PREVENTION OF GROUNDWATER WELLS FROM SALINIZATION BY SUBSURFACE DAMS: A 2D NUMERICAL MODELLING APPROACH

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Zusammenfassung

Eine anhaltende Salzwasserintrusion bei Sullurpeta (Andhra Pradesh, Indien) führte zur Versalzung der Haupttrinkwasserfassungen der Region und beeinträchtigte die regionale Wasserversorgung. Die installierten Versorgungsbrunnen sind überwiegend im Flussbett des Kalangi verfiltert. Im Jahr 2005 wurden entsprechende Abwehrmaßnahmen implementiert, welche zu einer nachhaltigen Reduzierung der Salzgehalte in den Fassungsanlagen führte. Mit Hilfe eines numerischen, dichtegekoppelten 2-D Grundwassermodells wurde die Implementierung einer hydraulischen Barriere (unterirdischer Damm) zur Abwehr einströmender salzhaltiger Wassermassen reproduziert und entsprechende Maßnahmen hinsichtlich ihrer Langfristwirkung auf das hydrogeologische System simuliert. Dafür wurde ein für die Zielregion typisches hydrogeologisches Profil in ein Finite-Elemente Modell überführt.

Die Simulation der ergriffenen hydraulischen Maßnahmen bestätigt eine erfolgreiche und nachhaltige Funktionsweise des unterirdischen Damms zur Unterbindung der Salzwasserintrusion. Weitere numerische Untersuchungen wurden hinsichtlich der hydraulischen Durchlässigkeit von möglichen und für die Dammkonstruktion geeigneten Sedimenten unternommen. Auch wurden verschiedene Brunnenförderszenarien hinsichtlich ihres Einfluss auf die Qualität von den geförderten Wassermassen simuliert und dienen damit der Optimierung der hydraulischen Maßnahme.

Abstract

Onward saltwater intrusion into the freshwater resources in the area of Sullurpeta (Andhra Pradesh, India) led to a major salinization problem of local ground water wells and impaired the quality of extracted freshwater water volumes regionally. The installed production wells are mainly tapping the riverbed sediments of the Kalangi River. In the year 2005, technical measures for the reduction and long-term prevention of high salinization levels were installed successfully. The implementation of a subsurface dam was simulated regarding its hydraulic effectiveness based on a 2-D density-driven groundwater flow model. Additionally, further supporting technical measures were modelled for optimization reasons. Here, the numerical 2-D model reflects a characteristic riverbed/aquifer sequence of the study area.

The numerical reproduction of installed hydraulic measures states a successful and sustainable implementation of the subsurface dam with respect to various production scenarios. In addition, further simulations were carried out to evaluate the influence of variable permeabilities of available natural construction materials (sediments) on the effectiveness of the hydraulic barrier.

1. Introduction

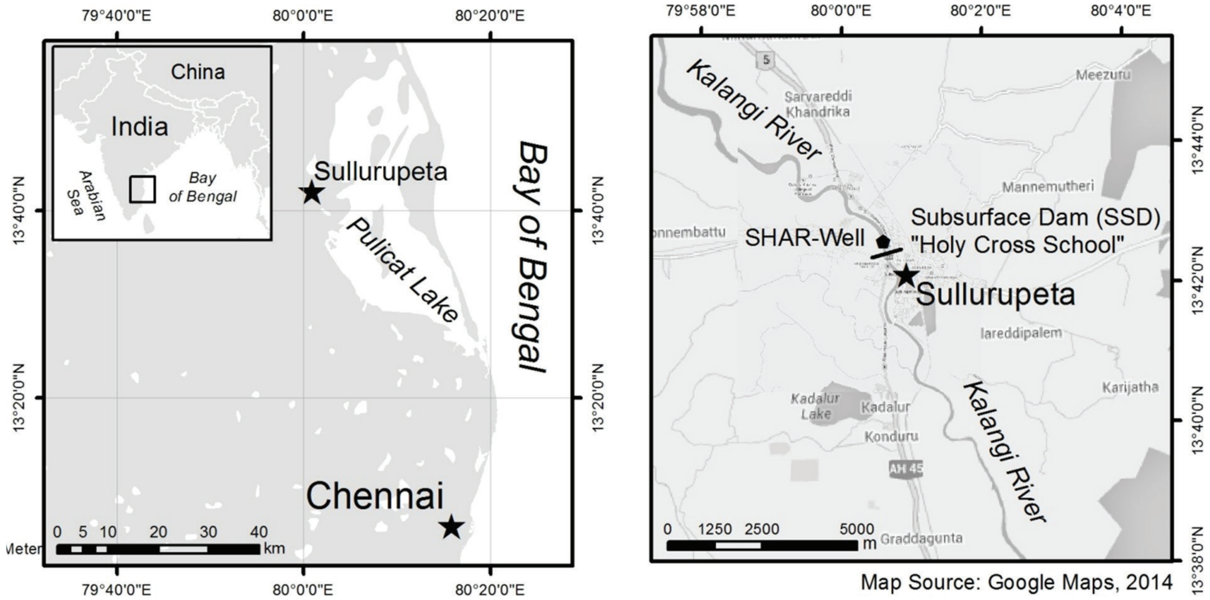
According to SHERBIN (2007), about 40% of the world's population live in a coastal zone of 100 km to the sea which are depending on freshwater resources. The phenomenon of saltwater intrusion constitutes a research objective already since the late 19th century. GHYBEN (1888) and HERZBERG (1901) worked on the estimation of spatial dimensions of freshwater lenses ("Ghyben-Herzberg Lens”) by using analytical models. Oftentimes, the overexploitation of groundwater in coastal aquifers initiates marine saltwater influxes which result in a salinization of the near shoreline freshwater resources.

