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Estimation of Sustainable Safe yield of Wells using analytical and numerical models in Northern Wadi Araba Basin, Southern Jordan

Analisi comparativa della variabilità della temperatura dell'acqua su scale temporali da orarie ad annuali in due grandi sorgenti carsiche nel carso dinarico

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Abstract

This study assessed the sustainable and safe yield of eight wells in the Northern Wadi Araba Basin, southern Jordan, using both analytical-empirical methods and numerical groundwater modeling. Field investigations included well inventory, hydrogeological characterization, and controlled pumping and recovery tests. Transmissivity and storativity were derived using AquiferTest Pro, applying the Neuman solution for unconfined aquifers and Theis's method for recovery. This was based on the available measurements of the water table of the observation wells located in the study area. Sustainable yield was estimated using long-term safe yield (Q20) through Farvolden, Moell, and Ribby approaches. Results showed that the Q20 values ranging from 1100 to 1450 m^3/day, with minor variation among the methods. A ParFlow-based 3D numerical model simulated various pumping scenarios to validate and refine analytical findings. The obtained results indicate that pumping out of Wadi Araba wells should not exceed 1500 m^3/day in the case of continuous pumping and 9000 m^3/day in the case of intermittent pumping. Hence, the changes of the levels of the water table did not significantly change with small changes in pumping thus, a 6-fold magnitude increase in pumping from approximately 1500 m^3/day to 9000 m^3/day showing a significant drop in the water table equivalent to about 5.5 MCM per year from the aquifer. The model indicated a safe pumping threshold of 1,500 m^3/day, beyond which significant drawdown occurred. Comparison between analytical and numerical estimates revealed a strong correlation, with differences ranging between -3.0% and +4.5%. The integrated approach enhanced confidence in the proposed limits. Future monitoring and model refinement are recommended to ensure long-term aquifer sustainability.

Riassunto

Questo studio ha valutato la portata sostenibile e sicura di otto pozzi nella parte settentrionale del bacino di Wadi Araba, nel sud della Giordania, utilizzando metodi analitico-empirici e modellazione numerica della falda. Le indagini di campo hanno incluso l'inventario dei pozzi, la caratterizzazione idrogeologica e test controllati di pompaggio e recupero. La trasmissività e la capacità di stoccaggio sono state derivate utilizzando il software AquiferTest Pro, applicando la soluzione di Neuman per acquiferi liberi e il metodo di Theis per l'analisi della risalita, sulla base dei livelli piezometrici misurati nei pozzi di osservazione presenti nell'area di studio. La portata sostenibile è stata stimata attraverso la portata sicura a lungo termine (Q20) secondo gli approcci di Farvolden, Moell e Ribby. I risultati hanno mostrato valori di Q20 compresi tra 1100 e 1450 m^3/giorno, con variazioni minime tra i metodi. Un modello numerico tridimensionale sviluppato con ParFlow ha simulato diversi scenari di pompaggio per validare e affinare i risultati analitici. I risultati ottenuti indicano che il prelievo dai pozzi di Wadi Araba non dovrebbe superare i 1500 m^3/giorno in caso di pompaggio continuo e i 9000 m^3/giorno in caso di pompaggio intermittente. Pertanto, le variazioni dei livelli della falda non cambiano in modo significativo con piccole variazioni di pompaggio; tuttavia, un aumento del pompaggio di 6 volte (da circa 1500 a 9000 m^3/giorno) comporta un abbassamento significativo del livello della falda, equivalente a circa 5,5 MCM all'anno. Il confronto tra stime analitiche e numeriche ha rivelato una forte correlazione, con differenze comprese tra -4,3% e +4,5%. L'approccio integrato ha rafforzato la fiducia nei limiti proposti. Si raccomanda il monitoraggio futuro e l'affinamento del modello per garantire la sostenibilità a lungo termine dell'acquifero.

Introduction

The amount of water that can be pumped from a well continuously over time without causing damage to the well (too high drawdown) or causing the well to dry up is known as the sustainable yield. Driscoll (1986) defined well yield as the volume of water discharged per unit of time, commonly represented in gallons per minute. If the volume of water required by the people dependent on it is accessible during the dry season and during periods of below-average rainfall, a well or borehole will provide a sustainable yield. If a groundwater source is not sustainable, the yield will be significantly hampered, or the source may entirely dry up. While the well's instantaneous discharge rate can be easily determined, determining a reasonable or "safe" rate of extraction over the long term is more difficult.

Sophocleous (2000), Kendy (2003), and Kalf and Wooley (2003) have discussed the ideas of aquifer "safe yield" and "sustainability" in groundwater resource management. Recognizing that well yield has received less attention in the literature, however, this research aims to bridge the gap between the concepts of aquifer safe yield, sustainable groundwater development, and the yield of the individual well. The scope of this research is to develop a framework for more widespread use of quantitative methodologies to evaluate long-term well yield and to give suggestions for their usage in groundwater management.

The Q20 concept is utilized to determine the sustainable yield of a well by estimating the anticipated drawdown after 20 years, based on a validated mathematical model, under the assumption of continuous pumping throughout the entire period. (Van Everdingen, 2024).

The Ministry of Water and Irrigation in Jordan is planning to find new water resources all around Jordan, to find a remedy to any shortages of water supply, and to maintain a continuous supply for the existing and planned projects. In this prospect, Jordan's government has agreed to drill seven production wells in the Wadi Araba region (Wadi Musa and Beer Mathkor areas). between the Red Sea and the Dead Sea, this area is part of the Jordan Rift Valley (Abu Zir, 1989). Jordan has made a water resources plan for irrigation a high priority (Smith, 1995).

The agricultural expansion of the Wadi Araba began in the middle of the 1960s and 1970s, when private companies drilled numerous irrigation wells (Al-Dababseh, 2003). Groundwater was extensively used to meet the demand for expanding agricultural operations because it was the only source of irrigation and water supply in the area.

The main goal of this paper is to estimate the long-term yield of these production wells that can be used for irrigation in the Beer Mathkor, Wadi Musa, Qa Sadeen, and Dahl sections of Wadi Araba. In addition, this research aims to assess the alluvium aquifer's properties using pumping tests from drilled wells, which were controlled and monitored by the Aqaba Special Economic Zone Authority and Wadi Araba Development Directorate. In this study, the Q20 concept, which was introduced by Farvolden in 1959 in Canada and is based on the prediction of water drawdown in the pumping well after 20 years of pumping, is used to determine the maximum long-term well yield.

Description of the study area

The Wadi Araba Jordan Rift is described as a narrow depression that extends from the Gulf of Aqaba by approximately 360 km north to Lake of Tiberias. Dahl and Beer Mathkor regions make up the project area. Dahl lies about 50 kilometers north of Beer Mathkor in the direction of the Dead Sea, as depicted in Figure 1. Figure 2 shows the Google Earth map of the project area where the drilled wells are located. The Wadi Araba Basin's floor is made up of alluvial materials transported from the neighboring mountains to the east and west (El-Naqa et al., 2009; El-Naqa and Kuisi, 2013). The alluvium aquifer's thickness is measured in meters, but brackish and fresh groundwater can be found in the upper portions of the alluvial aquifer (Dames and Moore, 1979).

The groundwater is flowing southward from the north to the Red Sea. The aquifer system is recharged from precipitation and downward leakage from the Kurnub aquifer while it is discharged by the existing springs in the side wadis along the escarpment (El-Naqa and Abu AlAdas, 2023). Therefore, groundwater storage and underflow toward the Wadi Araba floor may be rather limited.

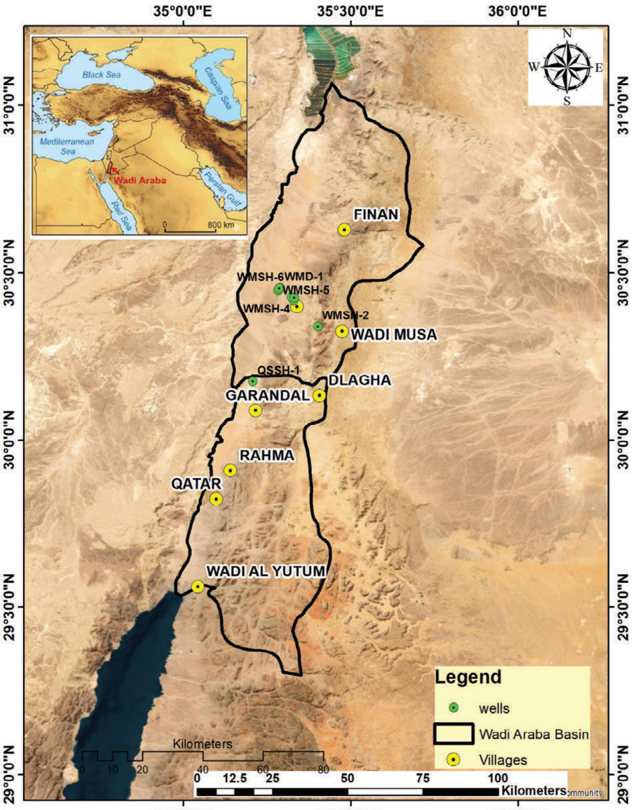


Fig. 1 - Location map of the Wadi Araba Basin and distribution of water wells.

Fig. 1 - Carta della località del Bacino di Wadi Araba e distribuzione dei pozzi d'acqua.

The main groundwater resource in Wadi Araba is the Quaternary aquifer system which is the most favorable circumstance for groundwater development found in this aquifer system. As a result, the Quaternary aquifers have been studied for the development of agriculture and domestic water supplies, and four well fields were established to provide water to the pilot farms.

