



Integrated Assessment of Groundwater Sustainability in a Semi-Arid Confined Aquifer: A Modelling and Managed Aquifer Recharge (MAR) Suitability Study of the Zinder Aquifer, Niger

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KEYWORDS

Aquifer,
Pumping,
Conductivity,
Transmissivity,
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ABSTRACT

The history of estimating aquifer properties is intertwined with the evolution of hydrogeology and the growing recognition of the vital role groundwater plays in sustaining human societies. This study combines pumping test data interpreted using the Cooper-Jacob and Theis methods to estimate the hydraulic characteristics of a constrained aquifer in the Zinder region of Niger. The study aims to assess the effectiveness of two traditional analytical techniques for aquifer characterisation, as well as to comprehend the regional variability of important physical parameters, such as transmissivity, hydraulic conductivity, and storativity. Using aquifer test software, parameters were determined for each of the 22 wells that were examined. The findings reveal notable variation in transmissivity values ranging from 2.08 to 141.36 m²/day and hydraulic conductivity, which ranges from 0.0321 to 2.28 m/day. Low values correlated with clay-rich lithologies, while high values were typically linked to wells that penetrated conglomerate and coarse sandstone layers. Although the Cooper-Jacob approach provided more variation in storativity values, it consistently yielded higher estimates of transmissivity and hydraulic conductivity than the Theis method. The significance of method selection in hydrogeological research is emphasised by this comparison analysis, especially for limited aquifers in semi-arid locations. The study offers important insights into aquifer behaviour by combining geological data with pumping test analysis. These discoveries have implications for future model calibration in comparable situations and sustainable groundwater management.

CITATION

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INTRODUCTION

Confined aquifers are particularly complex in terms of their characteristics and flow behaviour. They are restricted aquifers, defined by low-permeability layers in geological formations that limit the vertical movement of groundwater. It is an essential source of water supply and one of the sources of fresh water, and its importance for every form of life in the ecosystem is inevitable (Holland & Iserhien-Emekeme, 2015). Water scarcity is widespread around the world, and groundwater extraction is emerging

as a viable option for meeting rising water demands (Shaban et al., 2018).

The history of estimating aquifer properties is intertwined with the evolution of hydrogeology and the growing recognition of the vital role groundwater plays in sustaining human societies. Early developments in the field date back to the late 19th century when pioneers like Henry Darcy formulated fundamental principles governing groundwater flow (Darcy et al., 1856). Pumping tests (PT) are mostly exercised to assess the hydraulic characteristics of

aquifers, which are essential inputs for GW modelling and management (Srivastava and Guzman-Guzman 1994). with the introduction of pumping tests, allowing hydrogeologists and Engineers to gather valuable data on aquifer behaviour. The development of analytical solutions, such as Theis and Cooper-Jacob methods, further enhanced the ability to estimate critical parameters like transmissivity and storability. For now, water resources are largely sufficient, but they are not distributed in a balanced way on all the territory. Balance between needs and water resources, seems to be maintained for instance, this may not be the case if measures are not taken. The traditional way of practising irrigation will not favour water saving, although the population does not have a significant impact on water resources due to the large capacity of natural purification of the Niger River.

Description of the study area

Topography

The study site is to the south of the Sahara Desert and consists of isolated mountains, high and low plains, and valley depressions. The isolated mountains with elevations >500 m above sea level is mainly located in the east and northwest. High plains with elevations of 470–500 m is located in the north, alternating with low plains with elevations of 460–470 m, which are widely distributed in the study site. Maréchal et al. (2010) Valley depressions usually have elevations <460 m.

Geology

The study site is located on the southern edge of the Damergou basin. The main strata in the field include the Quaternary stratum (Q) and Cretaceous stratum (K). The Quaternary stratum (Q) is composed of eolian sand and sandy clay, with a thickness <7 m. The Cretaceous stratum (K) consists of the Farka group and Echkar group. The Farka group (Kenduiwo et. al. 2023) is mainly composed of

argillaceous sandstone and arenaceous mudstone, with a thickness ranging from 84 to 133 m. Underneath the Echkar group is the typical fluvial facies elastic sedimentary, with a thickness ranging from 54 to 158 m, including 4–8 sedimentary rhythmic strata. The upper sedimentary rhythmic strata (Dewandel and Jalut, 2010) are commonly composed of medium sandstone and fine sandstone; the lower sedimentary rhythmic strata are commonly composed of conglomerate and coarse sandstone. The deep aquifer doesn't receive any vertical recharge but rely on the lateral flow from the surrounding area (Akinfemiwa Akanbi, 2023).

Climate

Zinder climate is a tropical grassland transition with a dry season from October to May and a rainy season from June to September. Zinder's climate is characterized by high temperatures, low humidity, and considerable evaporation (Suprapti & Pongmanda, 2020). The Zinder Airport weather station's meteorological data indicates that the average annual precipitation is approximately 308 mm, with the precipitation from June to September accounting for approximately 95.1% of the total. This precipitation is typically characterized by thunderstorm rain or downpours. Approximately 40.9% of the yearly precipitation occurs in August. With an annual evapotranspiration capacity of roughly 4,700 mm, the region has extremely high evapotranspiration. With an average monthly evapotranspiration capacity of 500 mm, March and April typically have the maximum evapotranspiration.