Generally, estuaries and related surface waters are mainly carrying freshwater resources but frequently also tend to classify brackish inland water reserves due to temporal hydraulic impacts such as high tides or droughts. Such a phenomenon and the accompanying salinization of freshwater resources are observed in the river basin of the Kalangi River, near the Pulicat Lake in India. In Sullurpeta, nearby the Pulicat Lake, saltwater intrusion and the salinization of water production wells became a major problem due to the overexploitation of groundwater resources and reduced rainfalls in recent years. In particular the so called “SHAR well”, the main water production well for domestic water supply at the area of the Sriharikota Space Center (SHAR) was effected. This well is located near the Holy Cross School and produces water from the Kalangi river bed sediments. To overcome the salinization problem, a clayey subsurface dam (SSD) and an overlaid cement mortar check dam (20 m in both directions) were constructed in the river bed, 45 m downstream of the “SHAR well” in 2005. A rapid and substantial improvement of the regional groundwater quality was proven from groundwater monitoring and other indications such as Simpson ratio classification as a result. This paper addresses the long-term effectiveness and efficiency of the realized building measures for salinization prevention of the “SHAR well” by density driven fluid flow and transport modelling. Similar incidents were recently reported e.g. from the Kolleru Lake, India (Harikrishna et al. 2012) or study sites from Egypt (Sherif et al. 2012) and Tunisia (Gaaloul et al. 2012) etc. A detailed overview about ongoing research and related perspectives on saltwater intrusion is given by Werner et al. (2013).

2. Study area

According to fig. 1, the study region is located in direct vicinity of the city Sullurpeta and the Kalangi River, a hundred kilometres north of Chennai, State Andhra Pradesh, south-east of India. Sullurpeta is a major town of the study area and is having a population of about 50,000 inhabitants.

The alluvial sequence of the south-eastern Coromandel Coastline is about 700 kilometres long and reaches between 5 to 25 kilometres into the inland. The Kalangi River drains a basin of about 475 km² and is joining the



Map Source: Google Maps, 2014

Fig. 1: Location of the study area of Sullurpeta

salty Pulicat Lake and the Bay of Bengal, respectively. A constant water flow is only observed for about three months within a year. This period represents the main rainy season from October to December. During the rest of the year the water flows and the stream gauges are noticeable reduced. The river course is predominantly meandered nearby the study area of Sullurpeta.

3. Geology and Hydrogeology

The subsurface settings of the study domain are described in detail by Reddy et al. (2006) and Raju et al. (2013) and are presented here only as an overview. The region is widely covered by Cenozoic sediments consisting of clays, sands, pebbles and smaller boulders. The alluvial sediments (Holocene) are mainly present along the Kalangi river course. Locally, laterites are cropping out at the surface and attest an intensive and long-lasting weathering of the underlying parent rocks under wet tropical conditions. The bedrock unit is formed by archaic granitic gneisses and is related to the Peninsular Gneissic Complex (Geological Survey of India, 2005). The overlying laterites can still contain matrix features of their source rocks.

At the study location (Holy Cross School, Sullurpeta;fig. 2) the bedrock was encountered at a depth of 12 meters below ground surface. The hardrock unit is overlayed by 1 to 6 meters thick clay and is followed by a sandy sequence of about 6.5 meters in average. Fluvial riverbed sediments of the Kalangi are present in the top of this sandy sequence. These horizons are partially overlayed by lateritic clays and/or pedogenesis of up to 4 meters in thickness.

The riverbed underlying sandy horizon carries significant quantities of groundwater, especially during the rainy season. The aquifer's yield enables pumping rates of up to 70 m³ per hour in maximum. During the dry season, in the beginning of April, the groundwater table was found to be 0.5 m below the surface water table of the Kalangi and gradually dropped to about 6.0 m by the end of June (Muniratnam, 2004). Many wells in the region of Sullurpeta produce water from the high conductive riverbed sediments like the “SHAR well”. The water production in the region of Sullurpeta reached up to 1500 m³ per day during the rainy season and to about 800 m³ per day during the dry season. Higher pumping rates have not been possible as rapidly increasing salinity levels (app.1000 – 1100 mg/L) in the aquifer were observed.