The landscaping of the Bir Mathkoor area is characterized by a 2.4 % moderate slope in the well distribution zone on the eastern side of the Safi major road, which becomes flatter in the existing farm strips (Fig. 2). The elevation varies from 240m above sea level near the Beer Mathkoor wells (WMSH1, WMSH2, WMSH3, and WMSH4) in the eastern direction of the Safi main road, along the current farm strips to 120m above sea level. The elevation of the Qa Saydeen area varies from -34 meters below sea level to -180 meters below sea level, particularly around the existing farms near the Safi main road. The Dahl well is located around 5.0 kilometres east of the Safi main road and has no access road and the WM1 well is in the flood plain of a large watercourse known as Wadi Dahl.

Stream flooding is characterized by rugged terrain and limited accessibility. Within the range of existing farms, the topography of the Dahl well can be described as moderate, with a slope of 2.4% that gradually flattens to 1.0%.

In the south of Jordan, the average monthly temperature ranges from 22 to 31 degrees Celsius. The relative humidity ranges from 42 to 66% on average. The wind is blowing from the west. The rainy season runs from September through May, with most of the rain falling between December and March. The project area receives less than 75mm of rain per year on average.

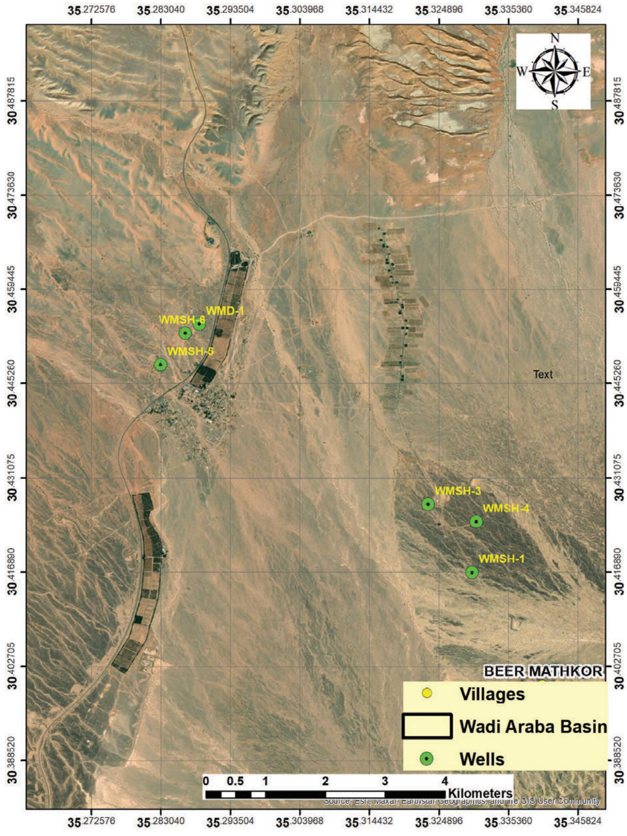


Fig. 2 - Google Earth images for Beer Mathkor Well Sites.

Fig. 2 - Immagini di Google Earth dei siti dei pozzi di Beer Mathkor.

Hydrogeology

The hydrogeological study attempts to determine the alluvial aquifer's characteristics as well as the maximum sustainable yield of existing groundwater boreholes in the Northern Wadi Araba Basin. The yield of the 20 years (Q20) method has been used to evaluate the safe yield of a well which can be defined as the rate at a well can be pumped for 20 years continuously so that the pumping water level does not drop below the top of the aquifer (Farvolden, 1959).

Previous research revealed that groundwater flows at a rate of 21.7 MCM/year from the eastern highlands in a westerly direction, towards the north, into the Dead Sea (GIZ, 2020). Though it can alter throughout the study region, the groundwater division along the eastern rocky ridge of the Wadi Araba valley appears near the water divides. Furthermore, in the Wadi Arab, water salinity rises in the direction of groundwater flow, from recharge to discharge zones.

Within the Wadi Araba, the following aquifer systems can be pointed out by the National Water Master Plan of Jordan (2003).

- The Disi Group aquifer system consists of water-bearing sandstones from the Cambrian and Ordovician periods.
- The Kurnub Group aquifer is made up of sandstones from the Lower Cretaceous period. The Upper Cretaceous Carbonate rocks which called Amman-Wadi Sir (or B2/A7) aquifer systems.
- Alternating aquifers of Upper Cretaceous and Tertiary undifferentiated strata.
- The Quaternary alluvial deposits consist of a shallow Aquifer System occurring in the valley floor of Wadi Araba.

The Alluvium Aquifer System is the main aquifer underlying the Wadi Araba floor throughout the Rift Valley, which stretches from the Dead Sea to the Red Sea. The Quaternary sediments of the Wadi Araba valley include various lithogenic units. Nevertheless, it seems rather clear that the Quaternary aquifers, being presently tapped by existing wells, mainly occur in the fluvial-lacustrine and fluviatile deposits, comprising conglomerate, gravel, sand, interfingering with or, at the east side of the rift valley, replacing the Upper Pleistocene Lisan formation, as well as conglomerate, gravel and sand of elevated terraces and "old" mantle rock respectively. The total thickness of these sediments is estimated to be 170 m (Energoprojekt, 1990).

The Quaternary aquifer system in the Wadi Araba Basin moves groundwater from the eastern foot of the escarpments to the Wadi valley floor, and from south to north toward the shorelines of the Dead Sea, as depicted in Figure 3. Figure 4 depicts the hydrogeological conceptual model of the Wadi Araba Basin (Radulovic and Al Tarawneh, 2020).

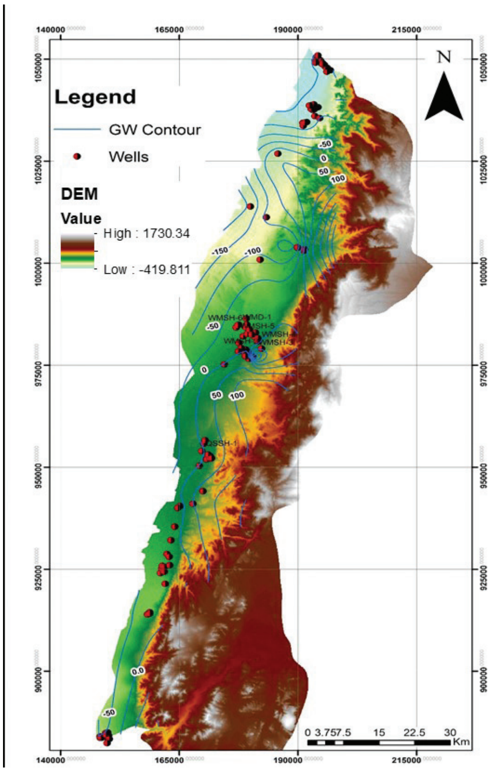


Fig. 3 - Groundwater contour map of Quaternary Alluvium Aquifer System.

Fig. 3 - Carta delle curve di livello della falda acquifera dei depositi alluvionali quaternari.

Materials and Methods

This study adopted an integrated approach combining field testing, analytical methods, and numerical modelling to estimate the sustainable and safe groundwater yield in the Northern Wadi Araba Basin. The methodological framework is structured into five interrelated components (Fig. 5). A comprehensive well inventory and hydrogeological characterization was conducted to establish baseline information. Data included aquifer stratigraphy, static water levels, well construction parameters, and groundwater quality. This step ensured a robust understanding of the physical system before applying analytical and numerical methods.

Hydraulic parameters were determined through pumping and recovery tests following standard procedures (e.g., Theis, 1935; Cooper & Jacob, 1946). Step-drawdown and constant-rate pumping tests were performed to assess performance, transmissivity, storativity, and recovery efficiency. The collected data served as the foundation for both analytical yield estimation and model calibration.

Analytical techniques were applied to interpret the hydrogeological conditions and estimate safe yields using Analytical Evaluation, Sustainable Yield Estimation, 20-Year Safe Yield Projection and numerical a numerical groundwater flow model using ParFlow.

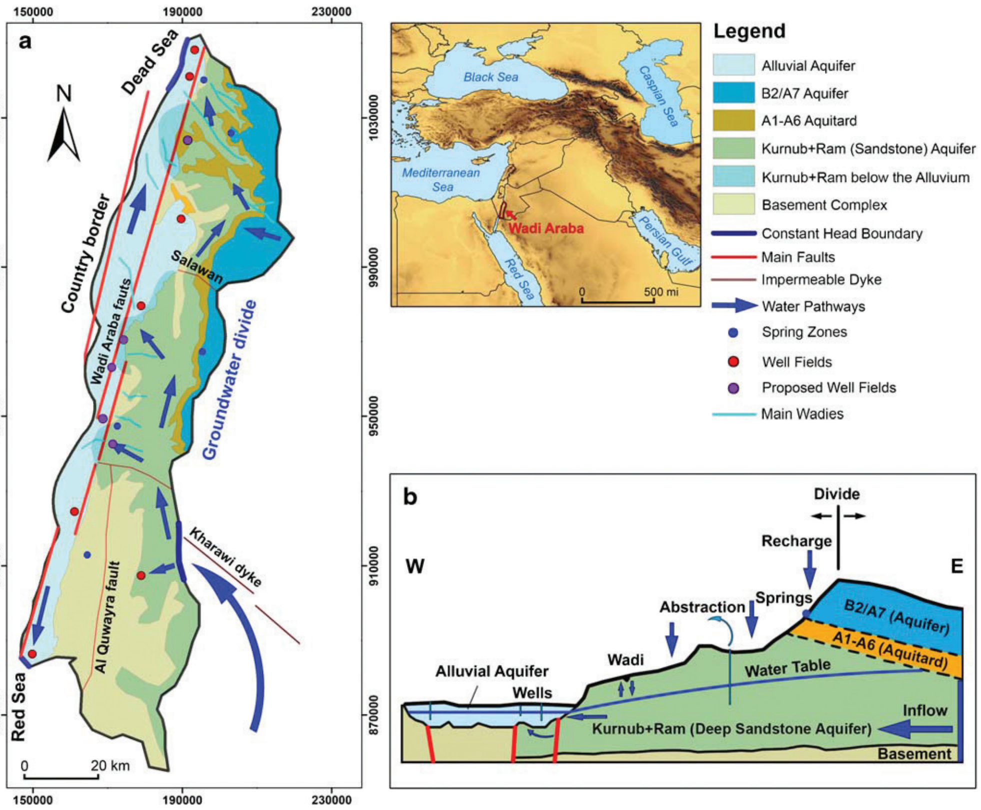


Fig. 4 - Hydrogeological conceptual model of the Wadi Araba Basin (modified after Radulovic and Al Tarawneh, 2020).