Only seasonal lakes, seasonal rivers, and depressions are scattered throughout the area; there isn't a single perennial river. With the exception of the rainy season, such surface water features often dry up quickly due to significant evapotranspiration and penetration as shown in figure 1.

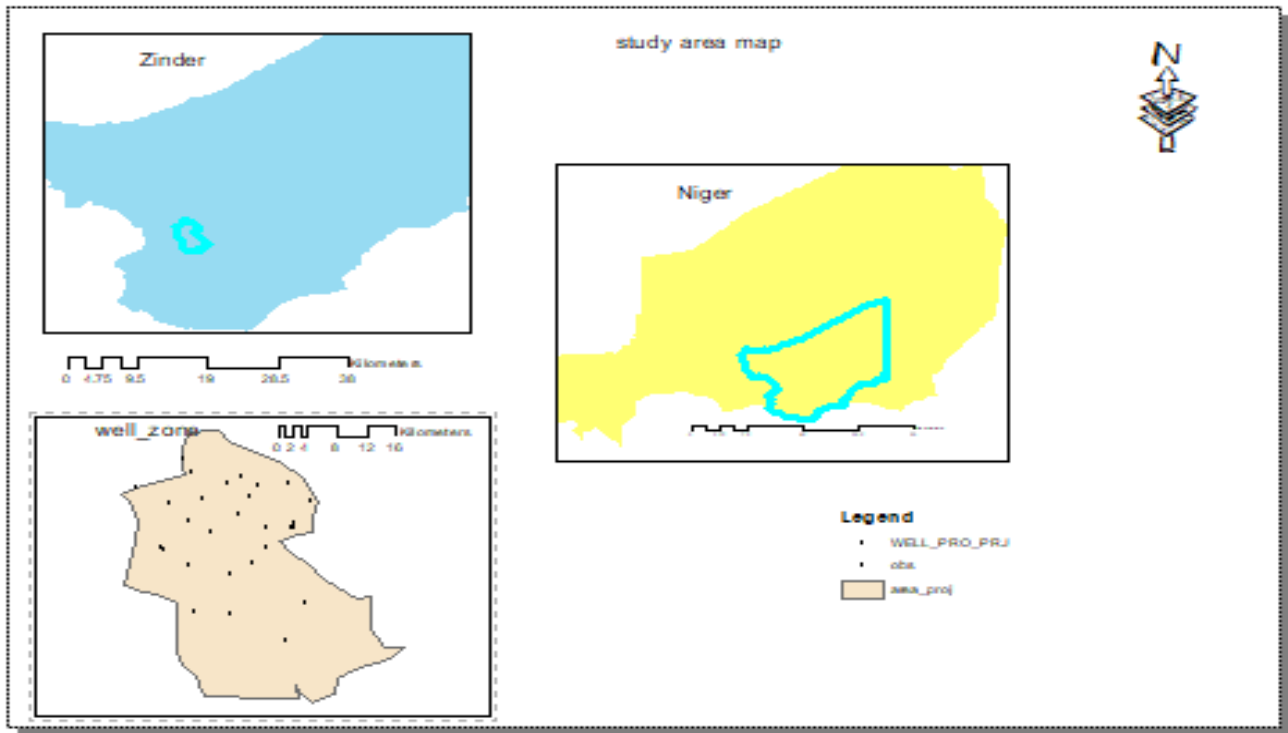


Figure 1: Represents the study area map

MATERIALS AND METHODS

Methods

This method is used to determine aquifer properties in the aquifer test software. The Theis equation, which describes transient groundwater flow toward a fully penetrating well in the confined aquifer is the basis for practically all methods for pumping test analysis (Dimple et al. 2022). Using the equation, transmissivity, and storage can be determined from the drawdown measurement without having to wait for the stabilization of the pumping water level as in the case of steady-state methods. In addition, only one observation well or sometimes the pumping well itself is enough to determine the aquifer hydrogeological parameters as opposite steady-state calculations where at least two (2) observation wells are needed.

$$s = \frac{Q}{4T\pi} W(u) \tag{1}$$

$$u = \frac{S}{4T\alpha} \tag{2}$$

in which Q = constant rate of pumping (L³ T); W (?) is commonly known as the well function in the ground-water literature (Bear 1972); a = t/ r²; t = time since the start of the pump (T); and r = distance of the observation well from the pumping well (L).

The Transmissivity is calculated using

$$T = \frac{Q}{4s\pi} W(u) \tag{3}$$

The Storage coefficient is calculated using

$$S = \frac{4Ttu}{r^2} \tag{4}$$

The hydraulic conductivity is calculated from the transmissivity and the aquifer thickness

$$K = \frac{T}{b} \tag{5}$$

Assumptions

The aquifer is homogeneous and isotropic, the aquifer is uniform in thickness and the pumping never affects its exterior boundary, the aquifer is confined and it does not receive any recharge, well discharge is entirely from aquifer storage, The pumping rate is constant, the aquifer test provides an interface that makes those assumptions flexible if not the case in the real aquifer characteristics.