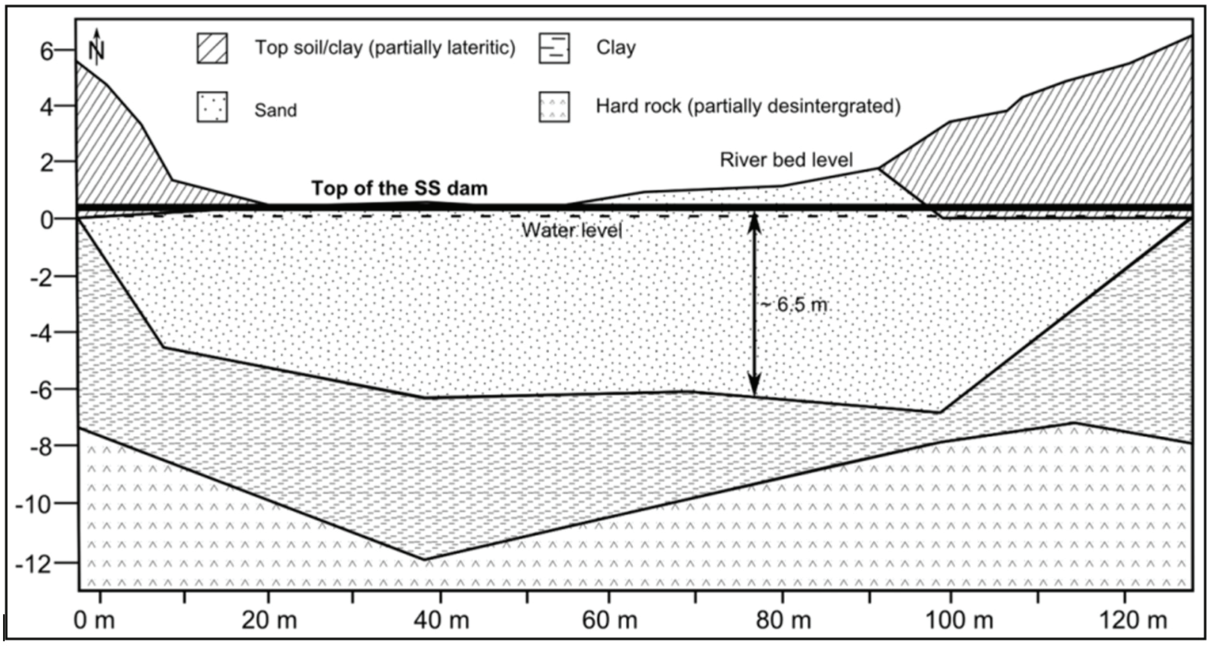


Fig. 2: Lithological profile through (perpendicular) the Kalangi river bed at the Holy Cross School.

The salinization of groundwater is not caused by intruding seawater through the aquifer as initially assumed, but rather by the infiltration of high saline stream water through the Kalangi riverbed. The groyne built at the Kalangi River estuary in 1984 was damaged and turned out to be insufficient against the intrusion of brackish saltwater originating from the Pulicat Lake. The distance between the groyne and Sullurpeta is about 10 kilometres. Surface water sampling revealed high salinization levels in river water. Furthermore, contaminated surface waters infiltrated into adjacent aquifers and anthropogenic activities intensified these effects.

After the successful implementation of the subsurface dam in July 2005 the onward saltwater intrusion was averted and the groundwater quality could be improved. Salt concentration levels in groundwater decreased from app. 1000 mg/L to 300 mg/L within one month. Furthermore, the groundwater production could be increased to about 2500 m³ per day during the rainy season and 1700 m³ per day during the dry season, respectively.

4. Methods and modelling approach

The numerical study was conducted by using a density-coupled finite element groundwater flow and transport model setup. The simulation code used was FEFLOW 6.0. The cross-sectional 2-D model is parallel to the Kalangi River course and represents the superficial aquifer sequence below the riverbed. The spatial dimensions are 150.0 m x 16.0 m.The riverbed slope nearby the “SHAR well” is approximately 0.33% (Raju et al. 2013). Four lithological units were assigned to the numerical model to incorporate the structural and hydraulic settings of the study region. According to Tab. 1, the sandy units of the superficial aquifer are of major interest in relation to the salinization problem and the current model study. In addition, the underlying clay horizon and basement are mainly impermeable and therefore predominantely act as aquitard layers.

