infiltrate into the groundwater systems from June till October. They do not drain the groundwater in the subsequent months. The TDS concentration of the infiltrating runoff in rivers/spreading channels is assumed to be 300 mg/l. At the coast, dams block some of the river mouths creating large freshwater reservoirs (Bhandaras) in the tidal flats. It is assumed that water from this bhandaras does not infiltrate significantly but acts as a hydraulic pressure wall decreasing sea water intrusion.

Figure 3 shows the resulting monthly-based groundwater balance for a normal year. It gives a net and positive annual groundwater balance of 40 mm/yr. In wet and dry years the net annual balance is assumed to be 55 and -112 mm/yr.

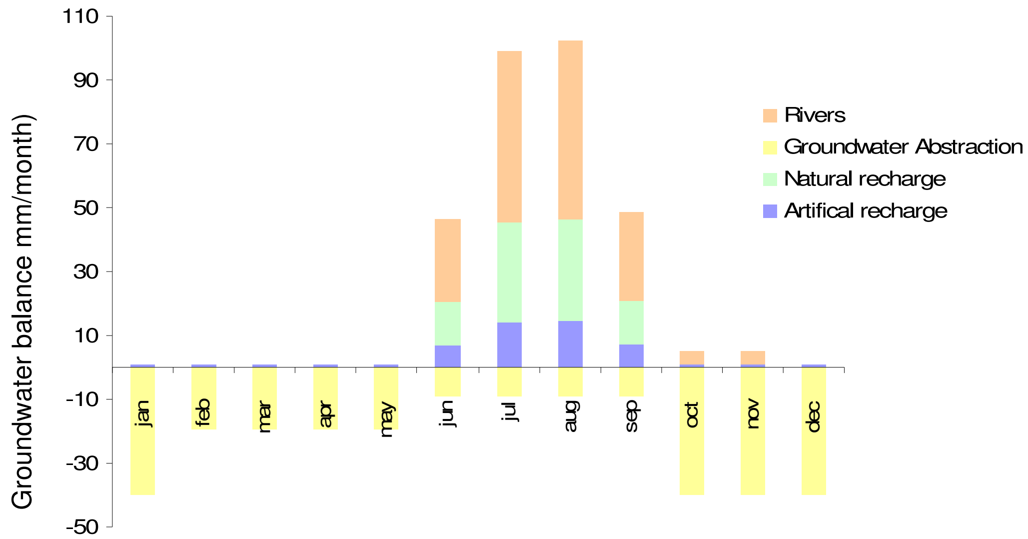

Figure 3. Monthly-based groundwater balance for a normal year

The orientation of the model domain is such that it grossly aligns with the water divides on the long sides such that there is no groundwater flow across those boundaries. At the coast (southern side) a constant head and a constant TDS boundary (seawater concentration) is used. At the northern side a constant head (with seasonal change) and a constant TDS is assumed. The initial head conditions are based on a head-surface level function based on observations. A typical saline intrusion wedge was defined based on measurement and expert judgment. The model was initially run till the solutes mass balance stabilizes. Final concentrations of that run are used as initial conditions for other simulations.

The high TDS concentrations encountered when dealing with seawater intrusion necessitates the full coupling of the groundwater flow and solute transport processes: due to the concentration differences, hydraulic properties vary in magnitude; high groundwater density cause gravitational groundwater flow. A combination of the codes Modflow and MOCDENS3D (Oude Essink 2001) facilitates this. The model domain has cells with constant lateral dimensions of 200 by 200 m and 41 layers of varying thicknesses.

Scenarios

This groundwater flow and transport model is developed to check the validity of the HLC-recommendations in the current and future context of technical, socio-economic and climate conditions. For that goal, following scenarios are developed with the support of a group of Gujarati water resources and agricultural researchers/engineers and socio-economic researchers and planners:

1) *Reference case:* the shown groundwater balance when normal monsoons prevail for 50 years

