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Water in extreme conditions (arid and polar regions)

title: **Well field design for abstraction of high volume saline groundwater from Thumbli Aquifer, Barmer Basin, Rajasthan, India**

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ABSTRACT

A huge volume of saline water exists in deep aquifers in the desert region of Rajasthan. However, these saline water resources are not in general economic use due to the relatively high cost of abstraction, processing and disposal of used water. Therefore, the stress on the limited supply of fresh groundwater remains high and the fresh water aquifer is not being replenished to the extent that it is being utilised. Consequently, the scarcity of the fresh water resources is a limiting factor in the economic development of the region. This paper deals with an example of the effective utilization of saline water resources for industrial use in the Barmer Basin of Rajasthan without creating an environmental impact and without generating any conflicts with the local stakeholders (community, farmers, public drinking water supplier).

The study made use of subsurface data associated with oil field exploration and production to locate a deep confined aquifer, define its geometry, hydraulic parameters, salinity and locate highly transmissive zones to sustain a continuous water supply to the oil field with minimal environmental impact. Based on the study, an 800m thick aquifer zone located 350mBGL consisting of well sorted, medium to fine grained sand and having a uniformity coefficient of 2.81 and hydraulic conductivity in range of 20 m/day–25 m/day has been identified. The salinity varies with depth from 5,500 mg/L at the top of the aquifer to ~10,000 mg/L at the bottom of the aquifer. The aquifer water is corrosive due to high chloride content (2200–2900mg/L), presence of Sulfur Reducing Bacteria (SRB, 1–10 mg/L), free carbon dioxide (220 mg/L) and oxygen (80 ppb).

The schematic study of oil field data, its integration with the hydrological properties of the aquifer, coupled with the drilling of test wells, long duration aquifer testing and detailed chemical analysis of the aquifer water has helped to understand the deep aquifer in a better way compared to the hydro-geological information originally available for this aquifer. Numerical flow and solute transport simulation has further helped to optimise the pumping rate and interwell spacing criteria. It has been found that it is possible to get the required volume of water with three high capacity water wells spaced 100 apart by tapping only 100 m of the upper portion of the aquifer; with screens of 10¾ inch diameter continuous slot wire wrapped 0.45 mm slot aperture. It was found that 316L metallurgy for well casing, screen and tubing was appropriate to meet the corrosion threat due to the highly corrosive nature of the aquifer water. The high uniformity co-efficient of the aquifer material has helped in deciding the natural development of a filter pack across the screen part of the well instead of using artificial gravel pack. Formation damage due to drilling fluid has been minimized by using potassium carbonate polymer mud system. All the three wells were tested at a pumping rate of up to 10,000m^3/day and well efficiencies were in the range of 75–80%.

Efficient saline water well field development has been achieved due to integration of oil field data, aquifer testing and numerical modeling. The integrated approach has helped to minimise the risk related to availability of resources, impact on the environment and conflict with the stakeholders. Efficient design of both the saline water delivery system and the wells further reduced the drilling and operational cost. This study provides opportunity to demonstrate judicious utilisation of the oil field data in defining the deep groundwater aquifer.

INTRODUCTION

Significant oil discoveries have been made in the Barmer sedimentary basin (Compton, 2009) located in the Thar Desert of Rajasthan (Figure 1). Several of these fields contain waxy crude with APIs of 16-22° and a pour point of around 60°C (Tandon et al., 2008). Development of such fields requires large volumes of water, typically 25,000 m^3/day, for pressure support. Finding such huge volumes of water in an arid desert region was a considerable challenge. Fresh water is available in the vicinity of the oil fields but its utilization for industrial purposes would jeopardize long term availability of water supplies to rural and urban populations of the desert. A detailed hydro-geological investigation was thus carried out to locate saline water aquifers that historically have no practical use for domestic or irrigation purposes. These aquifers should be sustainable for the life of the oil field developments where the water can be abstracted at high rates with minimum construction and operating costs.