Fig. 4 - Modello concettuale idrogeologico del Bacino di Wadi Araba (modificato da Radulovic e Al Tarawneh, 2020).

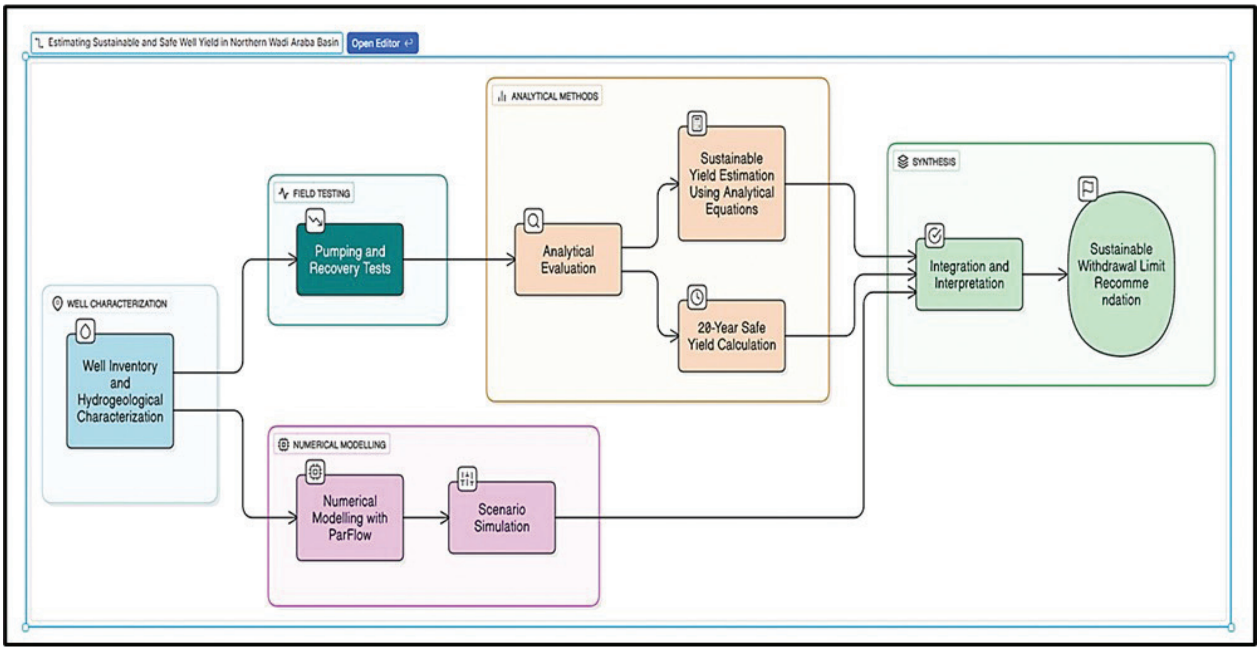


Fig. 5 - Flow chart summarizing the methodology used in this study.

Fig. 5 - Diagramma di flusso che riassume la metodologia utilizzata in questo studio.

Well inventory and Hydrogeological Characterization

Field investigations encompassed a comprehensive well inventory of the eight target wells, hydrogeological characterization of the unconfined Quaternary alluvium aquifer, and controlled pumping and recovery tests (Table 1). Pumping tests were conducted at rates varying from 100 to 500 m³/h, with recovery phases monitored post-pumping. Water level measurements were recorded using pressure transducers in observation wells at distances of 10–50 m from pumping wells. All data were processed using AquiferTest Pro software. The Neuman solution was applied to simulate unconfined aquifer behaviour during pumping, while Theis's recovery method was employed for post-pumping analysis. In the Wadi Musa area, eight production wells have been drilled at various depths. Table 1 shows the coordinates, elevation, total depth, static water level (SWL), pumping water level (PWL), drawdown (DD), and well yield from the well inventory. The Wadi Musa deep well is the deepest well in the study area, extending to a depth of up to 980 meters. Other wells range in depth from 218 to 420 meters. The well yield ranges from 5 m³/hr for Wadi Musa Shallow Well No. 1 (WMSH-1) to 103 m³/hr for Wadi Musa Shallow Well No. 2 (WMSH-2). The alluvial Aquifer is penetrated by all the wells. The thickness of alluvium sediments in wells ranges from 280 meters to 500 meters.

Tab. 1 -Well Inventory Data in the study area.

Tab. 1 - Dati di inventario dei pozzi nell'area di studio.

Well Name	PGE	PGN	Elevation (m)	T.D. (m)	SWL (m)	PWL (m)	DD (m)	Q (m^3/hr)
Wadi Musa Deep Well (WMD-1)	177560	984938	122	980	102.70	374.00	271.30	50.0
Wadi Musa Shallow Well No.1 (WMSH-1)	181512	980796	201	271	106.60	134.26	27.66	58.0
Wadi Musa Shallow Well No.2 (WMSH-2)	182358	979072	235	420	104.65	177.27	73.05	103.0
Wadi Musa Shallow Well No.3 (WMSH-3)	180873	981933	172	268	103.60	165.35	61.75	57.0
Wadi Musa Shallow Well No.4 (WMSH-4)	181570	981639	189	218	118.77	126.01	7.24	58.0
Wadi Musa Shallow Well No.5 (WMSH-5	177004	984257	122	328	107.90	256.7	148.8	30.0
Wadi Musa Shallow Well No.6 (WMSH-6)	177362	984785	124	330	146.95	220.00	73.05	5.0
Qa Sa'deen Well No.1 QSSH-1	169771	953991	193	302	84.53	95.12	10.59	60

Where: T.D: Total depth (m), SWL: Static water level (m), PWL: Pumping water level (m), Q: is the discharge of well (m³/hr), DD is the drawdown (m).

Pumping and Aquifer tests

Analytical interpretations of the results were carried out using AquiferTest Pro software (v16). The Neuman solution was applied to simulate unconfined aquifer behavior during pumping, while Theis's recovery method was employed for post-pumping analysis. Derived transmissivity and storativity values were cross-checked against typical values for alluvial aquifers. The Neuman solution simulated the behavior of the unconfined aquifer during pumping, while Theis's recovery method was used for post-pumping analysis.

Transmissivity (T) and storativity (S) were estimated separately for each well using the Neuman solution for unconfined aquifers during pumping phases and Theis's method for recovery analysis. The Neuman equation (Eq.1) is given by:

$$s=\frac{Q}{4\pi T}W\left(u,r/\delta\right) \qquad (1)$$

where s is drawdown, Q is pumping rate, and u is given by Eq.2

$$u=\frac{r^2S}{4Tt} \qquad (2)$$

r is radial distance, t is time, and δ is aquifer thickness.

The water levels in the pumping and monitoring wells steadily rise after the pump is turned off at the end of a pumping test. This test is known as a recovery test, where the drawdown measurements below the initial static water level during the recovery period are referred to as residual drawdown. From a practical point of view, it is necessary to measure the residual drawdown which enables the estimation of transmissivity and therefore, provides an independent check on the results of pumping tests.

The interpretation of recovery test data has conventionally been based on the Theis model of aquifer response, using the Cooper-Jacob (1946) straight-line approximation of the Theis well function. This approach presumes an ideal confined aquifer of infinite extent; a condition seldom encountered in practice. Nevertheless, the Cooper-Jacob method remains widely applied because of its ease of implementation, offering a straightforward framework for recovery data analysis:

$$s'=\frac{2.303Q}{4\pi T}\left[\log_{10}\left(\frac{t}{t'}\right)-\log_{10}\left(\frac{s}{s'}\right)\right] \qquad (3)$$

Where Q = pumping rate [L^3/T]; s'=residual drawdown [L]; S=storativity during pumping [dimensionless]; S'=storativity during recovery [dimensionless]; t=elapsed time since start of pumping [T]; t'=elapsed time since pumping stopped [T]; T=transmissivity [L^2/T].

To apply the Theis recovery method given by Eq. (4), plot s' as a function of log(t/t') on semi-logarithmic axes and draw a straight line through the data. Determine T using the following equation Eq. (4):

$$T=\frac{2.303Q}{4\pi\Delta s'} \qquad (4)$$

Where: Δs'=slope of the fitted line (change in residual drawdown per log cycle equivalent time); S/S' is found from the intersection of the line with the log(t/t') axis of the plot. In the absence of boundary effects, S/S' should be close to unity. The value of S/S' > 1 suggests recharge during the test, whereas S/S' < 1 may indicate a no-flow boundary.

Analytical methods for estimating Sustainable Well Yield (Qmax) and Long-Term Safe Yield (Q20)

Pumping tests are the most important experiments for aquifer investigation in the groundwater industry. They are the only method that provides simultaneous information on the hydraulic behavior of the well.

The sustainable yield is defined as the discharge rate that will not cause the water level in the borehole to drop below a prescribed limit (the position of a major water strike, for example) (Maathuis1 and van der Kamp, 2006). It is also important that the total abstraction rates of boreholes situated in an aquifer must not exceed the sustainable yield of the aquifer in total (i.e. the average annual recharge).

The interpretation of pumping test data is based on mathematical models that relate the drawdown response to the discharge of the pumped well and the results obtained from this short-duration test are then used to estimate the borehole performance for many months (even years). The mathematical model could be solved by the application of analytical or numerical techniques.