Jacob cooper method

The Cooper-Jacob (1946) method is a simplification of the Theis (1935) method that is valid for greater time values and smaller distances from the pumping well (i.e. smaller values of u). This method involves truncation of the infinite Taylor series that is used to estimate the well function W(u). Due to this truncation, not all early time measured data is considered to be valid for this analysis method. The resulting equation is:

$$s = \frac{2.3Q}{4\pi T} \log_{10} \left(\frac{2.25Tt}{r^2 S} \right) \tag{6}$$

Where:

s is the drawdown at the observation well

Q is the discharge from the pumping well

T is the transmissivity of the aquifer

r is the distance from the well to the observation point

t is the elapsed time since the start of pumping

S is the storativity of the aquifer

This solution is appropriate for the conditions shown in the following figure.

$$s = \frac{2.3Q}{4\pi T} \log_{10} \left(\frac{2.25Tt}{r^2S} \right) \tag{7}$$

Assumptions

The Cooper-Jacob Solution assumes the following:

The aquifer is confined and has an "apparent" infinite extent, The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping. The piezometric surface was horizontal prior to pumping. The well is pumped at a constant rate. The well is fully penetrating. Water removed from storage is discharged instantaneously with decline in head. The well diameter is small, so well storage is negligible

The values of u are small (rule of thumb $u < 0.01$), where u is the dimensionless argument to the well function, $u = \left(\frac{r^2S}{4Tt} \right)$, that is r is small and/or t is relatively large

The above equation plots as a straight line on semi-logarithmic paper if the limiting condition is met. Thus, straight-line plots of drawdown versus time can occur after sufficient time has elapsed. In pumping tests with multiple observation wells, the closer wells will meet the conditions before the more distant ones. Time is plotted along the logarithmic X axis and drawdown is plotted along the linear Y axis. Transmissivity and storativity are calculated as follows:

$$T = \frac{2.3Q}{4\pi\Delta s} \text{ and } S = \frac{2.25Tt_0}{r^2} \tag{8}$$

where:

t_0 is the X -axis intercept (i.e. where the extrapolated line of best fit intersects the time axis)

Theis's and Jacob cooper I method is used for estimating the hydraulic parameters by choosing the best-fit matching point

Pumping Test Analysis to investigate the range and average values of hydraulics parameters of the aquifer

Result

Table 1: Well information

Well	Depth	Elevation	East	North	Well radius (mm)	Casing (m)	Static water level(m)	Dynamic water level(m)
CZ1	209.4	450.79	8.941	14.147	400	215	48.19	50.02
CZ2	209	452.81	8.97	14.128	400	215	48.41	50.23
CZ3	208.61	453	8.916	14.173	400	215	49.08	50.96
CZ4	205.44	452.74	8.911	14.101	400	215	48.5	50.56
CZ5	264.49	456.79	8.94	14.079	400	215	51.81	53.28
CZ6	221.56	454.69	9.003	14.157	400	215	49.49	51.42
CZ7	219.82	460.17	8.945	14.221	400	215	54.19	56.38
CZ8	236.97	459.27	8.958	14.179	400	215	53	54.79
CZ9	263.37	463.62	9.007	14.213	400	215	57.13	59.33
CZ10	228.37	457.87	9.017	14.182	400	215	50.97	53.05
CZ11	222.43	462.7	8.99	14.202	400	215	56.1	57.79
CZ12	224.57	463.92	9.029	14.201	400	215	58.06	58.04
CZ13	224.18	462.44	9.067	14.203	400	215	54.78	56.38
CZ14	270.46	457.08	9.07	14.135	400	215	48.98	58.46
CZ15	229.6	459	9.092	14.177	400	215	51.78	51.79
CZ16	256.68	459.9	9.038	14.104	400	215	47.54	46.87
CZ17	185.74	458.04	8.874	14.195	400	215	54.02	56.4
CZ18	236.83	462.13	8.948	14.006	400	215	56.49	57.8
CZ19	242.31	458.61	8.994	14.002	400	215	52.3	53.38
CZ20	235.75	455.05	8.992	14.063	400	215	49.96	50.6
CZ21	309.99	455.05	9.048	14.058	400	215	53.26	53.53
CZ22	237.01	457.24	9.039	14.135	400	215	49.76	50.95

Theis Method

After the construction of observation wells, two groups of pumping tests with variable flow rates are conducted (as shown in table 1) using wells CZ04 (main well), CZG06

(observation well), CZ15 (main well) and CZG02 (observation well). The following wells undergo pumping tests in a number of interference wells: CZ10, CZ11, and CZ12 (first group); CZ14, CZ16, and CZ22 (second group);

and CZ06, CZ19, and CZ20 (third group). The water well, the pressure measurement well. The confined tables are where these wells traverse the aquifer. The examinations

take place from November 9, 2009, to February 2, 2010. (Curve of pumping test see appendix No1).