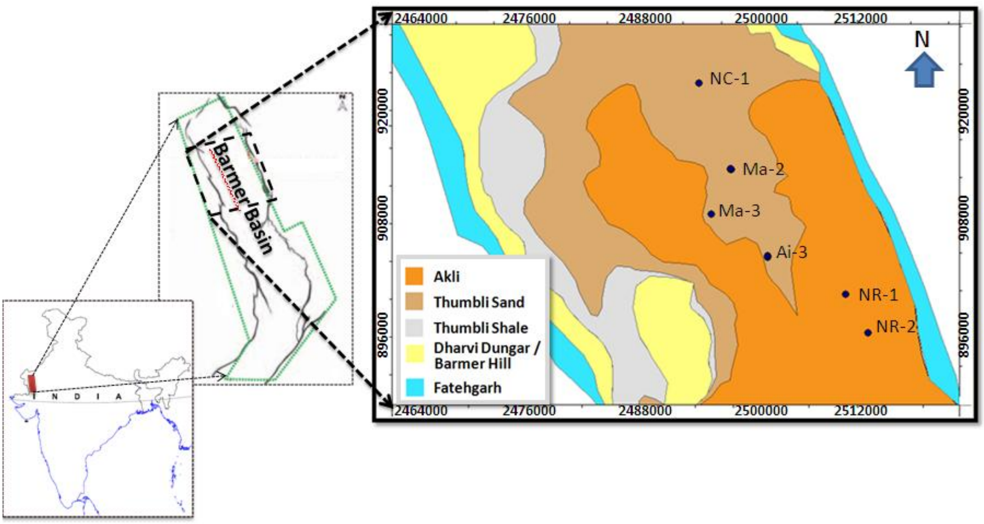

Figure 1. Geological setting of the Thumbli aquifer with respect to Barmer Basin and rift system.

METHODOLOGY

Initially, mapping of the stratigraphic layers in the Barmer Basin was carried out using available oil field seismic data, petrophysical analysis of the oil field log data and Modular Dynamic Formation Tester (MDT) data analysis. Once a potential saline aquifer distal to the fresh water aquifer was identified in the stratigraphic section, drilling of water production and observation wells at various key spatial locations was undertaken to conduct the aquifer tests and derive the field hydraulic parameters of the aquifer. This was followed by grain size and water quality analysis. The results of long duration Constant Rate Tests (CRT) were analysed to develop an understanding of the aquifer flow behavior. Step Drawdown Tests (SDT) were conducted to understand the well and aquifer losses in the pumping well associated with adopted drilling method and well design. Based on the integration of these types of data the aquifer was characterised and a numerical 3D flow and solute transport model was developed. Simulations were carried out with various geometric layouts of production wells with the objective of analysing drawdown interference for each producing well and its possible impact on the distant fresh water lens within the aquifer. Finally, locations of production wells, their optimal number and distribution throughout the aquifer and completion design were optimised.

AQUIFER PHYSICAL PROPERTIES AND CHEMICAL CHARACTERISTICS

The Barmer Basin is part of a failed rift basin contiguous with the Cambay Basin to the south, and defined in the west and east by extensional faults (Compton, 2009). The basin was tilted and inverted after the Miocene in response to the collision of India with the Asian Plate, such that much of the stratigraphy is exposed along the northern margin of the basin with regional dips inclined to the south. The stratigraphy of the basin (Table 1) comprises a syn-rift Fatehgarh reservoir overlain by a regional seal and source rock, the Barmer Hill Formation, which consists predominantly of bituminous shales and silica-rich diatomaceous sediments. The overlying Dharvi Dungar, Thumbli and Akli formations are shale-rich units with minor sands of fluvio-deltaic depositional origin, many of which were derived from the northeasterly or northwesterly basin margins. Regional studies of the basin indicate that the main fluvial channels had a major axial component along the rift basin.

Table 1. Lithological sequence of the Barmer Basin.