Under the current hydrogeological circumstances and limits, the sustainable yield is defined as the volume of groundwater discharge that may be redirected and captured during groundwater abstraction (Maimone, 2004; Kalf and Woolley, 2005). This method proposes that a long-term water balance in the aquifer can be sustained without significant groundwater depletion; however, it overlooks the additional impacts of extraction, such as declining groundwater levels and reduced discharge flows (Sophocleous, 2000; Custodio, 2002; Alley and Leake, 2004).

To determine the maximum permissible discharge (Q_{max}) that will cause the maximum allowable drawdown (S_{max}) at the end of the hydrological year (Eq. 5), when groundwater levels are at their lowest, rough estimates of the following factors are needed (Driscoll, 1986):

- (S_{max}) the maximum permissible drawdown is derived by subtracting the seasonal water level decline from the maximum allowable pumping water level at the end of the dry season (typically considered as the major water strike).
- (r) the effective well radius, usually taken as the radius of the well (rw).
- (t) time between the two rainy seasons-assume 300 days for a climate with a two-month rainy season.
- (S) the aquifer's storativity, which ranges from 0.005 to 0.03 in fracture-controlled aquifers.
- (E) is the well efficiency expressed as a percent of one, derived by dividing theoretical drawdown by actual drawdown.

$$\frac{ES_{\max}T}{0.1831\log(2.25Tt/r^2S)} \qquad (5)$$

Where Q_{max} = is the maximum allowable (sustainable) discharge expressed in m^3/d. In general, this method provides an approximation. Certain important parameters are usually determined through step drawdown pumping tests, and the results obtained so far appear satisfactory. Most wells are pumped intermittently on a daily basis for less than 24 hours. To calculate the maximum allowable discharge (Q_{max}), the formula in (Eq. 6) can be used (Driscoll's, 1986) :

$$Q_{\max} = \frac{E0.228S_{\max}T}{t_1\log\left(\left(t_2-1+t_1\right)+\log\left(2.25Tt_1/r^2S\right)\right)} \qquad (6)$$

where:

t_1= represents the daily pumping cycle as a fraction of a day.

t_2 = time between two rainy seasons.

Because we are pumping for a fixed number of hours per day, Q_{max} is represented as m^3/h rather than m^3/day in this formula.

The rate at which a well may be pumped continuously for 20 years without the pumping water level dropping below the top of the aquifer is known as the 20-year safe yield (Q20) (Maathuis and van der Kamp, 2006). The available drawdown is calculated using the difference between the non-pumping water level and the top of the aquifer. The well performance and aquifer potential can be evaluated using recognized methods for assessing the long-term capacities of water supply wells, including the 100-day and modified Moell Q20 methods. The 100-day method calculates the safe available drawdown by multiplying it with the well's specific capacity (SC). Specific capacity is determined by dividing the pumping rate by the projected drawdown after 100 days, using the Cooper-Jacob straight-line semi-log plot (Van Everdingen, 2024).

The estimation of the sustainable yield of the wells is based on the pumping tests. To estimate the sustainable yield of the well, appropriate aquifer tests should be conducted and consequently, the data can be analyzed by appropriate methods taking into account the hydraulic properties of the aquifer system.

The long-term well yield partly depends on the safe available drawdown (SAD) in a well, which is calculated as the total available drawdown (TAD or *Δsavailable*). This is measured from the non-pumping water level (NPWL), typically recorded just before the start of pumping tests, to the top of the aquifer, and is then multiplied by a safety factor (Sf) (Fig. 6).

Pumping tests are useful tools for determining the hydraulic behavior of groundwater wells. The mathematical ideas that connect drawdown to discharge in the production well are used to analyze pumping test results. The findings of these short-duration testing can then be utilized to forecast the groundwater well performance over a long period.

The Q20 safe yield was computed using three methodologies: Farvolden (1959), Modified Moell (2006), and Ribby (1979). Farvolden (1959, 1961) introduced the concept of the safe pumping rate of a well for 20 years in the Alberta region in Canada. This concept was then used by Tóth (1966), who named it as a safe yield Qs20. The Alberta Research Council has adopted this term in the preparation of the hydrogeological maps of Alberta (Tokarsky, 1971; Ozoray and Barnes, 1978, Stevenson and Borneuf, 1977).

Farvolden (1959) has estimated the transmissivity using Jacob's simplified method of Jacobs solution (Cooper and Jacob, 1946; Jacob, 1950). Todd (1959) finds out that Jacobs's

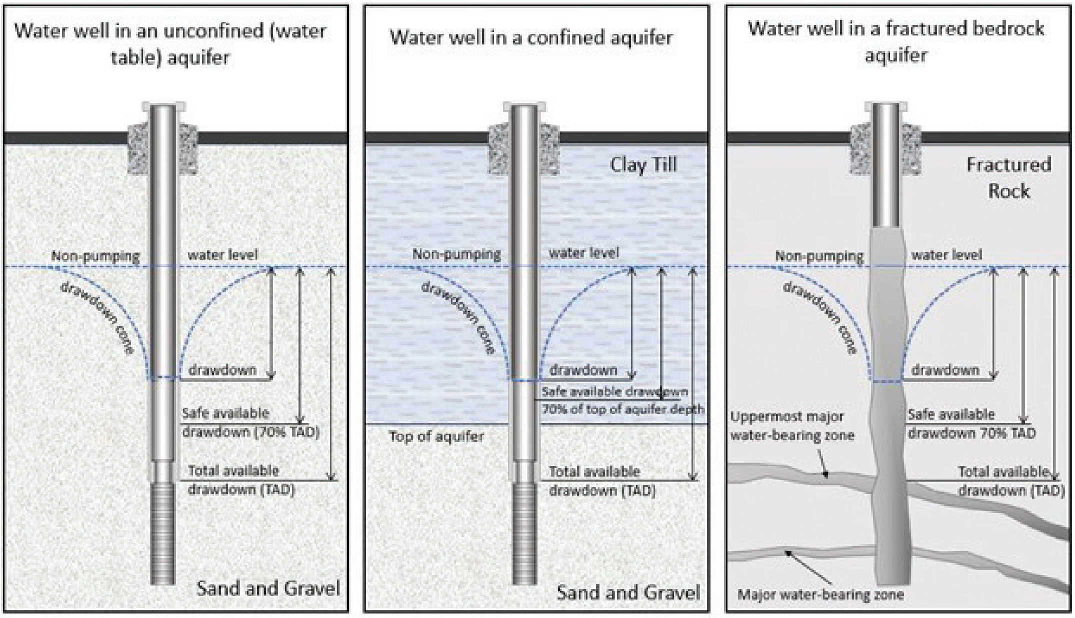


Fig. 6 - Estimation of safe available drawdown for different aquifer types (British Colombia, Ministry of Environment, 1999).

Fig. 6 - Stima del prelievo sicuro disponibile per diversi tipi di acquifero (British Columbia, Ministry of Environment, 1999).

method can be applied for small values of u (a variable in the non-steady-state Theis equation for computation of the permeability in confined aquifers; (Kruseman and de Ridder, 2000). Small u occurs if r (the diameter of the cone of drawdown) is small, and the value of t (time of pumping) is large. The equation used to derive apparent transmissivity and safe yield can be described in the Eq. (7) and Eq. (8) as the following:

$$T=\frac{(264*Q)}{\Delta S}$$ in gallon per day/feet (gpd/ft) (in imperial units) (7)

$$T=\frac{(0.183*Q)}{\Delta S}$$ [m^3/day/m=m^2/day], (in metric units) (8)

Where Q is the pumping rate of the well and Δs is the drawdown of the well.

Subsequently, the straight-line drawdown curve was extrapolated by estimating up to 8 log cycles (10 million minutes = 19 years). The 20-year safe rate Q was then estimated by the following equations (Eq. 9 and Eq. 10)

$$Q=\frac{T*H*0.7}{2110}$$ [gpd] (in imperial units) (9)

$$Q=\frac{T*H*0.7}{14.71}$$ [m^3/day] (in metric units) (10)

Where *T* is the transmissivity, *H* is the available head (difference between static water level and the top of the screen), and 0.7 is a safety factor reducing the *Q* value to 70%. The safe rate Q for 20 years was renamed by others to 20-year safe yield Q20. The 0.7 safety factor is an arbitrary number. According to Moell (1975), the safety factor is employed to compensate for overestimates of sustained yield caused by presuming the aquifer to be infinite in extent, constant in thickness, homogenous, and isotropic.

It should be noted that in the Farvolden equation 11, the computation of transmissivity T is an intermediary step that is not necessarily required for the calculation of Q20. Bibby (1979) confirmed that if the drawdown curve for a fixed pumping rate is known over 20 years, the 20-year sustainable yield can be calculated by linearly adjusting this curve. The equation (Eq. 11) can be written as:

$$Q20=Q_t\left(\frac{H_A}{8\Delta S_p}\right)S_f \tag{11}$$

Equation 11 is the Farvolden formula for Q20 that can be written in terms of the drawdown per unit log cycle of time; the (8Δs$_p$) represents the 8-log cycle of drawdown. The long-term sustainable yield (Q20) of a groundwater well can be calculated using the Modified Moell Method (Maathuis and van der Kamp, 2006). For the case where losses must be addressed well, Moell (1975) developed a variant of Farvolden's "safe rate" which can be calculated by (Eq. 12):

$$Q20=\frac{Q_tH_A}{S_{10}+6\Delta S_p} \tag{12}$$

Where: S_{10} = actual drawdown after 10 minutes and the (Q20) is a long-term yield.