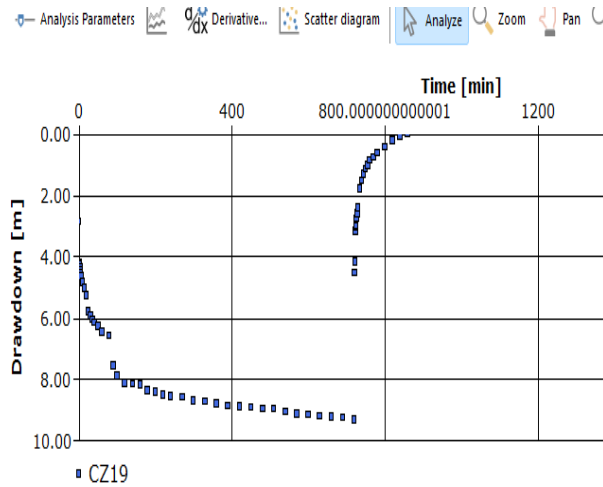


Figure 2: CZ19 analysis illustration

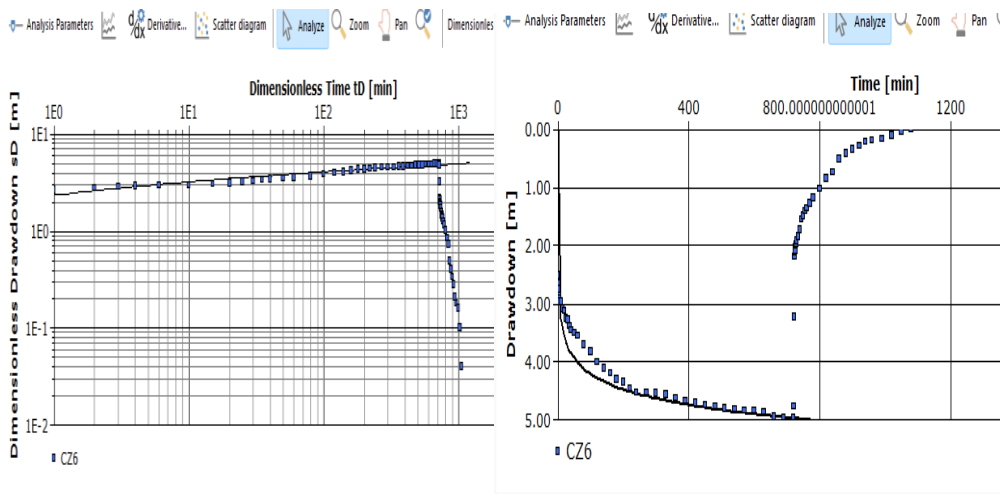


Figure 3: CZ6 analysis illustration

Aquifer parameter

Table 2: Hydraulic parameters

well	Depth (m)	Elevation (m)	Thickness (m)	hydraulic conductivity (m/d)	Transmissivity (m ² /d)	storability
CZ1	209.4	450.79	62	1.99	123	1.58×10 ⁻⁵
CZ2	209	452.81	90.5	0.85	76.9	3.43×10 ⁻⁵
CZ3	208.61	453	71.59	0.29	20.76	1.41×10 ⁻⁴
CZ4	205.44	452.74	65	1	65	1.42×10 ⁻⁶
CZ5	264.49	456.79	42	0.13	5.5	1×10 ⁻⁵
CZ6	221.56	454.69	79	1.31	103	4.70×10 ⁻⁵
CZ7	219.82	460.17	51	0.15	7.65	1.5×10 ⁻⁵
CZ8	236.97	459.27	62	1.8	111	1.5×10 ⁻⁶
CZ9	263.37	463.62	65	0.12	7.8	4.99×10 ⁻⁵

CZ10	228.37	457.87	65	0.0321	2.08	4×10^{-5}
CZ11	222.43	462.7	87	0.448	38.97	4.12×10^{-3}
CZ12	224.57	463.92	89	0.377	33.55	1.1×10^{-3}
CZ13	224.18	462.44	99	0.839	83.06	9.9×10^{-1}
CZ14	270.46	457.08	62	2.28	141.36	2.90×10^{-5}
CZ15	229.6	459	89	1.49	132.61	1.9×10^{-1}
CZ16	256.68	459.9	53	1.72	91.16	2.72×10^{-6}
CZ17	185.74	458.04	101	0.4	40.4	1×10^{-4}
CZ18	236.83	462.13	57	0.48	27.36	2.30×10^{-3}
CZ19	242.31	458.61	48	0.61	29.28	3.89×10^{-6}
CZ20	235.75	455.05	62.61	1.9	118.9	1.80×10^{-6}
CZ21	309.99	455.05	52	1.12	58.24	9.9×10^{-1}
CZ22	237.01	457.24	81	0.52	42.12	9.9×10^{-1}
average	233.7536		69.71364	0.90255		
min	185.74	450.79	42	0.0321		
max	309.99	463.92	101	2.28		

Well Lithology and Depth, the lithological composition found in the wells varies greatly depending on their depth. More compact formations are penetrated by deeper wells (such as CZ21, CZ14, and CZ12), which may have an impact on hydraulic conductivity and transmissivity. Because they are associated with coarse sandstone and conglomerate layers, wells with many water-rich sections, including CZ1, CZ2, and CZ12, show great potential for groundwater storage and flow.