Formation	Unit	Thickness	Lithology
Akli Formation & younger		0–>1000 m	Shales and lignites; sands in Miocene.
Thumbli Formation	Thumbli Sand	0–1000 m	Sand and semi-consolidated sandstones with interbedded clay, shale and lignite.
Thumbli Formation	Thumbli Shale	0–500 m	Shale, locally carbonaceous, rare sands.
Dharvi Dungar Formation	—	200–1200 m	Shales, locally carbonaceous, rare sands
Barmer Hill Formation	—	100–1,000 m	Shales and diatomaceous siltstones
Fatehgarh Formation	—	50–400m	Sandstones and shales

The Thumbli Formation is a major fluvial plain sequence with the Thumbli Sand Member representing a major channelised river deposit, sourced from the north eastern faulted flank in the northern part of the basin. The Thumbli aquifer is subaerially exposed in the north of the basin where it recharges but is overlain and confined by the shales of the Akli Formation to the south. The thickness of the Thumbli aquifer ranges between 0 m and 950 m. In the northern area of the basin it typically has high porosity and permeability. The unconfined portion of aquifer contains fresher groundwater at the water level but the water rapidly becomes saline with depth and reaches a maximum salinity of some 10,000 mg/L. The confined portion of aquifer water (overlain by Akli Formation) is saline (>3000 mg/L) and reaches maximum of 10,000 mg/L at depth. A summary of the physical properties of the Thumbli Sand Member aquifer is given in Table 2.

Table 2. Physical properties of the Thumbli aquifer.

Feature	Representative value
Boundaries	West and North – No flow (Thumbli Shale and Dharvi Dungar shale). East – No flow (fault truncated). South – No flow (gradational to finer textured lithologies).
Underlying aquiclude	Thumbli Shale and Dharvi Dungar Formation.
Overlying aquitard	Akli Formation
Saturated thickness	Saturated net sand yields a range in thickness of 0 m to 740 m.
Effective Porosity	Approximately 31% in the northeast of the aquifer, declining to around 10–20% towards the south-western boundary.
Storage coefficient	Storage coefficient 5.1×10^{-4}
Hydraulic conductivity	Khanji ka Tala (Ai-3) K_h = 13.5 m/day Madpura Barawal (NR1) K_h = 11.5 m/day
Recharge	An average long term value for recharge of 0.6 mm/year
Groundwater quality	5,000 – 10,000 mg/l TDS in confined zones

WELL LAYOUT AND WELL DESIGN

Based on the initial estimates from well logs, core cuttings, grain size estimation, pressure and permeability data obtained from oil wells, a total of 24 water production wells spread over 25 km^2 and set 1km apart were planned in the confined portion of the aquifer (below 350 m BGL) with each having installed capacity of 1,000m^3/day (Fig. 8). Grain size analysis (Fig. 2) indicates that the D_{50} of the aquifer material of the upper 100–150m zone is 0.45mm and uniformity coefficient (D_{40}/D_{90}) is 2.8 which formed the basis to natural filter pack around the screen.

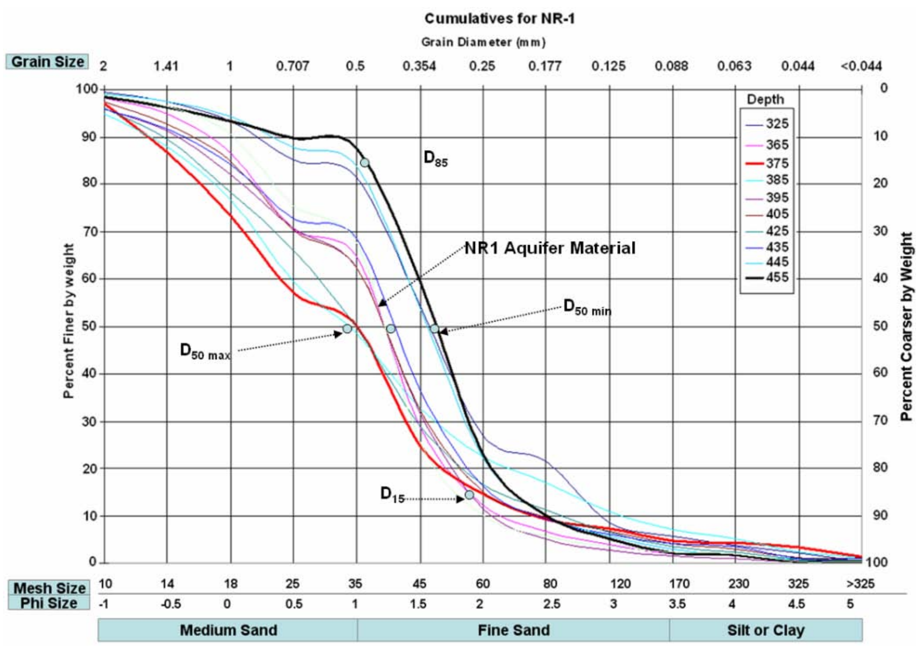

Figure 2. Results of grain size analysis of the aquifer in the NR-1 area.