Due to upwinding the methods “No upwinding” and “Full upwinding” considered as not suitable for the modelling. Firstly for reasons of stability and secondly, according Frolkovic & Shepper (2000), the “Full upwinding”-method is less appropriate for density-coupled transport processes because of a lot of unnecessary smoothing effects/are caused by the large amount of artificial dispersion. That affects the result in its representativeness. The basic idea of the “Shock capturing”-method is a nonlinear, anisotropic damping factor which removes numerical oscillations only at the discontinuities and in the direct neighbourhood. The consequence is a severely limited amount of artificial dispersion (Diersch 2009). For this reason the method considered is the most appropriate. Moreover, it corresponds to the nonlinear problem issue and it represents a compromise between representativeness (“No upwinding”) and stability (“Full upwinding”). The 2400 m² wide model domain was discretized into 44,077 triangular mesh elements and contains 22,461 computational nodes. The simulation time of the following invariant model scenarios was defined to 3650 days.

Three model scenarios were simulated and analysed concerning their hydraulic characteristics and mass fluxes (see also fig. 3 below):

Table 1: Lithological units and related parameters for hydraulic model characterization

Lithological units	Thickness [m]	k_F [m/s]	S_s [1/m]	ε [/]
Sand	6.5	10^{-3}	10^{-4}	0.2
Clay	5	10^{-9}	10^{-3}	0.05
Weathered bedrock	1.5	10^{-7}	10^{-4}	0.1
Bedrock (gneiss)	3.5	10^{-12}	10^{-4}	0.025

1. Density-coupled flow and transport modelling without any anthropogenic activities such as groundwater extraction ("SHAR well") or subsurface dams; (= saltwater intrusion through brackish water influxes under natural conditions)
2. Density-coupled flow and transport modelling and the implementation of an active groundwater production through an extraction well in a depth of 4.3 m below river bed ("SHAR well") (= saltwater intrusion and spatial distribution of saline waters in freshwater aquifers in consideration of anthropogenic interferences)
3. Density-coupled flow and transport modelling which incorporates active groundwater production ("SHAR well") in combination with active hydraulic measures (subsurface dam) (= saltwater intrusion and spatial distribution of saline waters in freshwater aquifers in consideration of anthropogenic interferences)

For respective transport modelling, the hydrodynamic dispersion was assigned iteratively to: longitudinal dispersion: 2.5 m; transversal dispersion: 0.25 m. The molecular diffusion was left at the default FEFLOW setting: 10-9 m²/s.

According to fig. 3, the following boundary conditions (BC) were assigned to the numerical model:

A constant saltwater head (1st kind flow BC - SWH) and a constant mass concentration of 5000 mg/L (1st kind mass BC - C_S) were assigned to the right border of the aquifer domain for representing the saltwater front. For density-driven problems, the freshwater head h_{fw} is handled as follows:

$h_{fw}=h_{sw}+\alpha*(h_{sw}-y)$

Where h_{sw} represents the assigned saltwater head, ā the predefined density ratio and y the spatial coordinate of the model domain. The density ratio was set globally to 0.0035 and describes the ration between the occurring maximum and minimum densities of the density-dependent transport problem. In addition, a constraint was added to the mass BC to make sure that only inflows will be affected by the mass flux and outflows remain unaffected.

Moreover, a groundwater influx (2nd kind flow BC – influx) paired with a constant mass