Distribution of Hydraulic Conductivity

The values of hydraulic conductivity vary from 2.28 m/day (CZ14) to 0.0321 m/day (CZ10). Well-sorted coarse sandstone and conglomerate, such as CZ1, CZ14, and CZ15, are linked to high values, which improve

permeability. Conversely, lower levels (CZ10, CZ5, CZ9) are associated with layers of fine sandstone and clay that hinder the flow of groundwater.

High K (>1.5 m/day): CZ1, CZ6, CZ8, CZ14, CZ15, CZ16, CZ20, CZ21

Medium K (0.5 – 1.5 m/day): CZ2, CZ4, CZ13, CZ17, CZ19, CZ22

Low K (<0.5 m/day): CZ3, CZ5, CZ7, CZ9, CZ10, CZ11, CZ12, CZ18

Wells with high K values are associated with a dominance of coarse-grained materials (coarse sandstone, conglomerates), enhancing permeability. Low K wells correspond to significant clay and mudstone content, which reduces water movement.

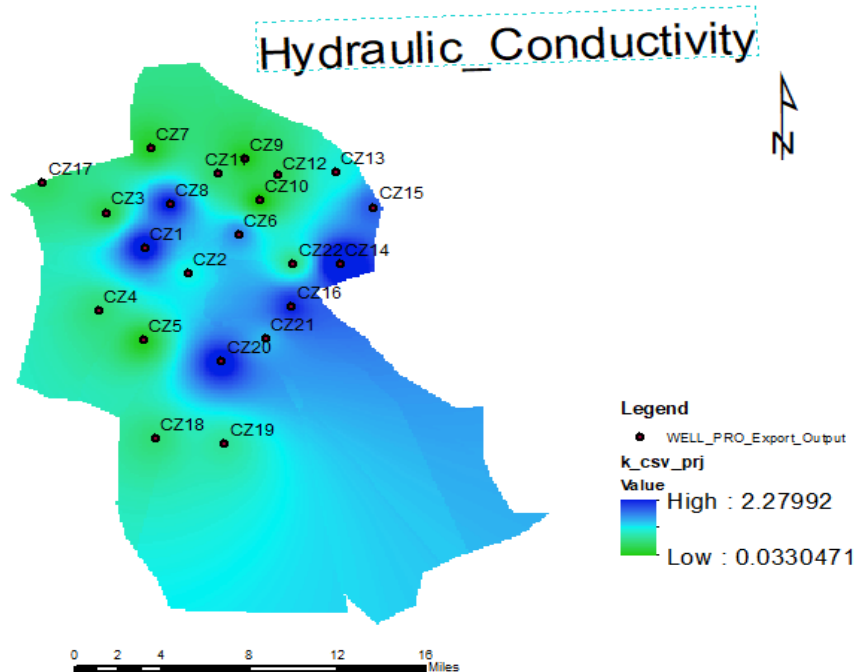


Figure 4: Spatial distribution of Hydraulic conductivity

Transmittivity

The values of transmittivity vary from 2.08 m²/day (CZ10) to 141.36 m²/day (CZ14). In areas where thick coarse sandstone and conglomerate predominate, high-transmissivity wells (>100 m²/day) like CZ14, CZ1, and CZ15 are located, allowing for effective groundwater circulation. CZ10, CZ5, and CZ9 are examples of low-transmissivity wells (<40 m²/day) that are linked to clay-rich strata that limit flow. Wells with moderate transmissivity (CZ6, CZ12, and CZ16) are found in diverse settings where layers of clay and sandstone interact. High transmissivity values suggest more productive aquifers. There are direct relationships between Trnassmissivity, Hydraulic conductivity and Aquifer thickness.

It is important to investigate the difference between the simulated and calculated T, using the well-known relation of the three parameters below

$$T = K \cdot b$$

Where:

T = Transmissivity (measured in units such as m²/ day)

K = Hydraulic conductivity (measured in *m/day*)

b = Saturated thickness of the aquifer (measured in meters)

In the table 3: we can see the differences and it is almost the same value (because the software uses the same relationship to simulate T)

Table 3: Calculated and simulated T

Well	Transmissivity calculated(m ² /d)	Simulated (m ² /d)
CZ1	123.38	123
CZ2	76.925	76.9
CZ3	20.7611	20.76
CZ4	65	65
CZ5	5.46	5.5
CZ6	103.49	103
CZ7	7.65	7.65
CZ8	111.6	111
CZ9	7.8	7.8
CZ10	2.0865	2.08
CZ11	38.976	38.97
CZ12	33.553	33.55
CZ13	83.061	83.06
CZ14	141.36	141.36
CZ15	132.61	132.61