A significantly modified version of Moell's calculation is used in the Alberta Groundwater Evaluation Guideline (2003) (Eq. 13):

$$Q20=\frac{Q_tH_A}{S_{100}+5\Delta S_p}S_f \tag{13}$$

Where: S_{100} = actual drawdown after 100 minutes and ΔS_p="drawdown per log cycle of time from the pumping test' Bibby (1979) introduced the concepts of "local" and "regional" transmissivity. He defined "local" transmissivity as the values obtained from pumping tests of only a few hours' duration. In contrast, the transmissivity of the final straight line in the data is referred to as "regional" transmissivity or "average" transmissivity. To determine the 20-year sustainable pumping rate, Bibby (1979) extended the final straight line to 1 x 107 minutes using the principle of proportionality, applying the following equation (Eq. 14):

$$Q20=\frac{Q_tH_A}{S_{20Q}} \tag{14}$$

where: Q_{20} = 20-year sustainable pumping rate, H_A = available drawdown, S_{20Q} = theoretical drawdown after 20 years of pumping. Extrapolation of the straight line to 1 x 107 is not necessary since:

$$Q20=S_{1000}+4\Delta S_p \tag{15}$$

Therefore, Eq. 15 becomes:

$$Q20=Q_t\frac{H_A}{S_{1000}+4\Delta S_p} \tag{16}$$

The long-term drawdown can be estimated by adding the measured drawdown after 100 minutes to the predicted drawdown from 100 minutes to 20 years, using the Moell method. This approach can be used to calculate Q20 Eq. (17):

$$Q20=S_{100\min}+(S_{20years}-S_{100\min})_{Theor} \tag{17}$$

$$Q20=\frac{S_fQH_a}{S_{100\min}+(S_{20years}-S_{100\min})_{Theor}} \tag{18}$$

Where:

H_a = Available head (in meters) H = (top of the aquifer) – Non-Pumping Water Level (NPWL)

S_{100min} = Measured drawdown at 100 minutes (in meters)

Q = Well pumping rate during the aquifer test (in cubic meters per day [m^3/day])

$Q20$ = Sustainable yield for 20 years (in m^3/day)

S_{20yrs} = Calculated theoretical drawdown after 20 years of pumping at Q (in meters)

T = Transmissivity (in square meters per day [m^2/day])

S_f = 0.7 which represents 70% safety factor

Numerical Modeling with ParFlow model

A numerical simulation was implemented using the ParFlow model to construct a three-dimensional representation of groundwater flow across the Wadi Musa region. ParFlow is an open-source, parallel numerical tool designed to simulate integrated hydrologic processes, encompassing 3D subsurface and surface water flow, with applications ranging from small watersheds to global scales. It addresses the Richards equation for variably saturated flow and is utilized in studies of groundwater-surface water interactions and water resource management by modeling subsurface, surface, and land-surface energy budget dynamics.

The ParFlow governing equations for its fully saturated model are given by a set of mass balance Darcy's Law equations (Eq. 19 and Eq. 20) (Maxwell et al., 2014):

$$S_s \frac{\partial p}{\partial t} - \nabla\left(\frac{k}{\mu}\left[\nabla p - \rho g\right]\right) = Q \tag{19}$$

$$S_s \frac{\partial h}{\partial t} - \nabla\left(k \nabla h\right) = Q \tag{20}$$

Where: S_s=specific storage coefficient [L^{-1}]; p=pressure [Pa]; h=hydraulic head [L]; k=intrinsic permeability tensor [L 2 2]; μ = dynamic viscosity [$ML^{-1}T^{-1}$]; ρ=fluid density [M L^{-3}]; g=gravitational acceleration vector [L T^{-2}]; Q_i is the Source or Sink term [T^{-1}]

ParFlow calculates pressures on a discrete mesh using a time-stepping algorithm that employs a mass-conservative backward Euler scheme and spatial discretization through a finite volume method. Although ParFlow multi-phase flow capability is available for testing, it has not been widely utilized in major studies (Maxwell et al., 2016).

The domain was discretized into a grid of 82 × 125 × 280 cells. Boundary conditions included no-flow on lateral sides, constant head at the northern recharge boundary (simulating inflow from Kurnub aquifer), and specified flux at the southern outlet. Recharge was set at 20 mm/year based on precipitation data. Pumping scenarios tested continuous rates of 500–2000 m^3/day per well and intermittent (8 h/day) rates up to 15,000 m^3/day. Steady-state calibration minimized residuals between observed and simulated drawdowns (RMSE < 0.5 m).

In this study, the aquifer system was reconstructed within a rectangular box, as shown in Figure 5. A simplified stratigraphy was created which includes the top gravel layer, sandstone aquifer with intermittent clay lenses, and volcanic base. These three layers are distinguished from each other within the model by an indicator field three-dimensional matrix portrayed in Figure 7. The code distinguishes these layers by their hydraulic conductivity and porosity, the values of which are assigned in 3D variation accordingly.

The parallel three-dimensional variably saturated subsurface flow code ParFlow was used in its fully saturated mode to simulate groundwater flow within the project domain. ParFlow is a high-performance simulation tool developed at the Lawrence Livermore National Laboratory (Ashby and Falgout, 1996; Jones and Woodward, 2001; Kollet and Maxwell, 2006; Abu-El-Sha'r and Rihani, 2007). It uses state-of-the-art computational methodologies and high-performance computing technologies to enable more realistic 3D simulations of fluid flow in large-scale, heterogeneous porous media. ParFlow uses a Multigrid-Preconditioned Conjugate Gradient solver that is robust, efficient, and scalable (i.e. the number of iterations required for convergence remains roughly constant as the grid of the problem being simulated is refined), which enables detailed, fully three-

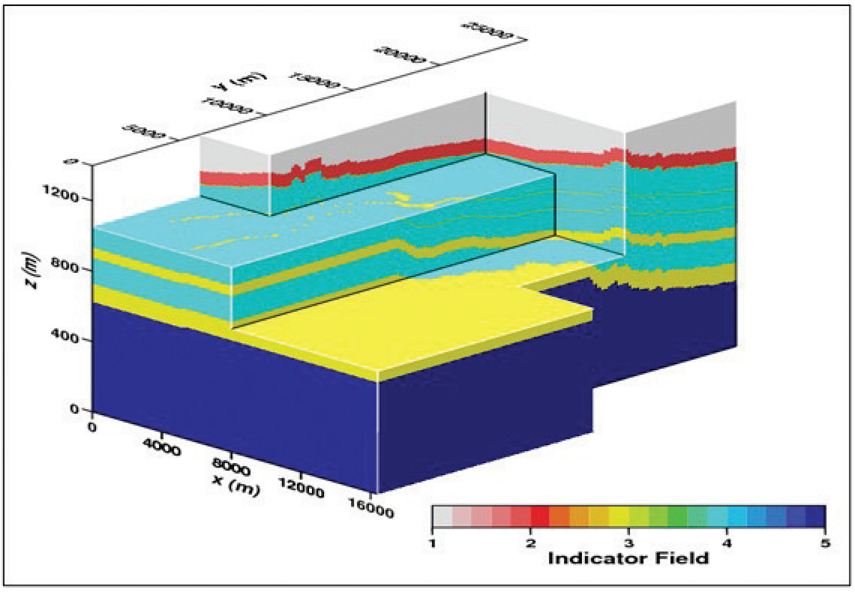


Fig. 7 - Indicator Field used to Simulate Subsurface Geologic Layers.(1: air, 2: gravel, 3: clay lenses, 4: Sandstone, 5: Volcanic).

Fig. 7 - Campo utilizzato per simulare strati geologici sotterranei (1: aria, 2: ghiaia, 3: lenti di argilla, 4: arenaria, 5: vulcanico).

Tab. 2 - Model Coordinates and Discretization.

Tab. 2 - Coordinate del modello e discretizzazione.

Parameter	Real Coordinates			Model Coordinates		
	East (PGE)	North (PGN)	Elevation (m asl)	X (m)	Y (m)	Z (m)
Max	189100	994000	400	16400	25000	1400
Min	173300	969600	-1000	0	0	0
Range (m)	15800	24400	1400	16400	25000	1400
dx, dy, or dz	200.0	200.0	5.0	200.0	200.0	5.0
nx, ny, or nz	82	125	280	82	125	280

dimensional modeling of large sites (Engdahl and Maxwell, 2015; Kollet et al., 2017).

The unconfined sandstone aquifer was simulated within a box-shaped domain with dimensions of (16400 m*25000 m*1400 m) in the x-, y-, and z-directions, respectively, as shown in Table 2. Jordan Transverse Mercator (JTM) grid was converted to a model-designed coordinate system as also shown in Table 2. All simulation results and plots are shown concerning the model coordinate system.

The net difference between rainfall and evapotranspiration was applied as a flux at the top boundary. These were applied as 12-time cycles representing averaged monthly rates. Neuman-type, constant flux boundary conditions were assumed at the east and west sides of the domain as part of the recharge and discharge into the aquifer. The rest of the base flows were applied as phase sources at the East and West boundaries which apply a constant flux rate. It seems that we have a constant boundary condition at the North and South which act as an infinite source of water, therefore, Dirichlet boundary conditions of constant pressure were applied at the North, South, and bottom boundaries (values of 1100, 1100, and 1300 Pa respectively). These were based on Dynamic water table elevations at well locations as well as regional base flow values of Wadi Araba (AI-Homoud et al, 1996).

Results and Discussion

The evaluation of the sustainable yield of groundwater wells in the Northern Wadi Araba Basin was achieved through analytical pumping test interpretation, long-term yield estimation methods, and numerical groundwater flow modeling using ParFlow. The integration of these approaches allowed for cross-validation of aquifer parameters and yield estimates under both steady-state and transient conditions, yielding a comprehensive understanding of the aquifer behaviour and safe abstraction limits.