2) *Reference case without artificial recharge:* this is a "what if" scenario to show the influence of the artificial recharge structures and bhandaras
3) *Business as usual – increase in population, increase in abstraction:* Saurashtra's population will grow 1% per year till 2025, after 2025 the population will grow 7% till 2050. Abstraction rates will increase accordingly (IWMI 2007).
4) *Business to the max:* In this scenario, agricultural production is maximized. Groundwater abstraction in summertime will increases to the level of the winter time.
5) *Reference case plus industrial zone development:* GoG is currently studying new coastal zone developing plans including industrialization. This scenario has an increase of industrial abstraction of about 5 million m^3/year
6) *Drought scenario – climate change, sea level rise:* Due to climate change sea level rises 0.5 cm/year. Also, the Saurashtra area gets drier. 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 is people's adaptation due to 22% less abstraction.
7) *Reference case plus water saving measures:* Farmers will adopt and implant water saving technologies without increasing their cultivated area to save pumping costs and ensure fresh water availability. This will result in a 30% abstraction reduction.

Preliminary results

Figure 4 shows map views with calculated TDS concentrations (mg/l) in the shallow part aquifers for the reference case. The left part shows the 'current situation' (year 2000) and the right part shows the 'future situation' (let's say year 2050). The figure shows 3 distinct geographical zones. First, the aquifer underlying the sea clearly shows high TDS concentrations. Secondly, there is a zone where the limestone aquifers outcrop having the freshest groundwater, mostly with a TDS less than 3,000 mg/l. thirdly, the basalt outcropping zones in the northern part show TDS values between 3,000-10,000 mg/l.

According to the model calculations the limestone zone gets slowly fresher in the next 50 years. The reference case is based on normal monsoon years where we estimated a net groundwater replenishment of about 40 mm/year from the top system. In case we would take into account the effects of dry monsoon years (with a negative groundwater flux) the calculated change might be less significant or even turn direction. The basalt aquifers turn more saline. In this zone there is limited infiltration of fresh precipitation and a limited amount of artificial recharge. Groundwater abstraction causes upconing of saline groundwater that is assumed to exist at greater depths in the basalt. Vertical profiles (not shown here) do not show a lateral movement of some sort of fresh/saline groundwater interface as is often displayed in maps with salinity fronts.

Figure 5 shows the calculated temporal change of averaged TDS concentrations for

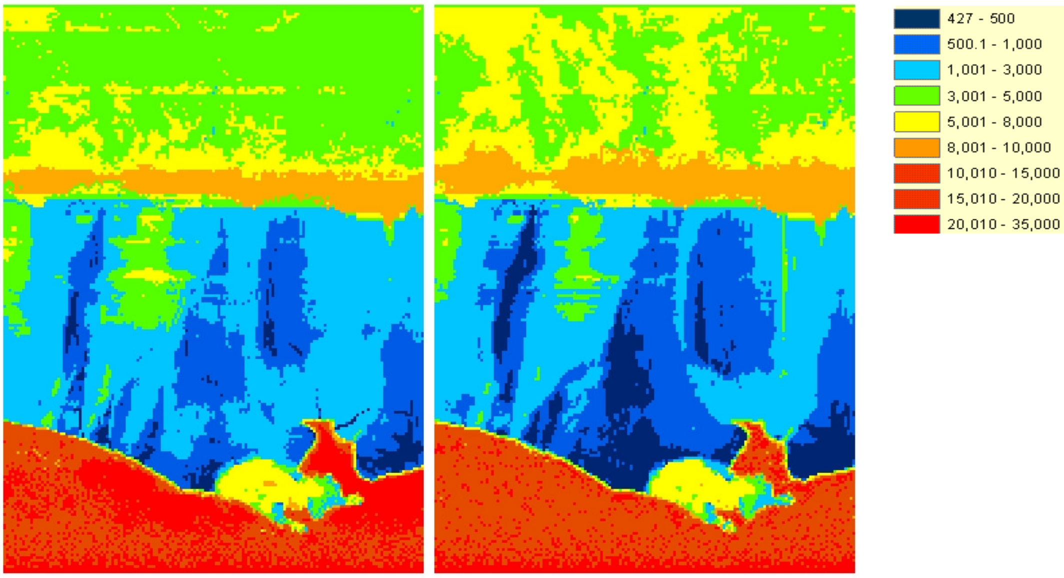

Figure 4. Calculated TDS concentrations (mg/l) in the shallow aquifers for the reference case for the year 2000 and 2050