CZ16	91.16	91.16
CZ17	40.4	40.4
CZ18	27.36	27.36
CZ19	29.28	29.28
CZ20	118.959	118.9
CZ21	58.24	58.24
CZ22	42.12	42.12

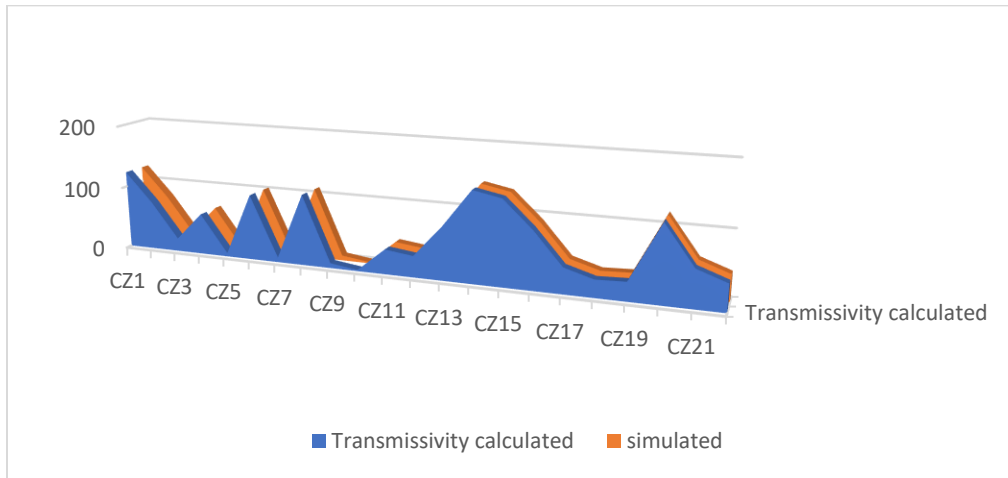


Figure 5: Illustrated calculate and simulated T

Transmissivity

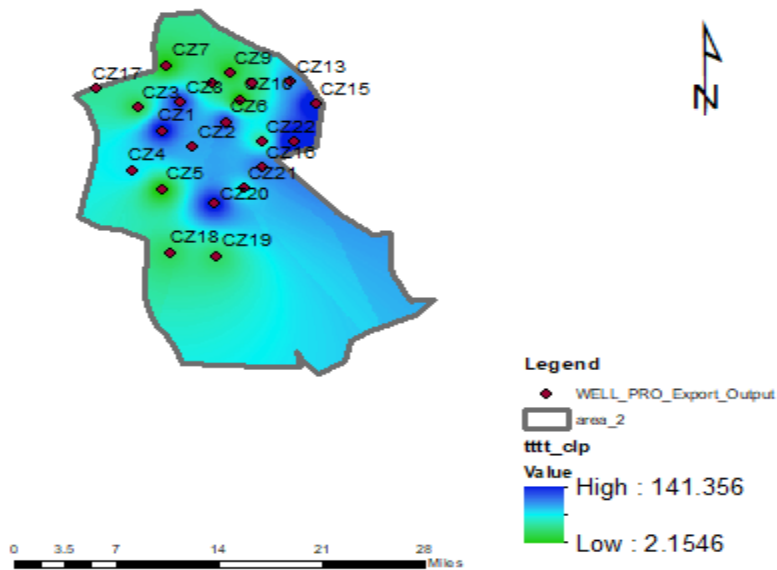


Figure 6: spatial distribution of T (m²/d)

Classification of the Transmissivity

Jiri Krasny [1993] proposed classification between the transmissivity and variation according to the magnitude of the transmissivity

Table 4: Based on Jiri Kransy classification (1993)

Magnitude of Transmissivity (m ² /day)	Class of Transmissivity Magnitude	Designation of Transmissivity Magnitude	Specific Capacity (m ² /day)	Groundwater Supply Potential
>1000	I	Very high	>864	Regional importance
100 - 1000	II	High	86.4 - 864	Lesser regional importance
10 - 100	III	Intermediate	8.64 - 86.4	Local water supply
1 - 10	IV	Low	0.864 - 8.64	Private consumption
0.1 - 1	V	Very low	0.0864 - 0.864	Limited consumption
<0.1	VI	Imperceptible	<0.0864	Very difficult to utilize for local water supply

Table 5: Transmissivity Analysis based on Transmissivity magnitude classification

Well	Transmissivity Calculated (m ² /day)	Simulated (m ² /day)	Class of Transmissivity Magnitude	Designation of Transmissivity Magnitude
CZ1	123.38	123	II	High
CZ2	76.925	76.9	III	Intermediate
CZ3	20.7611	20.76	III	Intermediate
CZ4	65	65	III	Intermediate
CZ5	5.46	5.5	IV	Low
CZ6	103.49	103	II	High
CZ7	7.65	7.65	IV	Low
CZ8	111.6	111	II	High
CZ9	7.8	7.8	IV	Low
CZ10	2.0865	2.08	IV	Low
CZ11	38.976	38.97	III	Intermediate
CZ12	33.553	33.55	III	Intermediate
CZ13	83.061	83.06	III	Intermediate
CZ14	141.36	141.36	II	High
CZ15	132.61	132.61	II	High
CZ16	91.16	91.16	III	Intermediate
CZ17	40.4	40.4	III	Intermediate
CZ18	27.36	27.36	III	Intermediate
CZ19	29.28	29.28	III	Intermediate
CZ20	118.959	118.9	II	High
CZ21	58.24	58.24	III	Intermediate
CZ22	42.12	42.12	III	Intermediate

This table classifies each well based on its transmissivity value.

