Numerical Groundwater Flow Modelling in Support of Mine Water Supply in an Endoreic Groundwater System, Tasiast Mine, Mauritania

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Abstract

Tasiast Mine is located on the western margin of the Sahara Desert. Water for mine operations is supplied from a wellfield located 60 km west of the mine site and 25 km from the Atlantic coast. The wellfield abstracts highly saline water from depths of >80m. The key regulatory requirement is to show that abstraction will not impact either water supply for local communities or baseflow to ecosystems. Since 2012 a 3D numerical groundwater flow model has been used, and updated annually, as part of regulatory compliance. Unlike most groundwater systems, natural groundwater elevations at the wellfield are below mean sea level, and simulating the interaction between abstraction at the wellfield and the groundwater system at the coast is challenging, requiring the ocean to act as a recharge boundary rather than a discharge zone. Extreme evaporation rates (>4m/year), driven by constant dry offshore winds and the fine-grained nature of surface materials, means that significant amounts of groundwater are removed from depth inland due to wind-induced negative soil pressures. A 1D SEEP-W model was developed to quantify the recharge deficit developed over time in the coastal plain, together with determining the depth below which evaporation stops. These outputs were incorporated into a 2D numerical model transect, representing 5km of the coastal plain, which determined the interaction between sea water intrusion and evaporation. The 2D model shows that evaporation efficiently removes water from the system, with pseudo steady-state conditions being achieved after 1,200 years of simulation. Evaporation from the coastal plain becomes the dominant driver within the local water balance, with the upward flux from the coastal flats balancing the inflow rate from the ocean. From the initial head distribution, groundwater levels quickly drop below sea water level due to evaporation. Deeper groundwater levels occur at greater distances from the coast, where the influence of sea water intrusion decreases. Modelled groundwater levels reached equilibrium after ≈2,000 years which is consistent with the period (<2.5k BP) since hyper arid conditions are considered to have developed in the wellfield area. The modelling demonstrates that natural below sea level piezometric levels result from high vertical flow (evaporation) which is not compensated by horizontal flow either from the ocean, or aquifer units to the east. The modelling approach has had regulator acceptance and maintained confidence in the ability of the 3D groundwater model to simulate the complex groundwater system and underpin predictive simulations of wellfield operation

Keywords: Endoreic Basins, Evapotranspiration, SEEP-W Modelling

Introduction

The Tasiast Mine is an open pit gold mine operation located in the Inchiri Wilaya region of Mauritania, approximately 280 km to the northeast of the capital city of Nouakchott. Water for mine operations is supplied from the Sondage wellfield which is located 60 km to the west of the mine site and 25 km to the east of the Atlantic coast. The wellfield lies 5 km from the western boundary of the Parc National du Banc d'Arguin (PNBA), a national park designated by UNESCO as a World Heritage site for its marine and coastal environments. Although the wellfield is located at a considerable distance from the mine site, it was selected as the mine water supply due to the fact that it is a highly saline water body present at depths of >80m below ground level, and was therefore neither of use as a potential water supply for local communities nor provides baseflow to any surface drainages or ecosystems.

The wellfield currently comprises 44 operational abstraction wells, oriented approximately north-south over a distance of about ≈20km, with the saline water transmitted the 60km to the mine site via three pipelines. Approximately 15 wells are operated at any one time, with the location of these wells being moved around the wellfield according to an operational plan, which is reviewed every 3 months. The aim of varying the location of operating wells is to ensure that abstraction is evenly distributed across the full area of aquifer covered by the wellfield. The Sondage is currently licensed to abstract a daily volume of 30,000 m^3 to the end of December 2034. To date, the daily abstraction rate has averaged between 8,000 and 13,500 m^3, with a maximum daily rate of about 24,500 m^3/d being recorded in 2012. The average abstraction rate during Q4 2020 was 13,279 m^3/d.

Groundwater is abstracted from a 5-10 m thick semi-confined sand layer, further details of which are provided below. Mean annual rainfall in the region averages about 100 mm, while the mean annual potential evaporation is 1-2 orders of magnitude greater at about 4000 mm.

A numeric groundwater flow model has been developed in order to assess the potential extent of drawdown related to wellfield operation that may develop over the period of the license (through to 2034). The model is used to assess both potential impacts to fresh water aquifers located to the north and south of the wellfield, as well as potential impacts to important ecological receptors in the Parc National du Banc d'Arguin (PNBA) west of the wellfield.

In order to replicate the baseline condition that pre-Sondage water levels were below sea level, the model was originally set up with a constant head boundary (CHB) set at -6 masl at a distance of approximately 6km inland from the coast. As part of a subsequent third party review of wellfield operation it was requested that the regional numerical model be modified so that the CHB was set at 0 masl along the coast. This change was aimed at allowing the model to simulate drawdown to the coast, and therefore predict whether any impact may occur within the PNBA, including to the coastal elements of the park. This paper details how these changes have been incorporated within the groundwater modelling approach.