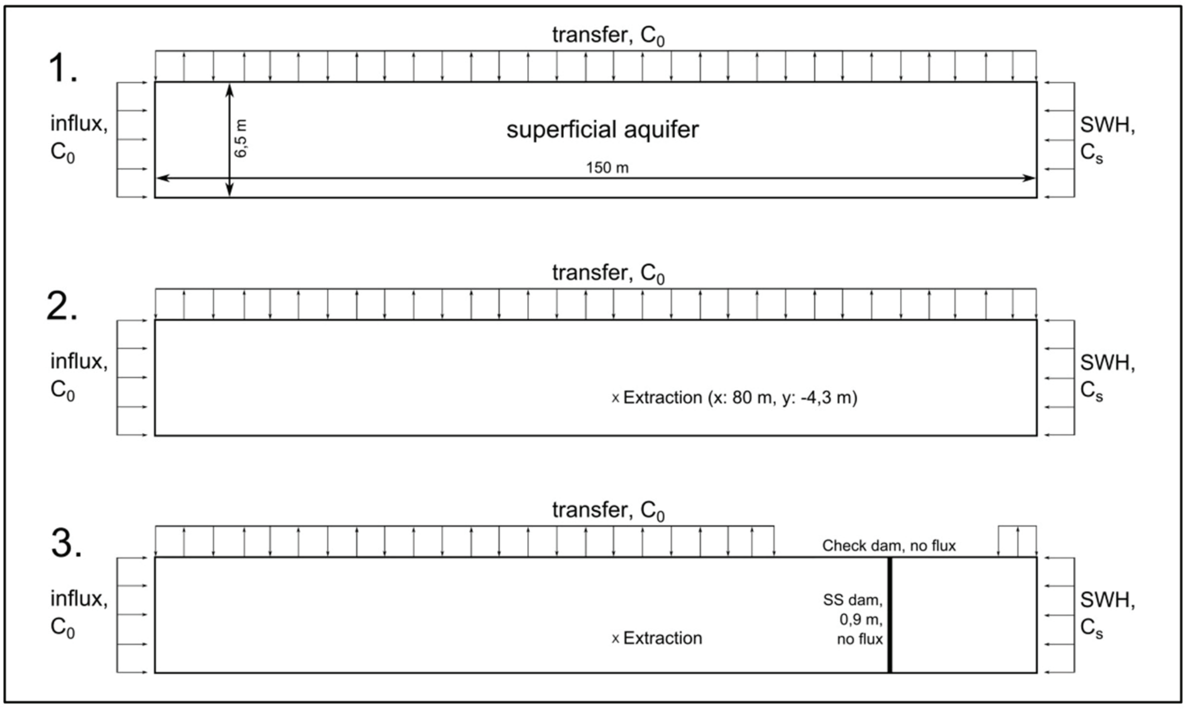


Fig. 3: Realized, consecutive, three-step modelling approach and BC of the numerical model.

boundary condition of 0 mg/L (1st kind mass BC – C_0) was defined along the left border of the model domain for representing freshwater inflow. The groundwater influx BC was set to be time-variant in order to characterize annual seasonality due to e.g. climatic variability.

A transfer flow boundary condition (3rd kind flow BC – transfer) was assigned to the model's top for representing the exchange between the Kalangi River and the underlying sediments based on surface water level variations. Time-variant water levels were derived from available stream gauge data. According to Raju et al. (2013), the Kalangi is entirely carrying freshwater and therefore a constant mass boundary (1st kind mass BC – C_0) of 0 mg/L was defined.

For the second and third simulation scenario an extraction well was implemented in the model domain by using a Well BC (in FELFOW 4th kind). This extraction measure represents the "SHAR well" that exploits water from the sandy alluviumin a depth of 4.3 m below river bed. Time-variant extraction rates differ seasonally and are in the proportion of 1:1.8 (dry/rainy season).

A subsurface dam was simulated in the third modelling scenario. Therefore, a 0.9 m wide dam was realized in the model which stretches across the whole vertical sandy sequence and intrudes 0.5 m in the underlying clay horizon. The hydraulic conductivity of the dam material was assigned to 10-10 m/s. For this scenario, the extraction rates of the implemented "SHAR well" were doubled.

The model characterization and parameterization is mainly based on available information from previous studies given in Muniratnam (2004), Raju et al. (2006), Ramakrishnan & Vaidyanadhan (2008) and Raju et al. (2013). Due to a lack of groundwater monitoring data, the model calibration mainly focuses the reproduction of observed aquifer dynamics such as the seasonal salinization of the freshwater aquifer during the dry season paired with measured salinities in the range of 1000-1100 mg/L.

5. Results

According to the simulation results obtained from the 1st modelling scenario, a distinctive intrusion of saline waters is observed predominantly during the dry season from February to April. In consequence of low net recharge and low groundwater levels during this period, saline waters can enter the aquifer continuously due to reduced hydrostatic counterpressures and increased density contrasts. Several spatially limited mixing zones were outlined from the simulation results along the intrusion front. These zones then form a joint mixing cell and even accelerate the whole intrusion process due to given density contrasts. According to Diersch (2014), this phenomenon is described as "fingering".

With respect to the cross-section through the superficial aquifer in fig. 4 (on top), the intrusion front reaches its maximum at the end of the dry season in July and is of about 34 meters in length. The saltwater intrudes in a form of a wedge into the freshwater body. High precipitation rates from August to December go along with increased freshwater inflows which then initiate a complete push back of the salinization front within 2.5 months. Then, inflows continue loading the aquifer for more than 6 weeks until the annual intrusion dynamic restarts again.

Active groundwater extraction of the "SHAR well"(2nd modelling scenario) leads to extensive impacts on the natural groundwater flow dynamics and saltwater distribution pattern. According to fig. 4 (in the middle), the saltwater front is reaching the well location unhindered and high salinities are spread over wide areas of the aquifer and no "classic" intrusion wedge is distinguishable anymore. Salinities of about 1000-1100 mg/L are reproduced by the model at the well location which correlates with available monitoring data of the "SHAR well" reported in Raju et al. (2013). Upconing effects as described by Bear & Cheng (2010) could not be identified.

Observed salinity concentrations rapidly decrease in close vicinity of the extraction well.