Storability

Storability (S) measures the ability of an aquifer to store and release water. CZ12, CZ13, CZ15, CZ16, CZ21, and CZ22 show comparatively higher specific storage because of the constrained aquifer's compressibility effects. Low

Storability ($<1 \times 10^{-4}$) was observed in CZ1, CZ2, and CZ4, these wells indicate minimal water release under pressure changes, characteristic of highly consolidated confined formations.

Table 6: Summarizing the storability classification

Class	Storability Range (S)	Zones	Characteristics
Very Low	$S < 1 \times 10^{-5}$	CZ4, CZ8, CZ20	Minimal water storage, often confined aquifers with coarse sands or rigid materials.
Low	$1 \times 10^{-5} \leq S < 1 \times 10^{-4}$	CZ1, CZ2, CZ7, CZ14	Moderate storage, associated with sandstones and conglomerates.
Moderate	$1 \times 10^{-4} \leq S < 1 \times 10^{-3}$	CZ6, CZ10, CZ17	Higher compressibility, mixed lithology including fine sands or sandy clays.
High	$S \geq 1 \times 10^{-3}$	CZ11, CZ12, CZ13, CZ21	Significant storage potential, linked to clay-rich or silty layers.

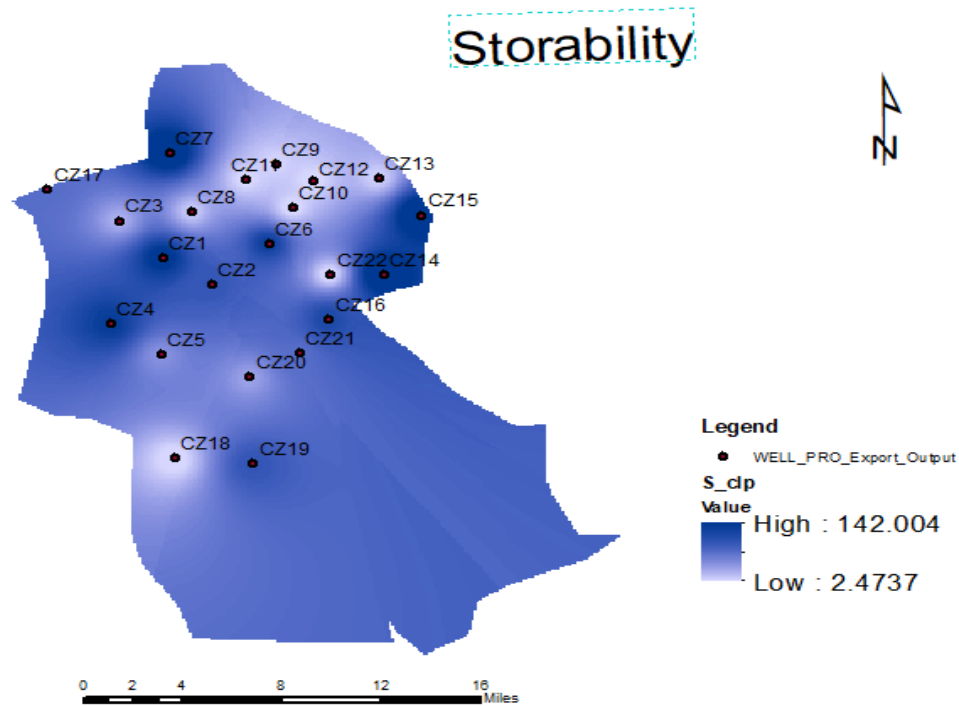


Figure 7: Spatial distribution of storability

Table 7: Comparison with Jacob cooper method

Wells	Theis			Jacob cooper		
	T(m ² /d)	K(m/d)	S	T(m ² /d)	K(m/d)	S
CZ01	123.00	1.99		90.90	1.47	1.58×10 ⁻⁵
CZ02	76.90	0.85	3.43×10 ⁻⁵	134.00	1.48	
CZ03	20.76	0.29	1.41×10 ⁻⁴	51.30	0.72	1.29×10 ⁻⁶
CZ06	103.00	1.31	4.70×10 ⁻⁵	166.00	2.10	5.00×10 ⁻¹
CZ09	7.8	0.12	4.99×10 ⁻⁵	22.00	0.29	1.41×10 ⁻³
CZ14	141.36	2.28		205.00	3.31	2.90×10 ⁻⁵
CZ16	91.16	1.72	3.17×10 ⁻⁵	154.00	2.91	4.23×10 ⁻⁴
CZ18	27.36	0.48	2.30×10 ⁻³	31.90	0.56	2.72×10 ⁻¹
CZ19	29.28	0.61	3.89×10 ⁻⁶	112.00	0.65	1.10×10 ⁻⁵
CZ20	118.00	1.90	4.79×10 ⁻⁵	65.30	1.04	2.21×10 ⁻⁵
CZ21	58.24	1.11	1.80×10 ⁻⁶	46.90	0.90	1.21×10 ⁻⁵