the scenarios. These concentrations are averaged over about 100 observations of locations in the upper part of the limestone aquifers. All scenarios show a salinity decrease after 50 years like the reference case. Scenarios 3, 4 and 5 taking into account population growth, profit maximizing and industrial development with groundwater use, result in less freshening. Scenario 6 taking into account climate change even shows a salinization trend after 30 years. A combination of these scenarios is not hard to imagine and may be the future reality. In that case the accumulated result for this area is likely to be groundwater salinization. Scenario 7 shows the clear effect of groundwater saving technologies on salinity reduction. The results of scenario 2 (removing the artificial recharge) were expected to show less salinity reduction.

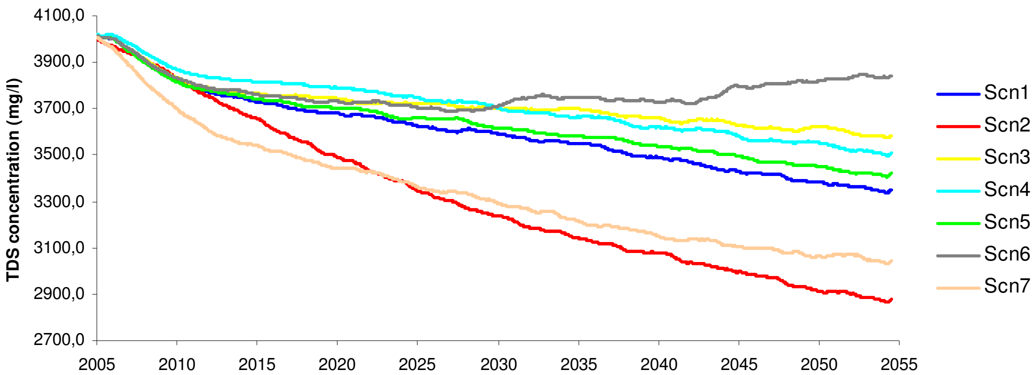

Figure 5. Calculated change of averaged TDS concentrations with time for the various scenarios in upper part of limestone aquifers

The reason for this trend is investigated and will lead to an updated and improved groundwater flow and solutes transport model for this area.

Discussion & Conclusions

This study shows the benefits of a groundwater resources management approach. It uses aquifers and river-basins as research units instead of villages or talukas and is based on data analysis. It integrates the effect of climate, hydrogeology, land and water use and technical intervention and adaptation in stead of focusing on single topics. In this approach, context changes are not seen as unforeseen circumstances complicating plan development but explicitly and continuously anticipated upon. It is thought that this approach is very supportive to the engineering approach and the people-oriented approach already used by the GoG and NGOs in the area.

An important tool in the groundwater resource management approach is the computer model that can simulate groundwater system processes. The groundwater flow model and solutes transport model as presented in this paper is very useful for understanding the various complex processes that are hidden under the surface. For example this model shows that up-coning of deep saline groundwater is the most logical reason for the salinization in the shallower aquifer instead of lateral sea water intrusion. Visualized results of such models are powerful teaching and awareness raising aides.

The model as presented here has not been calibrated extensively and must be considered as a prototype with opportunities for improvement. Still, it can already be used to calculate the effects of various scenarios in order to relatively score and prioritize them. The groundwater model may be use to validate Kumar et al.'s claim (2008) that rainwater harvesting and artificial recharge have little impact on the river basins scale.

This groundwater flow model is based on relatively scarce data. The usefulness of data measured twice a year in dug wells is already been criticized by Moench et al. (2003). Ideally, the data is monitored in observation wells explicitly developed for that reason. Monitoring density and frequency is ideally based on an understanding of the nature and magnitude of hydrogeological processes. The groundwater flow model developed for this study would improve greatly when it could be based on data that is truly geo-referenced. Secondly, the salinity distribution at depths deeper than the dug wells is hardly known while it may form a dominant source for the salinization at shallower depths. Measuring salinity at greater depths seems logical. Thirdly, the effects of the various artificial recharge structures are not well understood. Close and frequent monitoring of surface water levels, streamflows, groundwater heads and TDS concentrations in surface and groundwater in and close to the structures is therefore needed.

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