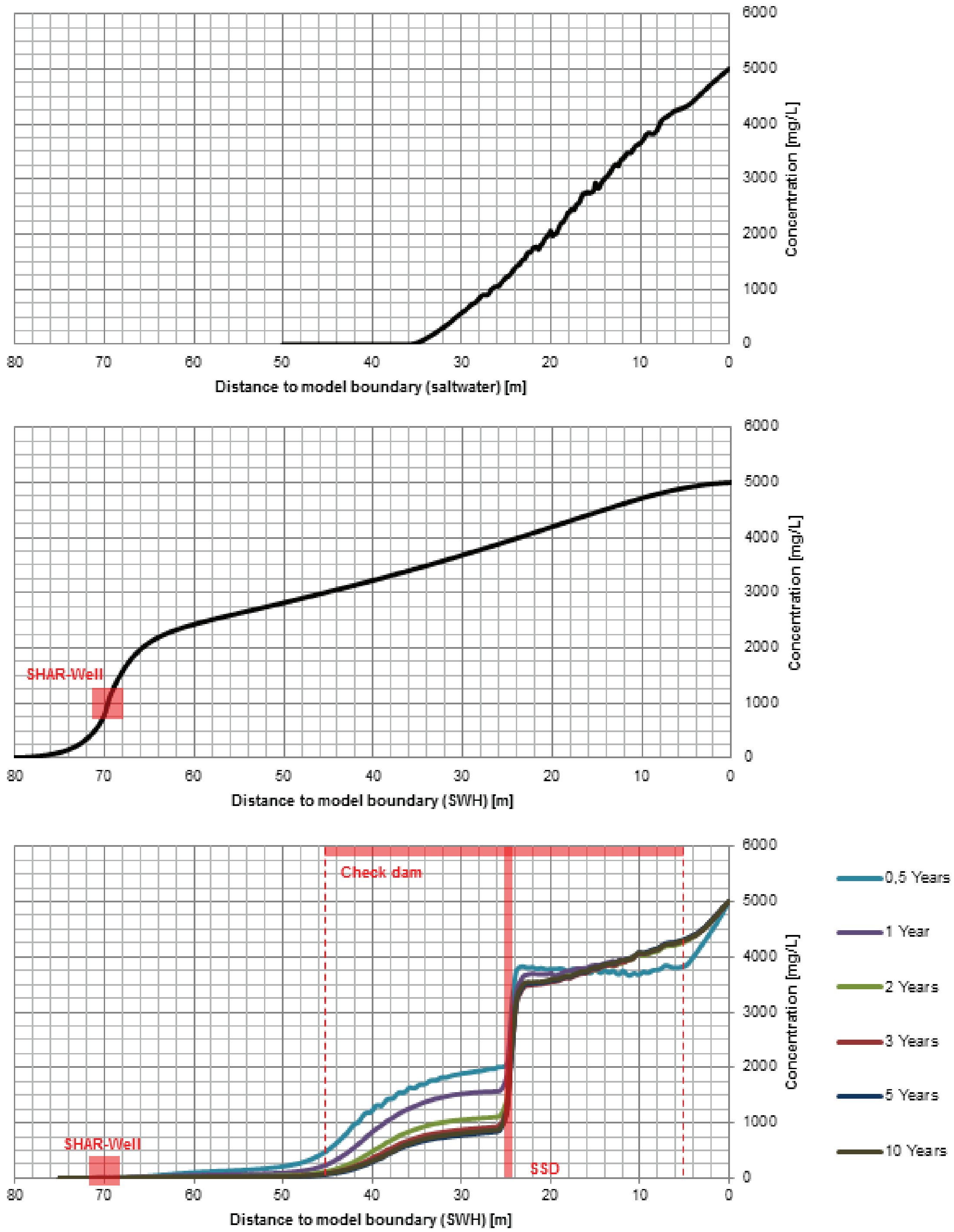


Fig. 4: All cross-sections through the superficial aquifer are orientated at a depth of 4.3 m. 1st modelling scenario (on top): A distinctive salinization front is present in the aquifer at the end of the dry season: the high salinities (5000 mg/L) at the right model boundary (mass BC - CS) are decreasing towards the aquifer's centre along a length of approximately 34 meters. 2nd modelling scenario (in the middle): Spatial dimension of the saline intrusion front in consideration of active groundwater production at the "SHAR well" location (red mark): salinity levels from groundwater monitoring of about 1050 mg/L could be reproduced by the calibrated model. 3rd modelling scenario (below): The hydraulic barrier effect of the installed subsurface dam (red line – SSD) successfully impedes an intrusion of saline waters and reduces the salinity levels at the "SHAR well". Model results indicate that steady-state conditions will be reached after app. 3 years of active groundwater withdrawal after dam construction.

While under natural conditions (1st modelling scenario) the maximum of saltwater intrusion is reached after seven months of the monsoon, the salinization front in consideration of active water extraction (2nd modelling scenario) already forms its maximum after two months in February/March. During the dry season the production well is predominantly extracting saline downstream waters while during the rainy season mainly upstream freshwater is withdrawn.

A subsurface dam was implemented as a hydraulic measure for the prevention of aquifer salinization in 2005. With respect to the simulation results of the 3rd modelling scenario, it can be concluded that this construction widely influences the hydraulic regime and led to a significant reduction of monitored salinities within the aquifer (fig. 4 below). Based on the findings, the subsurface dam successfully blocks an upstream salinization front in regards to an active groundwater production of the “SHAR well”. A sustainable hydraulic effectiveness can be stated in the long-term. Salinities of about 1000 mg/L are expected to be present in the downstream next to the subsurface dam and then decline in direction to the extraction well location.