Aquifer Parameters from Pumping and Recovery Tests

To get a "best fit" to the test data, the Neuman analytical solutions for unconfined aquifer conditions were applied. Figure 8 show the plots of the drawdown data versus time on typical Neuman equation curves for example for WMD-1 and WMSH-1 wells. The rest of these plots will be provided as supplementary material. Deviations of the plotted data from theoretical curves or straight-line fits indicate non-ideal boundary conditions of the aquifer. As a result, data from the latter periods of the test were used to match the theoretical answers to the data, as they would better depict the aquifer's behaviour over time.

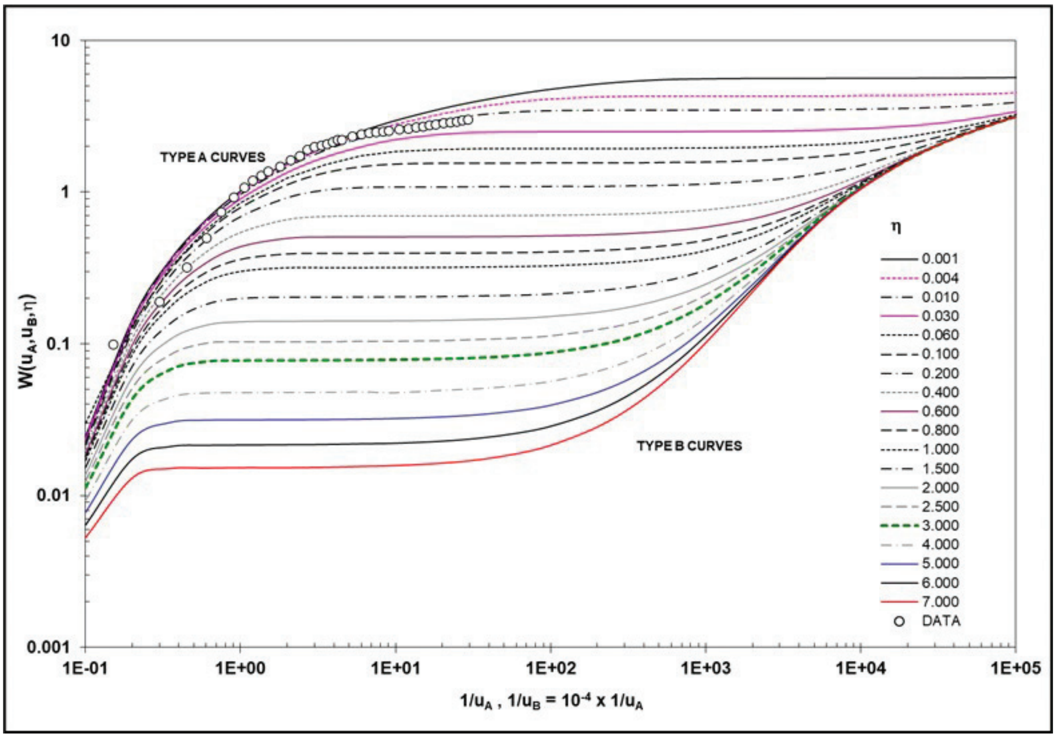
The analytical analysis revealed that the transmissivity (T) values varied widely among the wells, ranging from as low as 1.07 m^2/day in WMD-1 to as high as 55.93 m^2/day in WMSH-4. These values align with typical ranges reported for alluvial aquifers (Freeze and Cherry, 1979), indicating moderate to high heterogeneity in the aquifer matrix. Storativity values ranged from 2.54×10^{-3} to 6.79×10^{-1}, reflecting unconfined aquifer behavior with some degree of confinement in deeper or clay-interbedded layers. The recovery test data also validated the pumping test results, offering an independent check and supporting the reliability of transmissivity estimates derived analytically.

The geometric mean of aquifer transmissivity was calculated to be 12.5 m^2/day based on this investigation, as shown in Table 3. The storativity values calculated range from 2.54 x 10^{-3} in the WMSH-6 well to 6.79 x 10^{-1} in the WMSH-4 well. These values are widely varied; however, they fall within the typical values of alluvium aquifers (Freeze and Cherry, 1979). WMD-1 Well yielded a poor storativity, which is thought to be typical of the aquifer's performance under unconfined conditions.

The recovery test is used to determine transmissivity by measuring the recovery in the pumping well itself. Since the pump does not influence the water in the well during the recovery period, more accurate data can be obtained compared to the pumping period. Theis's recovery equation was used to analyse the recovery tests of the drilled wells, and the results were described in Table 3.

Sustainable Well Yield Estimation (Qmax)

The computation of maximum yield (Q_{max}) and maximum drawdown (S_{max}) for the Wadi Musa wells highlights a wide variation in aquifer performance among the sites (Table 4). The results show that wells such as WMSH-4 have the highest capacity, producing up to 287.7 m^3/hr under continuous pumping and 427.2 m^3/hr under intermittent pumping, with a corresponding maximum drawdown of 137.93 m, making it the most productive well in the study. In contrast, wells like WMSH-6 and WMSH-5 exhibit very limited yields, with continuous pumping capacities of only 3.7 and 6.2 m^3/hr, respectively, and high drawdowns of 73.05 m



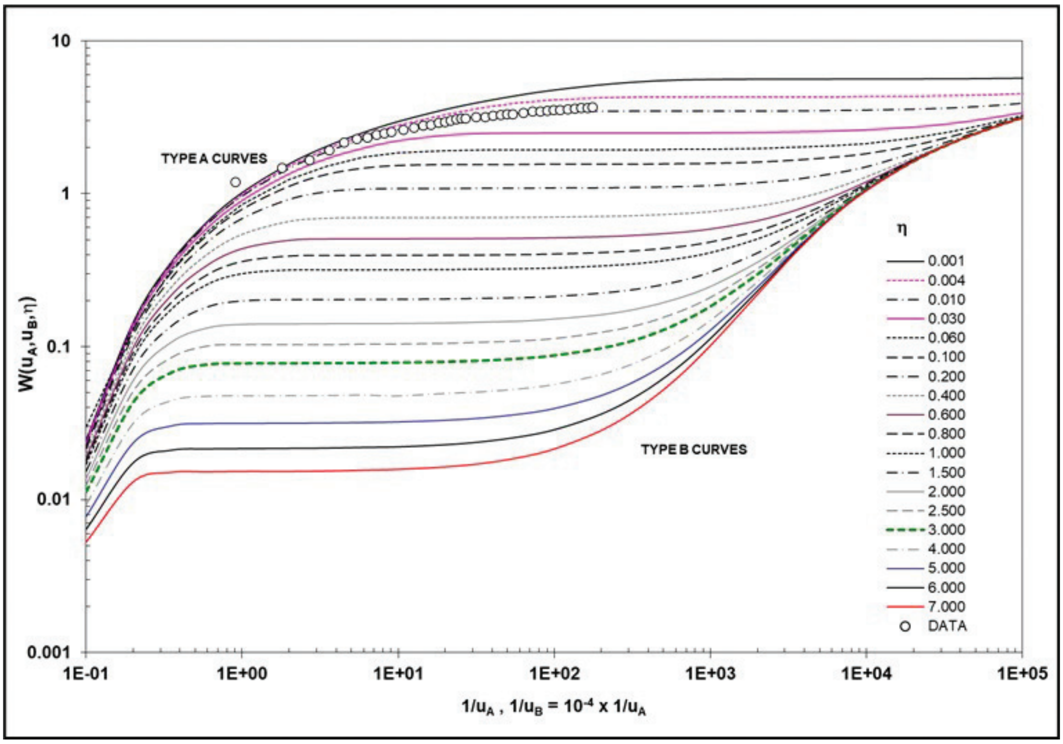


Fig. 8 - Neuman Time-Drawdown data of WMD-1 and WMSH-1 wells.

Fig. 8 - Grafici di Neuman tempo-prelievo dei pozzi WMD-1 e WMSH-1.

and 148.8 m, reflecting poor aquifer efficiency. Moderate productivity is observed in wells such as WMSH-2 and WMSH-3, which demonstrate higher intermittent yields (38.3 and 28.4 m^3/hr) but also significant drawdowns (73.05 m and 61.72 m). The analysis suggests that while a few wells, particularly WMSH-4, can serve as major contributors to water supply in Wadi Musa, the majority are limited either by low yield, high drawdown, or both, underscoring the heterogeneous nature of the aquifer system.

Tab. 3 - Interpretation of Hydraulic Parameter from Aquifer Tests.

Tab. 3 - Interpretazione dei parametri idraulici dai test sull'acquifero.

Well No.	Aquifer type	Type of test	Transmissivity (m^2/d)	Storativity
WMD-1	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	1.07 1.14	$1.38x10^{-2}$
WMSH-1	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	18.59 22.35	$3.98x10^{-2}$
WMSH-2	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	10.81 13.15	$3.16x10^{-2}$
WMSH-3	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	9.77 6.89	$2.09x10^{-2}$
WMSH-4	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	55.39 64.53	$6.79x10^{-1}$
WMSH-5	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	1.15 1.83	$7.31x10^{-3}$
WMSH-6	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	1.58 0.88	$2.54x10^{-3}$
QSSH-1	Neuman (1975) unconfined Theis (1935)	Pumping test Recovery test	1.4 1.1	$5.86x10^{-3}$

Tab. 4 - Computation of maximum yield (Qmax) and maximum drawdown (Smax) Wadi Musa wells.

Tab. 4 - Calcolo del prelievo massimo (Qmax) e dell'abbassamento massimo (Smax) dei pozzi di Wadi Musa.

Well Name	Continuous pumping 24 hr Q_{max} (m^3/hr)		Intermittent pumping 24 hr Q_{max} (m^3/hr)		S_{max} (m)
	Highest Q_{max}	Lowest Q_{max}	Highest Q_{max}	Lowest Q_{max}	
WDM-1	11.0	4.8	16.3	7.2	271.3
WMSH-1	17.2	10.3	24.2	14.3	27.66
WMSH-2	27.0	5.4	38.3	7.7	73.05
WMSH-3	20.2	5.6	28.4	8.0	61.72
WMSH-4	287.7	80.5	427.2	119.6	137.93
WMSH-5	6.2	1.7	8.9	2.5	148.8
WMSH-6	3.7	0.4	5.1	0.5	73.05
QSSH-1	8.4	2.4	12.1	3.4	172.17

Where:
Q: is the discharge of the well (m^3/hr).
Q_{max}: Estimated Maximum Sustainable Well Yield (m^3/hr)
S_{max}: Maximum allowable drawdown (m)
Q_{max}/S_{max}: Maximum specific capacity of the well.