A test well (Fig. 3) and 3 observation wells were drilled and CRT (Fig. 5) and SDT were carried to ascertain the hydraulic conductivity, storage coefficient and boundary effects in the proposed field.

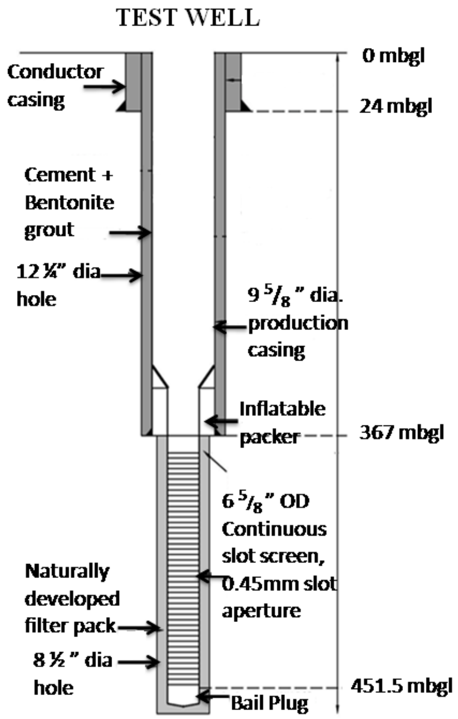

Figure 3. Schematic of the Test well drilled for aquifer testing in the saline part of the aquifer to produce 2400 m³/day.

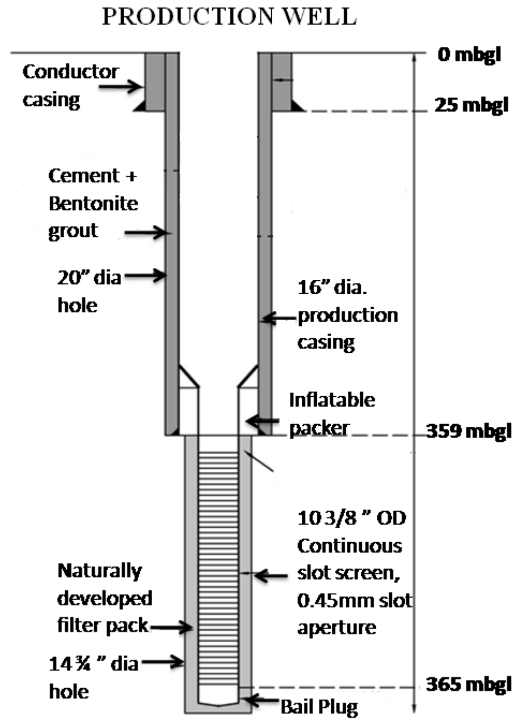

Figure 4. Schematic of the production well drilled in the saline part of the aquifer to produce 10000 m³/day.

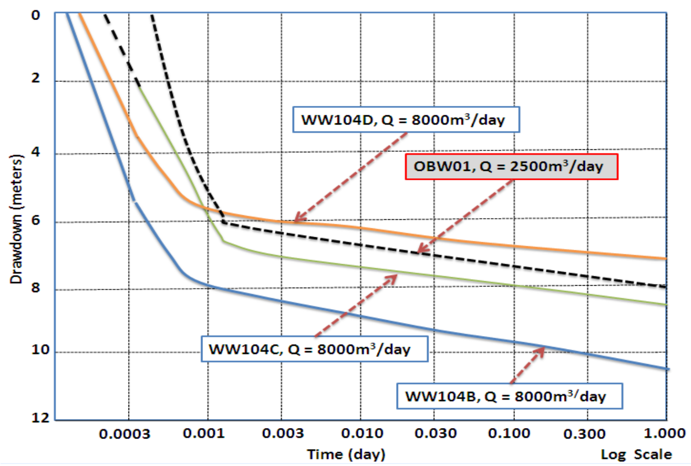

Figure 5. Drawdown curves of Production well WW104-B, C and D each pumping at rate of 8000 m³/day and OBW01 (Test well) pumping ≅ 2500 m³/day.