The observed salinity levels at the “SHAR well” could be reduced significantly from app. 1050 mg/L to less than 100 mg/L within a few weeks and could be proven to be stable in the long-term (fig. 5). The well primarily extracts non-saline freshwater (app. 80% during the dry season and app. 90% during the rainy season) and only secondarily surface water (app. 20% during the dry season and 10% during the rainy season) which infiltrates through the riverbed.

This surface water influx is estimated to range between 0.06 (rainy season) and 0.09 $m^3/m^2/d$ (dry season). According to fig. 6 (on top), the model indicates that active pumping is essential for ensuring the effectiveness of the dam for salinization prevention. Moreover, lower pumping rates would result in higher salinization levels and a large saltwater intrusion front, respectively.

Different hydraulic conductivities of the construction material for the dam were tested regarding their hydraulic effectiveness. With respect to the results shown in fig. 6 (below), it can be stated that materials or sediments with hydraulic conductivities of higher than 10-6 m/s, such as fine sands, are not suitable for providing an effective hydraulic barrier effect. Hydraulic conductivities of 10-7 m/s (silty/clayey sands) reduce observed salinities and increase the hydraulic effectiveness, but increased water fluctuations are still indicated by the model. Material hydraulic conductivities (clayey silt or clay) of 10-8 m/s or lower ensure a sufficient hydraulic barrier effect and avoid any water fluctuations. A higher hydraulic effectiveness of even lower permeable materials than 10-8 m/s could not be identified through model simulations.

6. Discussion and conclusions

The presented study focused on the evaluation of effectiveness and efficiency of a subsurface dam for preventing groundwater production wells from salinization. Therefore, three different modelling scenarios were analysed for the characterisation of groundwater flow dynamics and the dimensioning of saltwater intrusions.

Results of the 1st modelling scenario do not show a sharp freshwater/saltwater front as expected and rather indicate a smooth transition zone. Therefore, the analytical so-called sharp-interface methods of Ghyben-Herzberg (1888, 1901), Glover (1959) or Stack (1976) should only find limited methodological application when addressing nonlinear saltwater intrusion problems. Similar findings are presented in Kopsiaftis et al. (2009).

With respect to the hydraulic effectiveness of the subsurface dam it can be stated that an appropriate functionality could be proven based on model simulations made. At this stage, further active hydraulic improvements are not needed. Established drinking water standards in relation to expected salt

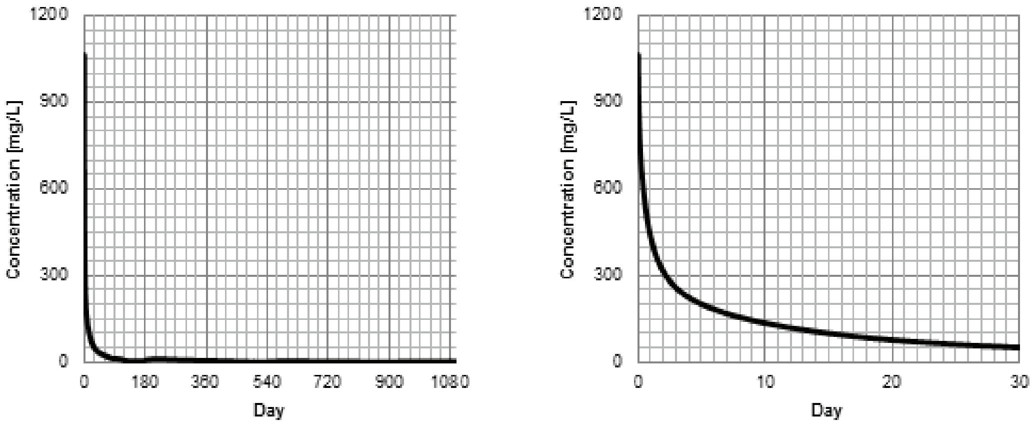


Fig. 5: Left: Significant reduction of high salt concentrations at the "SHAR well" location (extraction) after about 30 days of the implementation of the subsurface dam with respect toactive water extraction. Right: Long-term hydraulic effectiveness can be stated based on model simulations.