Hydrogeology

Amended NAG test

The Sondage wellfield abstracts saline groundwater from a series of sand layers that occur near the base of the Continental Terminal sedimentary sequence. The sand layers form an aquifer unit which is about 5-10 m in thickness, and occurs at a depth of about 80 m below ground surface in the area of the wellfield. The sand unit is overlain by a series of interbedded low permeability sands, silts and clays, also assigned to the Continental Terminal sequence, and which form a semi-confining layer to the aquifer unit. These overlying sediments produce little water during drilling of boreholes, however downward leakage is expected to provide recharge to the underlying aquifer.

The entire sedimentary sequence dips to the west and is present at a progressively greater depth westwards under the Banc d'Arguin national park (PNBA). The sedimentary sequence is underlain by crystalline basement rocks.

Figure 1 shows a west-east section that illustrates the conceptual hydrogeological model.

The depth of the water table in the area of the Sondage is approximately 36-46 m below ground level, which is approximately 4 to 6 meters below mean sea level. This is consistent with the below mean sea level groundwater levels reported from other areas of the Coastal Terminal sequence in northwest Mauritania (IWACO 1995).

The origins of these coastal depressions in piezometric elevation (referred to as endoreic basins) which are present in Saharan Northern Africa have been described in a number of scientific papers since the 1960s (Achambault 1960). Models for the development of these basins, which are found from the Atlantic coasts of Mauritania and Senegal to inland regions of Mali and Chad, include sea level change, evapotranspiration, over abstraction, geological subsidence and drainage to deeper aquifers.

In coastal zones, the development of these inland hydraulic gradients promotes the intrusion of saline marine waters and the potential for salinization of potable water. This potential impact has led to considerable research being undertaken on the Trarza aquifer (part of the Continental Terminal Aquifer) in Mauritania, which supplies drinking water to Nouakchott from the Idini wellfield (Aranyossy and Ndiaye 1992, Lacroix and Semega 2005 and Mohamed *et al* 2014). Studies of water levels, isotopes and mathematical modelling all confirm the importance of evaporation in the maintenance of these depressions, with Lacroix and Semega (op cit) proposing that the endoreic conditions in the Trarza aquifer developed subsequent to the sea level rise which began 18k years BP and which reflect the fact that steady state conditions relative to current sea level may have still not developed.

Under natural conditions in these basins groundwater is removed through evaporation, with this process operating most effectively along the coastal area where saturated groundwater occurs close to the ground surface. The very high average evaporation rate (>4m/year) found inland, and which is driven by the constant dry offshore winds and the fine-grained nature of the shallow materials, means that significant amounts of groundwater may be removed from depth further inland as a result of wind-induced negative soil pressures and upward unsaturated groundwater gradients.

TDS concentrations reported from wells located in the coastal plain west of the Sondage range from about 100,000 to 140,000 mg/L. These data illustrate the effect of the evapo-concentration that occurs within the coastal plain (sabkha) zones, resulting in salinity values that are significantly higher than both seawater (≈ 25,000 mg/L) and TDS values measured at the Sondage (16,000 to 50,000 mg/L).

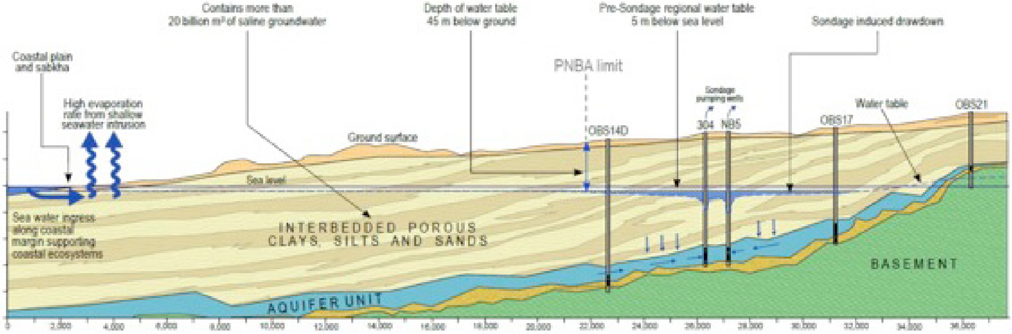

Figure 1 Conceptual cross section of the hydrostratigraphic units and flow mechanisms controlling groundwater elevations in the Sondage and PNBA area.