The test well was drilled with a pre-hydrated bentonite (PHB) mud system (Bentonite, Caustic Soda, Barite and Lignosulphate). The long duration CRT showed the aquifer hydraulic conductivity was 10 m/day in the area. Based on the hydraulic properties of the aquifer (Fig. 6 and 7), a numerical groundwater flow and solute transport model was set up.

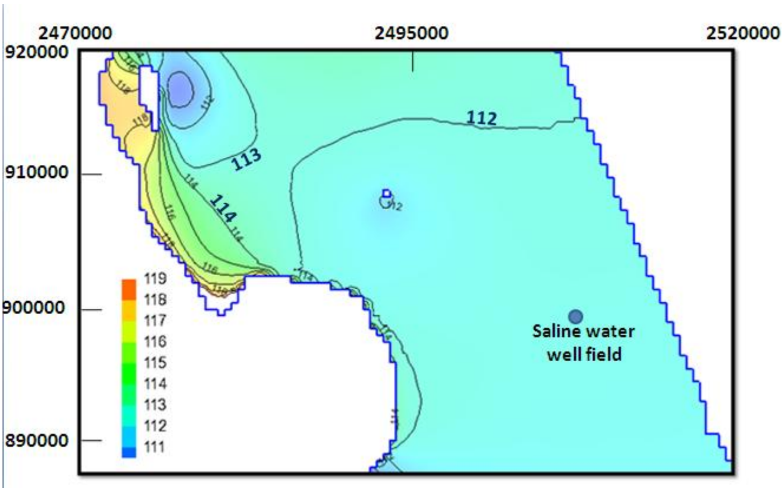

Figure 6. Hydraulic Head within the aquifer.

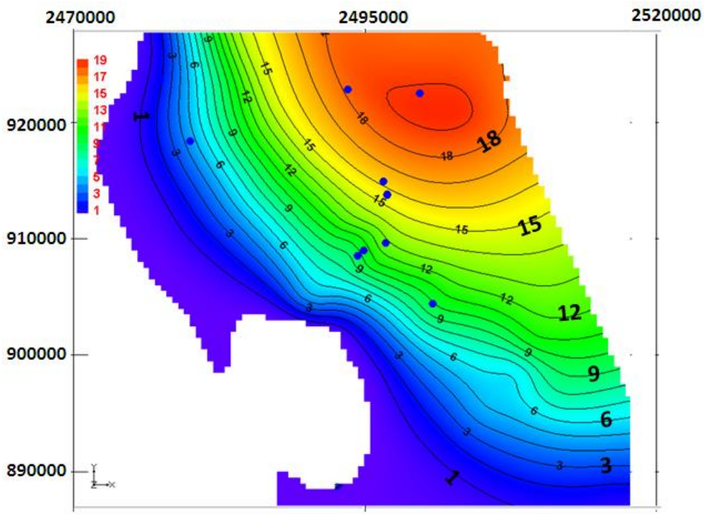

Figure 7. Hydraulic conductivity within the aquifer.

Various scenarios were examined using the ground water model. Simulations were carried out with different well layouts to understand the flow (Fig. 8) and solute behaviour of the aquifer. Drawdown and interference between pumping wells with different well numbers and geometries was also analysed. Modeling and analytical calculations suggest that the required yield could be achieved with three wells (Fig. 8) spaced at a distance of 100 m. Each well could deliver 10,000m^3/day.