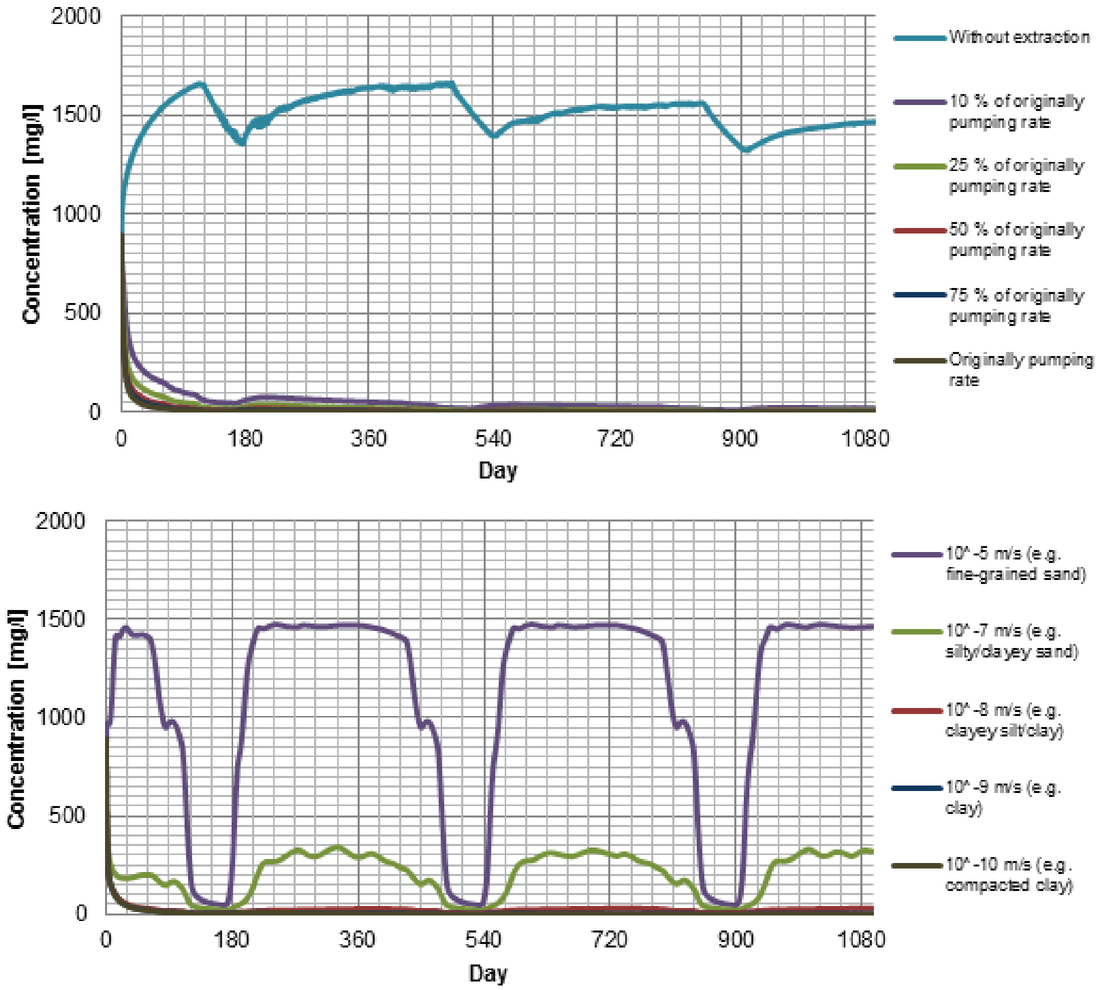


Fig. 6: Influence of variable pumping rates on salinity levels at the "SHAR well" (on top). Influence of different materials and hydraulic conductivities on the hydraulic barrier effect of the subsurface dam (below).

concentrations are fulfilled, but should be monitored permanently in appropriate intervals. Numerical investigations on acceptable hydraulic conductivities for construction materials of subsurface dams indicate to be at least in the magnitude of 10-8 m/s for an effective implementation. Moreover, an ongoing and permanent groundwater withdrawal is essential for the effectiveness of the subsurface dam.

The current modelling study should be seen as supporting information about the general hydrogeological scenery of the study region. Due to a lack of available field data, the verification of the obtained model results is limited. Therefore, an entirely accurate representation of the study area cannot be assured and spatial deviations in terms of groundwater quality/salinities are expected. In consequence, at this stage, exact mixing patterns and mass concentrations are difficult to indicate. Further simulation should be carried out as soon as additional field data is available.

According to the Central Groundwater Board of India (CGWB) and Rao (2007), an overexploitation of freshwater resources in the Nellore District is evidently and is in the dimension of some decimetres per year. Before the construction of the subsurface dam, groundwater depletion was also observed in the area of Sullurpeta (Raju et al. 2013). Today, due to its successful implementation and hydraulic effectiveness, the groundwater extraction rates of freshwater resources for water supply could even been increased.

The current model will be used to study further dynamics in the Sullurpeta region such as groundwater residence times with respect to hydro-geochemical objectives in consequence of the naturally occurring high contents of arsenic and fluoride in sediments. In addition, a more comprehensive 3-D model study at a river basin scale and in consideration of all anthropogenic impacts on the hydrogeological system will provide more reliable information about the study region and would actively support a sustainable management of the freshwater resource.

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