SUST Journal of Engineering and Computer Sciences (JECS), Vol. 24, No. 2, 2026

Groundwater Availability in Madani Locality, Gezira State, Sudan: A Hydrogeological Assessment of Aquifer Properties

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Abstract* - In this study, the hydrogeological parameters of the Greater Madani Locality in Sudan, as well as the availability of groundwater, are evaluated. An investigation was carried out into 37 operating wells that were chosen following a set of predetermined criteria and confirmed to be operational. The study area lies above Quaternary alluvial deposits of the island formation and is characterized by complex hydrogeological conditions ranging from semi-confined to unconfined aquifers. To assess the aquifer's capacity to transport and store groundwater, specific criteria and methods were employed, including the Cooper-Jacob straight-line method, the Theis recovery method, and the Theis-Hantush solution for leaky aquifers. The analysis revealed significant variation in hydraulic parameters across the study area. The transmissivity ranged from 82.09 to 843.32 m²/day, with an average of 295.02 m²/day. Based on the Transmissivity, the aquifer exhibited a moderate to high capacity for groundwater transport, particularly in the northern and central regions of the study area. Hydraulic conductivity ranged from 1.78 to 21.08 m/day (mean: 7.20 m/day), reflecting variations in rock formations, sediment sorting, and clay layer distribution. Additionally, calculated storage coefficients ranged from 0.007 to 0.8460 (mean: 0.1034), confirming variations in confinement conditions and high storage capacity. Specific well capacity ranged from 67.29 to 691.53 m³/day/m. The spatial maps from the Surfer program showed that groundwater availability and well productivity are significantly higher in the northern regions compared to the southern regions. These hydraulic parameters provided a crucial basis for the sustainable management of groundwater resources and the optimal development of well fields, in line with the increasing demand for groundwater for various uses in central Sudan.

***Index Terms*—Groundwater availability, Hydraulic conductivity, Transmissivity, Storage coefficient, Specific capacity, Aquifer properties, Greater Madani Locality.**

المستخلص—في هذه الدراسة، تم تقييم المعايير الهيدروجيولوجية لمنطقة مدني الكبرى في السودان، بالإضافة إلى مدى توافر المياه الجوفية.. اجري تحليل على 37 بئراً عاملة اختيرت بناءً على معايير محددة، وتأكد من تشغيلها. تقع منطقة الدراسة فوق الرواسب الغرينية الرباعية لتكوين الجزيرة وتتميز بظروف هيدروجيولوجية معقدة، تتراوح من طبقات المياه الجوفية شبه المحصورة، إلى غير المحصورة. ولتقييم قدرة طبقة المياه الجوفية على نقل المياه الجوفية وتخزينها، استخدمت معايير وطرق محددة، بما في ذلك طريقة الخط المستقيم كوبر-جاكوب، وطريقة استرداد ثيس، وحل ثيس-هانتوش لطبقات المياه الجوفية المتسربة. كشف التحليل عن اختلاف كبير في المعلمات الهيدروليكية عبر منطقة الدراسة. تراوحت النفاذية من 82.09 إلى 843.32 م²/يوم، بمتوسط 295.02 م²/يوم. بناءً على قابلية النقل، أظهر الخزان الجوفي قدرة متوسطة إلى عالية على نقل المياه الجوفية، خاصة في المناطق الشمالية والوسطى من منطقة الدراسة. تراوحت الموصلية الهيدروليكية من 1.78 إلى 21.08 م/يوم (المتوسط: 7.20 م/يوم)، مما يعكس الاختلافات في التكوينات الصخرية، وفرز الرواسب، وتوزيع طبقة الطين. بالإضافة إلى ذلك، تراوحت معاملات التخزين المحسوبة من 0.007 إلى 0.8460 (المتوسط: 0.1034)، مما يؤكد الاختلافات في ظروف الحبس وسعة التخزين العالية. وتراوحت سعة الآبار النوعية من 67.29 إلى 691.53 متر مكعب/يوم/م. وأظهرت الخرائط المكانية، لبرنامج سيرفر، أن توافر المياه الجوفية، وإنتاجية الآبار أعلى بكثير في المناطق الشمالية مقارنة بالمناطق الجنوبية. وقد وفرت هذه المعلمات الهيدروليكية أساسًا حاسمًا للإدارة المستدامة لموارد المياه الجوفية، والتطوير الأمثل لحقول الآبار، بما يتماشى مع الطلب المتزايد على المياه الجوفية لمختلف الاستخدامات في وسط السودان.

I. Introduction

Groundwater is the primary and reliable water source for arid and semi-arid regions, where surface water systems experience seasonal fluctuations. Determining hydrogeological parameters, particularly the permeability coefficient (T) and storage coefficient (S), is crucial for assessing an aquifer's capacity to transfer and release water under pumping pressure. These parameters directly influence groundwater well productivity, water table decline rate, and long-term well efficiency. Rapid urbanization, agricultural intensification, and population growth in the Greater Madani area have placed significant strain on the local water supply networks [1]. The sustainable development of these resources is severely hampered by a lack of modern, sophisticated, and spatially distributed hydrogeological assessments. Existing data are often fragmented, incomplete, and disconnected, leaving a critical research gap regarding the sedimentary aquifer system under continuous extraction. Therefore, a systematic evaluation of hydraulic characteristics is essential to prevent water table decline and improve well field design [2].