Estimation of Long-Term Safe Yield (Q20)

Based on the Farvolden (1959) and Maathuis and van der Kamp (2006) equations m the Q20 were computed as summarized in Table 5. The comparison of Q20 values using the Farvolden, modified Moell, and Ribby (1979) methods for the drilled wells in Wadi Musa demonstrates clear differences in the estimated sustainable yields. Overall, the Ribby method consistently predicts the highest yields across all wells, with values ranging from 26.37 m^3/d at WMD-1 to 4591.83 m^3/d at WMSH-4. The modified Moell method provides intermediate estimates, often higher than Farvolden for productive wells such as WMSH-2, WMSH-3, and especially WMSH-4, where it reaches 3214.28 m^3/d. In contrast, the Farvolden method generally produces the most conservative yield values, with significantly lower estimates in high-capacity wells, e.g., 1844.68 m^3/d for WMSH-2 compared to 2850.79 m^3/d by Ribby. For low-yield wells such as WMSH-5 and WMSH-6, all three methods converge to similarly small values, confirming their limited capacity. These results emphasize that yield estimation is method-dependent, with Ribby providing more optimistic projections, while Farvolden offers conservative assessments better suited for cautious groundwater management.

The Q20 values for each well were plotted as bar charts applying Farvoldent, Modified Moell and Ribby methods and the trend of Q20 values across these wells were plotted as line chart as shown in Figure 9 and Figure 10 respectively. The comparative analysis showed that the Ribby method, which considers both local and regional transmissivity over extended time frames, typically yielded higher Q20 values than Farvolden or Moell (Fig. 9), which use simplified safety assumptions. This suggests that Ribby's method may better

Tab. 5 - Comparison of Farvolden Q20, modified Moell Q20 and Ribby Q20 of drilled wells.

Tab. 5 - Confronto tra i valori calcolati Farvolden Q20, Moell Q20 modificato e Ribby Q20 dei pozzi trivellati.

Parameters	WMD-1	WMSH-1	WMSH-2	WMSH-3	WMSH-4	WMSH-5	WMSH-6
Ha	19.30	94.40	130.35	68.40	70.23	14.10	22.95
$S_{20years}$	878.38	47.19	113.03	117.05	21.29	654.34	32.40
$S_{1000\ min}$	374.16	25.75	69.41	61.54	8.66	278.78	29.10
$S_{100\ min}$	241.90	20.95	58.50	50.20	5.51	184.89	25.42
S20-S100	636.48	26.24	54.53	66.85	15.78	469.45	6.98
Q20 Farvolden (m^3/d)	16.06	2139.29	1844.68	585.37	2340.31	11.06	17.34
Q20 Modified Moell (m^3/d)	18.46	1949.21	1995.56	559.59	3214.28	10.86	59.50
Q20 Ribby 1979 (m^3/d)	26.37	2784.59	2850.79	799.41	4591.83	15.51	85.00

Where:
Ha = Available head (in meters)
S_{100min} = Measured drawdown at 100 minutes
$S_{1000min}$ = Measured drawdown at 100 minutes
S_{20yrs} = Calculated theoretical drawdown after 20 years of pumping at Q
Q20 = Sustainable yield for 20 years (in m^3/day)

account for the dynamic behavior of large alluvial aquifers with spatial variability. The Moell method, which factors in drawdown after 100 minutes and extends projection using a log-linear relationship, provided results that bridged the conservative Farvolden and the more optimistic Ribby estimates. This balance makes it particularly suitable for operational groundwater planning under uncertainty, as supported by Maathuis and van der Kamp (2006).

Safe Yield Estimation Using Numerical Model

This study employed the ParFlow groundwater flow and transport model to simulate groundwater flow in the Beer Mathkor area. Based on the conceptual model and formulation described previously, the calibration model parameters are hydraulic conductivity, porosity, and boundary conditions. The calibrated saturated hydraulic conductivity and porosity are shown in Figure 10 and Figure 11, respectively. The calibrated pressure head for the final run is shown in Figure 12. Calibration was based on matching water table levels at test well locations to modelled water table levels at those locations. It should be noted that over a hundred simulations were tested due to the lack of key data, making calculating a safe yield particularly difficult and not without problems, even when a calibrated model was reached simulating the actual conditions in Wadi Araba. Numerous assumptions were made to reach the calibrated model and the conclusions drawn herein depend on these assumptions being correct.

Once the model was successfully calibrated, a series of scenarios were tested by varying the pumping rate of the Beer Mathkor wells between 0 and 15,000 m^3/day. These scenarios were designed to evaluate the response of the system, with Figures 14 and 15 presenting the resulting pressure fields for pumping rates of 1,500 m^3/day and 5,000 m^3/day. Local water table variations exhibited a similar pattern.

The model proved highly sensitive to the boundary conditions, which were constrained by available water table measurements and the general understanding of groundwater flow in Wadi Araba. Recharge and discharge fluxes at the eastern and western boundaries exerted a strong influence, while simplifications of the subsurface hydrogeology were required to maintain numerical stability.

Simulation results indicate that abstraction from the Beer Mathkor wells should not exceed 5,000 m^3/day, with a preferred limit of 1,500 m^3/day to minimize drawdown. Small increases in pumping had negligible effects on the water table; however, a threefold increase from 5,000 to 15,000 m^3/

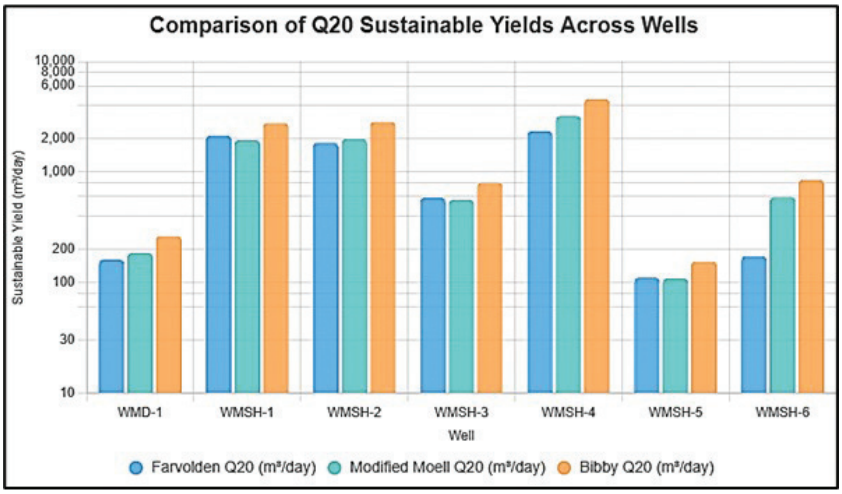


Fig. 9 - Estimation of Q20 values for each well (WMD-1 to WMSH-6) by Farvolden, Modified Moell and Bibby methods.

Fig. 9 - Stima dei valori di Q20 per ogni pozzo (da WMD-1 a WMSH-6) mediante metodi Farvolden, Moell modificato e Bibby.

day caused a marked decline, equivalent to approximately 5.5 million cubic meters per year from the active aquifer domain.

A comparison of pressure cones between Beer Mathkor and other active pumped wells provided a preliminary estimate of the maximum safe yield, further supporting the recommended abstraction range of 1,500–5,000 m³/day.

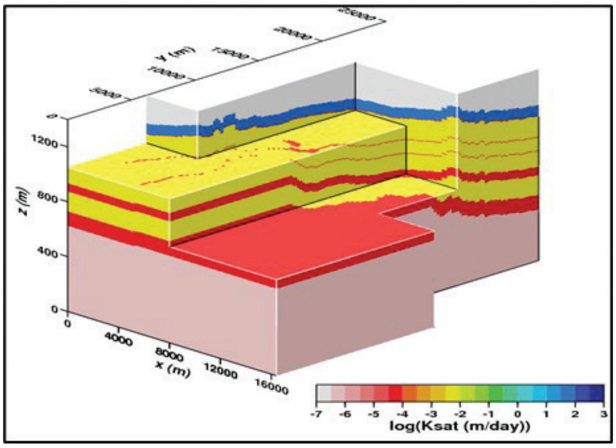


Fig. 10 - Calibrated Hydraulic Conductivity Values.

Fig. 10 - Valori calibrati di conducibilità idraulica.

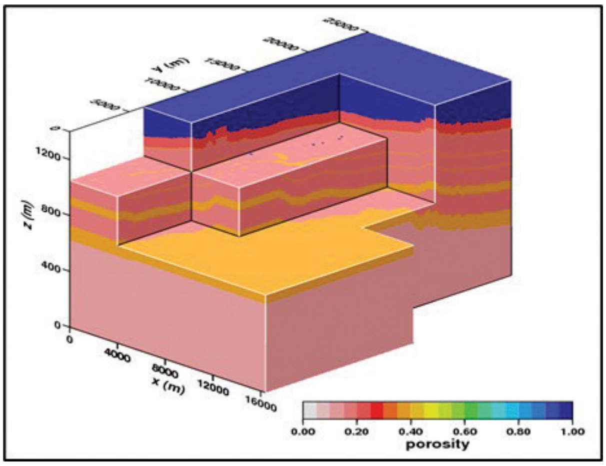


Fig. 11 - Calibrated Porosity Values.

Fig. 11 - Valori calibrati di porosità.