The sabkhas developed in the coastal plain are sustained by periodic flooding by extreme high tides, with the infiltrated sea water being evaporated from shallow depths and resulting in deposition of concentrated salt deposits (Figure A2). This groundwater near the coast, containing TDS concentrations significantly higher than sea water, will act as a recharge boundary to the inland basin where regional groundwater elevations sit below sea level.

Numerical modelling of the sabkha groundwater system

A variably saturated flow model was developed to simulate the impact of evaporative losses on groundwater levels in the coastal flats and sabkhas present the coastal margin of the PNBA. The numerical modelling allows the influence on groundwater elevation of each component of the water balance (sea water intrusion, evapotranspiration, recharge, groundwater flow) to be evaluated, and the development of natural below sea level groundwater elevations, as seen in the monitoring network associated with the Sondage, to be assessed. This detailed modelling was then used as the basis for updating how the coastal plain is simulated in the regional groundwater model.

The conceptual model of processes controlling the formation and maintenance of the coastal sabkha groundwater system was combined with meteorological data derived from the Mauritanian national weather station network to undertake 1D SEEP-W modelling of the recharge deficit that will accumulate over time in the coastal plain, together with the determination of the extinction depth that will develop within the coastal plain deposits. The outputs from the 1D modelling study were then incorporated into a 2D model section across the coastal plain, which was used to evaluate lateral and vertical flows; in particular the influence of sea level as a constant head boundary to the groundwater system. The results of this coastal modelling study were then used to underpin how both evaporation and the presence of the ocean was incorporated into the regional 3D groundwater flow model.

The model outputs show that evaporation removes water efficiently from the system in the first 50 years of simulation. Pseudo steady-state conditions are subsequently achieved after 1200 years of simulation. Contours of total pressure head simulated in the model after 2000 years are shown in Figure 6-7 and demonstrate that evaporation from the coastal plain becomes the dominant driver within the local water balance, with the upward flux from the sabkha/coastal flats eventually balancing the inflow rate from the constant head boundary.

The numerical modelling of the coastal plain hydrogeological system demonstrated that groundwater elevations decrease to greater than -5 (masl) at a distance of 5 km inland from the coast, as evaporation exceeds

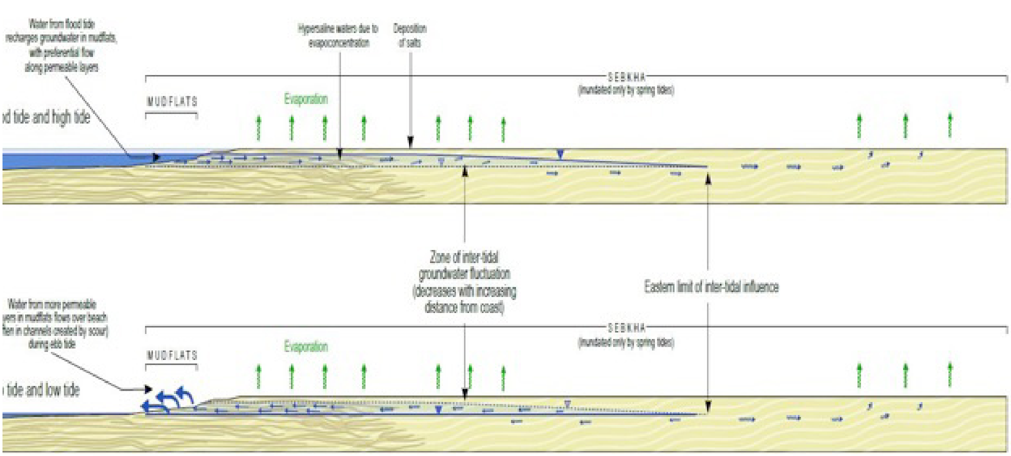

__Figure 2__ Schematic cross section of the interaction of tidal flooding and sea water intrusion in the coastal plain of the PNBA.

the rate of sea water ingress to the system. This is consistent with observed conditions in the region, as well as the extinction depth of 6-10 m which the 1-D numerical modelling predicted for evaporation in the tight soils in the area. This range of values is in accordance with literature values (Shah *et al*). Figure A2 also illustrates the self-buffering nature of the groundwater system. Any fall in groundwater levels inland of the coast would result in reduced evaporation which, in turn, would naturally mitigate the drawdown.

Based on the results of the coastal model and the review of antecedents, it is demonstrated that the natural distribution of piezometric levels below sea level is the result of high vertical flow (evaporation) which is not compensated by horizontal flow, either from the sea to the west or ny inflow from aquifer units along the other boundaries of the model. The boundary condition is assigned with a potential evapotranspiration equivalent to 2.500 mm/yr in the entire area of the regional flow model. A review of regional meteorological station data shows this value to be equivalent to the potential evaporation (PE) value at the coast (where humidity may be high) and to be considerably less than inland values which are measured at >4,500 mm/yr. Based on the results of the coastal model, the extinction depth in the regional model (below which evaporation is effectively zero) is fixed to 7.5 m.