Discussion of Comparative Analysis Between Theis and Cooper-Jacob Methods

The comparison between the Theis and Cooper-Jacob methods reveals important insights into how methodological choices can influence the estimation of aquifer parameters. These variations are particularly significant for decision-making in groundwater modelling and resource management. Three key parameters—transmissivity (T), hydraulic conductivity (K), and storativity (S)—were examined across eleven observation wells (CZ01 to CZ21), and the results are discussed below.

Transmissivity estimates derived from the two methods showed a clear trend: the Cooper-Jacob method generally produced higher transmissivity values compared to the Theis method. For instance, in wells CZ06, CZ14, and CZ16, transmissivity values from Cooper-Jacob were 166

m²/d, 205 m²/d, and 154 m²/d respectively, compared to 103 m²/d, 141.36 m²/d, and 91.16 m²/d from Theis. This trend suggests that the Cooper-Jacob method, which simplifies the analysis by focusing on the straight-line portion of the semi-log plot (late-time data), tends to overestimate transmissivity in many cases. The Theis method, by contrast, considers the full drawdown-time relationship, which may offer a more balanced and accurate assessment, especially in the early stages of pumping. However, in a few wells such as CZ20 and CZ21, the transmissivity from Theis slightly exceeded that from Cooper-Jacob, indicating that localized aquifer characteristics or data variability might influence these discrepancies.

In terms of hydraulic conductivity, a similar pattern was observed. Since conductivity is derived from transmissivity

and aquifer thickness, the higher T values from Cooper-Jacob naturally resulted in higher K estimates as well. For example, well CZ16 showed a jump from 1.72 m/d (Theis) to 2.91 m/d (Cooper-Jacob), and CZ06 rose from 1.31 m/d to 2.10 m/d. Such variations highlight the impact of method selection on flow parameter estimation, particularly in groundwater models where accurate K values are essential for predicting flow paths and rates. Interestingly, some wells like CZ20 and CZ21 displayed only minor differences in conductivity between the two methods, suggesting more stable hydraulic behavior or less sensitivity to methodological assumptions.

The storativity values demonstrated the most substantial and variable differences. The Cooper-Jacob method produced highly inconsistent and often extreme storativity values, particularly in wells CZ06 and CZ18, where estimates reached 0.5 and 0.272 respectively. These values are notably high for confined aquifers and suggest that the Cooper-Jacob method might have captured delayed drawdown responses or boundary effects. In contrast, Theis estimates in these wells were significantly lower and more consistent with expected storativity ranges for confined systems, such as 4.70×10^{-5} and 2.30×10^{-3} . In wells where both methods produced values, the Theis method generally provided more conservative and realistic estimates. In well CZ03, for example, Theis yielded 1.41×10^{-4} , while Cooper-Jacob estimated only 1.29×10^{-6} , a discrepancy of more than two orders of magnitude. These results emphasize the sensitivity of storativity calculations to the quality of drawdown data and the assumptions embedded in each method.

While both methods are valuable in groundwater investigations, their outcomes can differ markedly, especially in heterogeneous aquifers or when data quality varies. The Theis method, though more data-intensive, appears to offer more stable and consistent parameter estimates. On the other hand, the Cooper-Jacob method, despite its simplicity and ease of use, may introduce greater uncertainty, particularly in storativity estimation. Therefore, a combined or iterative use of both methods, supported by field knowledge and calibration data, is recommended to improve the robustness of aquifer characterization.

CONCLUSION

Significant regional heterogeneity in aquifer behaviour has been found during the examination of the hydraulic properties of the Zinder restricted aquifer. This variability is primarily caused by lithological variations and the parameter estimate approach. Both the strengths and weaknesses of the Theis and Cooper-Jacob approaches have been shown through their application to pumping test data. The Cooper-Jacob approach produced more inconsistent and frequently unrealistic storativity estimates for confined systems, although producing

greater transmissivity and conductivity values in the majority of wells. This is a more dependable method for modelling confined aquifers with complex geology and limited recharge since it took into account the entire drawdown curve, which resulted in more solid and cautious estimations. The study confirms that coarse-grained units, particularly those composed of sandstone and conglomerates, are associated with high aquifer productivity, while fine-grained layers restrict groundwater movement. These findings underline the importance of integrating lithological context into hydrogeological interpretations. For future groundwater resource planning and numerical modeling in the region, it is recommended to use both methods in tandem, supported by field data and local geological knowledge. This approach will improve the accuracy of predictive models and enhance the effectiveness of water resource management strategies in arid and semi-arid regions like Niger.

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