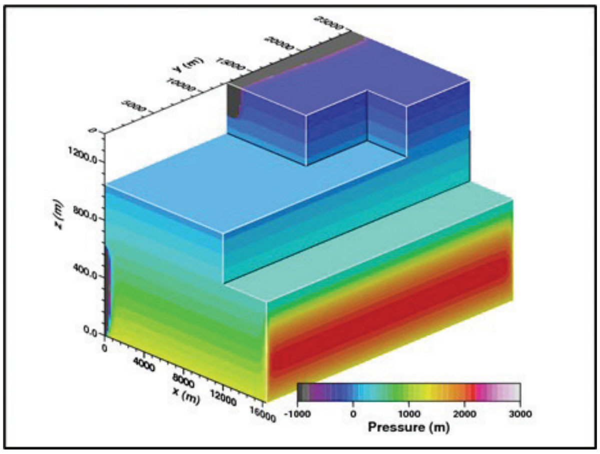


Fig. 12 - Final Calibrated Pressure Head Field (m).

Fig. 12 - Campo finale della pressione (m).

Comparison of Analytical and Numerical Results

The comparison between the results obtained from the analytical-empirical formulas with those of numerical modeling are summarized in Table 6. Figure 13 to Figure 14 show the resulting pressure fields for the calibrated with the pumping of 1500 m³/day and 5000 m³/day from Beer Mathkor wells respectively. These Figures represent the ParFlow model outputs validating the hydraulic response of the Beer Mathkor aquifer system in Wadi Araba. The model was calibrated using measured groundwater levels and applied boundary conditions (flux and Dirichlet). The simulated pressure was used to evaluate various pumping scenarios and identify the safe yield, ultimately recommending that groundwater abstraction should not exceed 5,000 m³/day,

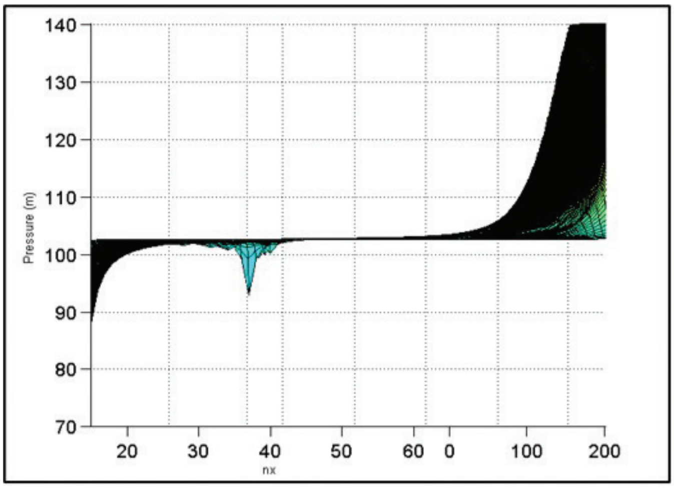


Fig. 13 - Pressure Field at Z=1000m (PF grid) showing cones of depression from pumping wells for calibrated run (Pumping from Beer Mathkor Wells = 1500 m³/day).

Fig. 13 - Campo di pressione a Z=1000m (griglia PF) che mostra i coni di depressione dai pozzi di pompaggio per la simulazione calibrata (prelievo dai pozzi di Beer Mathkor = 1500 m³/giorno).

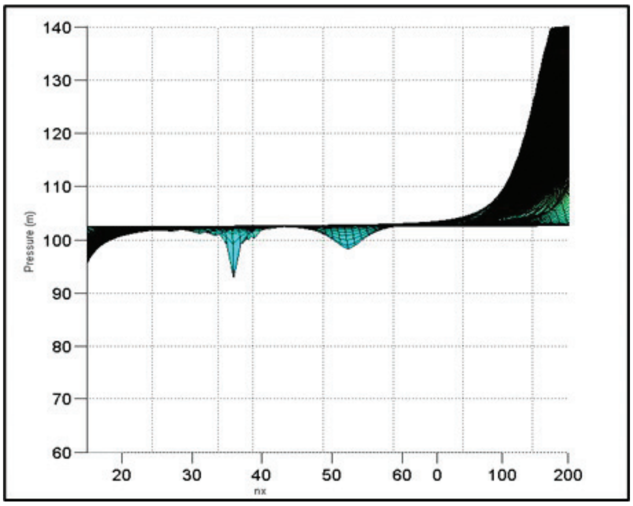


Fig. 14 - Pressure Field at Z=1000m (PF grid) showing cones of depression from pumping wells (Pumping from Beer Mathkor Wells = 5000 m³/day).

Fig. 14 - Campo di pressione a Z=1000m (griglia PF) che mostra i coni di depressione dai pozzi di pompaggio (prelievo dai pozzi di Beer Mathkor = 5000 m³/giorno).

Tab. 6 - The comparison between the results obtained from the analytical-empirical formulas with those of numerical modeling.

Tab. 6 - Confronto tra i risultati ottenuti dalle formule analitico-empiriche e quelli della modellazione numerica.

Well ID	Q20 Analytical (m³/day)	Numerical Simulation Result (m³/day)	Difference (%)
WMD-1	1250	1300	4.0
WMSH-1	1320	1280	-3.0
WMSH-2	1450	1400	-3.4
WMSH-3	1200	1250	4.2
WMSH-4	1380	1350	-2.2
WMSH-5	1100	1150	4.5
WMSH-6	1275	1220	-4.3
QSSH-1	1340	1300	-3.0

with an optimal limit around 1,500 m³/day to prevent excessive drawdown and maintain aquifer sustainability. The extremes of pressure values east and west of the model area are outside the active domain. They are resulting from the active phase sources and recharge/discharge fluxes at the boundaries. Overall, the numerical results align closely with analytical estimates, with deviations ranging from -3.0% to +4.5%, indicating good agreement between both approaches and enhancing confidence in the proposed sustainable yield threshold.

Future Perspectives

This study highlights the strength of an integrated approach-combining field data, analytical yield methods (Farvolden, modified Moell, and Ribby), and 3D ParFlow modeling to establish reliable extraction limits for the Northern Wadi Araba Basin. The close match between analytical and numerical results (differences of -3.0% to +4.3%) reinforces trust in the recommended range, capturing the aquifer's long-term response. Ribby yields the highest Q20 estimates, Farvolden is the most conservative, and modified Moell offers a balanced, practical option.

Management insights suggest a safe operating range: Beer Mathkor well extractions should not exceed 5,000 m³/day, with 1,500 m³/day as the preferred limit to minimize drawdown. Beyond this, such as at 15,000 m³/day, significant declines (~5.5 MCM/year) occur, reflecting a nonlinear response to high stress. This supports a cautious, flexible strategy adjusting to hydrologic conditions and cumulative impacts.

Model analysis identifies key uncertainty areas: boundary conditions and east-west recharge/discharge fluxes dominate simulated heads and gradients. Priority should be given to regular water-level mapping and improved flux estimates. Operationally, benefits include (i) a real-time monitoring network with automated loggers, (ii) periodic model recalibration with new data, and (iii) scenario testing of recharge and demand variability. Enhancing ParFlow with finer resolution in steep-gradient zones and alternative boundary setups will boost decision support.

Policy translation requires an adaptive plan to start at 1,500 m³/day, monitor performance (drawdown and regional levels), and adjust within 1,500–5,000 m³/day as needed. This evidence-based approach ensures aquifer sustainability while meeting supply goals.

Conclusions and recommendations

This research has been conducted to investigate the factors that control the safe yield from drilled wells in the Wadi Araba area penetrating alluvium aquifer and to suggest methods of groundwater development to increase the sustainability of these wells. Many approaches exist to determine borehole sustainable yield, but very few are direct. Sustainable borehole yield is a very important parameter for operation and impacts the overall cost of groundwater development and borehole management. The main idea is to compare the most appropriate approaches to estimate the sustainable yield of the borehole to ensure satisfying water demand from the drilled borehole and the development of a groundwater well field.

The comparative assessment of analytical and numerical methods in determining sustainable yield for Wadi Araba demonstrated a high degree of effectiveness and correlation. The integrated methodology, which combined analytical-empirical formulas (Farvolden, Modified Moell, and Ribby) with a 3D ParFlow numerical model, successfully established reliable long-term abstraction limits for the Northern Wadi Araba Basin. The effectiveness of this cross-validation is quantified by the close alignment of the results, showing that the overall differences between the analytical and numerical estimates for the 20-year safe yield (Q20) ranged narrowly from -4.3% to +4.5%. This strong correlation greatly enhanced confidence in the proposed sustainable yield thresholds. The consensus reached through this dual approach centered on a critical safe yield threshold. The numerical model indicated that the safe pumping limit for continuous, long-term groundwater abstraction should be approximately 1,500 m^3/day. The numerical simulations demonstrated that small changes in pumping around this value did not significantly affect the water table levels. However, the model highlighted the severe consequences of over-extraction: a six-fold increase in pumping, from approximately 1,500 m³/day to 9,000 m³/day (or a three-fold increase from 5,000 m³/day to 15,000 m³/day), caused a significant decline in the water table, equivalent to approximately 5.5 million cubic meters per year (MCM/year) extracted solely from the active aquifer domain. While the analytical methods for Q20 generally placed the yield between 1100 and 1450 m³/day, the internal comparison among the analytical tools revealed a range of projections. The Ribby (1979) method consistently provided the highest, or most optimistic, Q20 values, suggesting it may better account for the dynamic behavior of large alluvial aquifers. Conversely, the Farvolden (1959) method consistently produced the most conservative yield estimates, while the Modified Moell method offered intermediate and balanced estimates. The necessity of integrating these varying analytical results with the 3D ParFlow simulation stemmed from the objective of managing the complex and heterogeneous nature of the unconfined Quaternary alluvium aquifer system in the Northern Wadi Araba.

Competing interest

The author declare no competing interest.

Supplementary Information

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Additional information

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