Calibration of the regional numerical flow model

The extent of the regional impact assessment groundwater flow model was defined so that it covers the Sondage wellfield and its potential wider area of influence, and ensures that the edges of the model do not influence the results of the model during the simulation. The model area is equivalent to 15,819 km² and the entire inland area of the PNBA is included in the model domain. The model domain includes the Boulanouar and Benichab wellfields, which provide potable water supply to the cities of Nouakchott and Nouadhibou. Extending the model to include these areas allows regional groundwater level data provided by the Centre National de Resource d'Eau (CNRE) to be incorporated in the model.

A steady state calibration was established using data from both the Sondage and the regional data obtained from the CNRE. A transient calibration of the model, covering the period 2007 through Q1 2019, was then carried out using the measured abstraction rates from both the Sondage wellfield, and the local community abstractions at Chami and Wad Chebka.

Residuals indicate a highly successful calibration, with all but a few locations exhibiting residual errors in the +5 to -5% range.

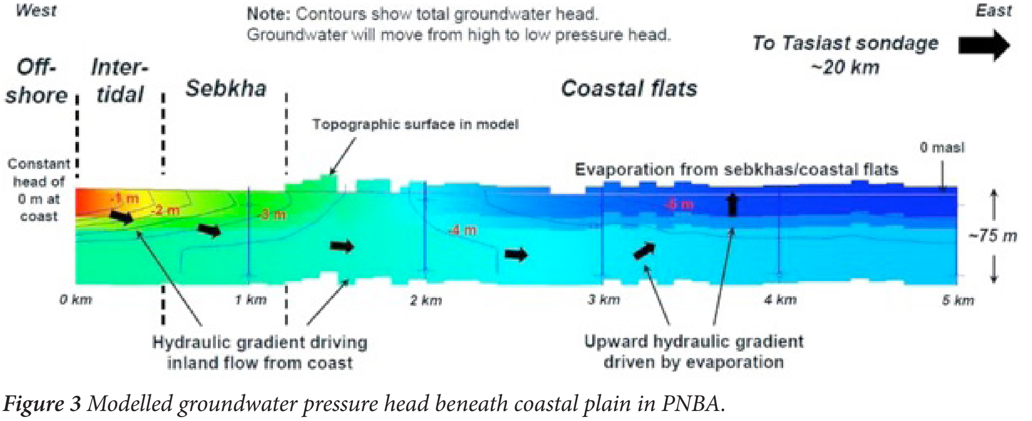

***Figure 3** Modelled groundwater pressure head beneath coastal plain in PNBA.*

The calibrated transient model was then used to run a series of predictive future simulations, including a conservative simulation based on the Sondage wellfield abstracting at the maximum permitted rate of 30,000 m^3/d through to the end of 2034. The model simultaneously simulated an increasing abstraction from the community wells at both Chami and Wad Chebka, to reflect the potential for population growth in both communities, coupled with a period of no groundwater recharge occurring during the entire simulation period.

Along the eastern boundary of the PNBA the most conservative model predicts that the water table will fall from 38.5 mbgl at present to 42.6 mbgl (in 2034). The simulated drop in the water table decreases going to the west (beneath the PNBA) and does not extend within 12 km of the coastal plain. The potential amount of evaporation along the coast is about 50 times greater than the permitted abstraction of the Sondage and therefore abstraction at the Sondage wellfield will not influence groundwater levels along the coast. In addition the updated model predicted, for all simulated cases, that Sondage abstraction would have no potential impacts on the "fresh" water zones to the north and south of the Sondage.

Conclusions

The model shows good calibration to the extensive database of well levels and pumping volumes to date. The model also replicates the condition, observed in the field, whereby groundwater levels in the area are naturally 4-6 m below sea water level. The model scenarios were run based on the highly conservative assumption that future abstraction would immediately occur at the maximum licensed rate of 30000 m3/d, and which is in fact more than twice the current abstraction rate. Even under this conservative approach the predictive model shows that drawdown will not affect water levels in community wells located to the north and south of the wellfield; and would therefore also not impact on the urban wellfields of Boulanouar and Benichab which are located further afield, and neither will the drawdown affect groundwater levels at the coast inside the PNBA. The current Life of Mine for the Tasiast operations is 2035. Given this relatively short timeframe for ongoing operation of the wellfield the groundwater flow model has not been run to date to simulate potential impacts associated with climate change. However the increased frequency of flooding of the coastal plain that should occur in response to rising sea levels should result in a shallower groundwater table inland from the coast, with the result that the area of drawdown associated with the wellfield will be reduced even further.

Acknowledgements

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