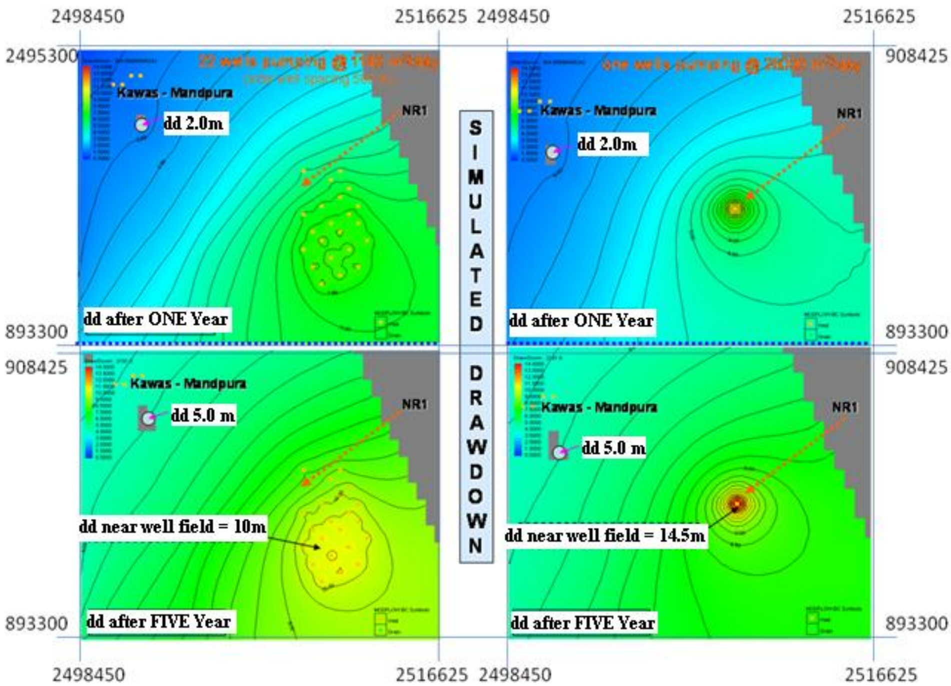

Figure 8. Simulated drawdown in aquifer with two different well layout (five wells and 24 wells) using MODFLOW 2000 (USGS) computer code.

The required volumes of water can thus be attained with the use of three high capacity water wells (Fig. 4) by tapping only 100m of the upper portion of the aquifer spaced 100m apart with and completed with $10^{3}/_{4}$ inch diameter continuous slot wire wrapped screens with 0.45mm slot aperture. It was also found that 316L metallurgy for well casing, screen and tubing was appropriate to meet the corrosion threat due to the corrosive nature of aquifer water (Table 3).

Table 3. Aquifer water quality corrosion related parameters.

Parameters	Range
Total Dissolved Solid	5000–5500 mg/L
Chloride	2200–2900 mg/L
Carbon Dioxide	220–300 mg/L
Sulfur Reducing Bacterial	1–10 count per litre
Oxygen	80ppb
Corrosivity	up to 28 mils (~0.7mm) per year

Formation damage has been minimized by using K_2SO_4 (a water-based mud system including $CaCO_3$, K_2SO_4, and KOH) with a mud weight 9.4–10ppg for drilling the sand lithologies. The improved design (Fig. 4) and mud system has helped to get the required volume of water with three high capacity wells located 100m apart instead of drilling 24 wells spread over 25 km^2. The new design has helped to achieve well efficiency up to 80% at pumping rate of 10,000m^3/day (Fig. 5).

CONCLUSION

This study demonstrates the use the oil field data to locate a deep confined aquifer (in this case the Thumbli aquifer), and define the geometry, hydraulic parameters, and salinity of the aquifer, as well as target the high transmissibility zones. Detailed technical evaluations using this extensive database indicated that huge volumes of saline groundwater resources are available within the Thumbli aquifer and that these can be accessed for abstraction without impacting the associated shallow freshwater lens. Numerical flow and transport simulations confirm that there is no risk related to availability of the resources and environmental impact on other usable groundwater resources.

The numerical model has been used in optimizing the well count and distribution for water abstraction. Only three high capacity wells, spaced at a distance of 100m with a screen of $10^{3}/_{4}$ inch diameter continuous slot wire wrapped 0.45 mm slot aperture are required to produce 25,000 m^3/day saline groundwater by tapping the 100 m upper portion of aquifer. This integrated data acquisition, modeling and analysis approach has reduced drilling and operational costs significantly.

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