Through the utilization of transmissivity and storage coefficients, it is possible to ascertain the capacity of groundwater layers to transport and release water via wells. These coefficients are indicative of the effectiveness and productivity of the wells.

Groundwater in the Greater Madani Locality region faces multiple challenges. The main problems include limited up-to-date, comprehensive information on its hydrogeological characteristics, coupled with increasing pressure on groundwater resources because of population growth, agricultural expansion, and urban development, raising concerns about potential groundwater degradation [3]. The primary objective of this study is to present a hydrogeological evaluation of groundwater potential and aquifer behavior in the Greater Madani Locality.

The specific objectives are:

1. To evaluate the hydraulic properties, specifically (Transmissivity (T), Hydraulic Conductivity (K), Storage Coefficient (S), and Specific Capacity (SC)) across the 37 selected operational production wells in the study area. *1.*
2. To compare three analytical pumping test methods (the Cooper-Jacob straight-line method, the Theis recovery method, and the Theis-Hantush leaky aquifer model) to ensure structural validation.
3. To draw contour maps of the calculated hydraulic parameters (T, K, S, and SC) across the locality by using software (Surfer).
4. To simulate groundwater flow directions.

II. Literature Review

It is necessary to understand the geological structure, the history of silt deposition, and hydrodynamic modeling to comprehend the dynamics of groundwater movement in sedimentary soils. The sedimentary basin in central Sudan, particularly the Gezira Structure, consists of non-homogeneous hydrogeological gradients. The structural framework is defined by a Precambrian basement complex, irregularly overlain by Cretaceous Nubian Sandstone formations, which are in turn overlain by Quaternary Gezira Formations [1].

These formations are complex alluvial deposits composed of unconsolidated gravel, sand, silt, and expanded clay. Recent advances in the hydrogeology of sedimentary basins confirm that alluvial aquifers exhibit significant spatial variability, leading to transitional conditions between unconfined and semi-confined aquifers that are influenced by the presence of clay layers [4]. Additionally, the recharge and vertical flow mechanisms in multi-layered alluvial systems are strongly influenced by the spatial continuity of low-permeability and impermeable layers [4, 15].

Vertical seepage and boundary impacts are significant factors that must be taken into consideration in sedimentary ecosystems, particularly when evaluating sustainable development. As a result of constant lateral seepage from the Blue and White Nile rivers, which form a key border that refills these aquifers, prior regional studies have demonstrated that there is a dynamic interaction between aquifers and surface hydrology in the central region of Sudan [6]. However, earlier studies in the Gezira region have been limited to computer tools and out-of-field data that have not been updated.

Furthermore, other assessments have confirmed that unregulated water extraction in the arid regions of central Sudan faces significant operational constraints due to the presence of unexplored, low-permeability clay layers, basaltic thresholds, and hardened sandstone barriers that impede lateral groundwater flow [3]. Despite these findings, previous studies in the Gezira Basin suffer from a fundamental methodological deficiency, relying on local, one-size-fits-all assessments without comprehensive, integrated spatial modeling. Older studies haphazardly applied standard Theis or Cooper-Jacob methods, neglecting potential vertical seepage through semi-insulating layers [8]. To overcome these limitations documented in previous studies, this study combines multi-method analytical interpretations of water pumping with high-resolution geostatistical interpolation across 37 well locations, providing an updated and structurally hydrodynamic framework for the area.

III. Materials and Methods

A. Study area

Located in the middle of Sudan, Greater Madani Locality is a significant administrative region that falls under the jurisdiction of Al Jazirah State. The administrative capital of the state is Wad Madani, which serves as the site of the state's political and economic center. It is a vital center for hydrogeological studies because the Madani Locality plays a significant role in agriculture, the distribution of water resources, and the development of the region.

Geographically, Greater Madani Locality lies between latitudes 14.36° and 14.44° North and longitudes 33.46° and 33.58° East. It is situated at the heart of the Gezira Scheme, the most important agricultural project in Al Jazirah State, and it's bordered from the south by South Al Jazirah Locality and from the north by Al Kamilin Locality [5], as shown in Fig. 1.

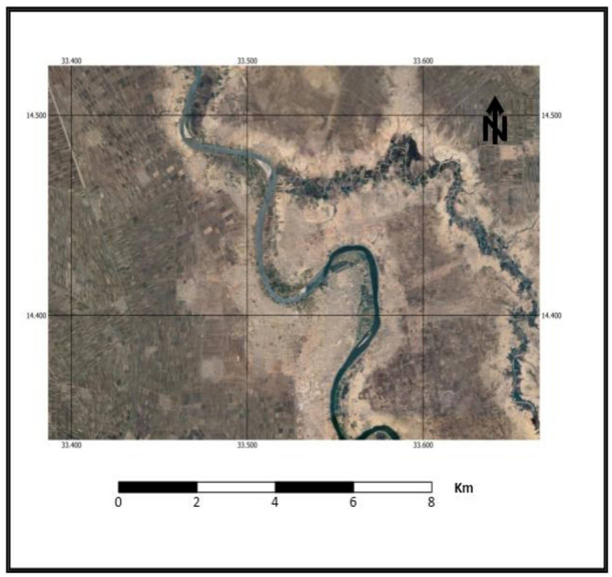

Fig. 1. Map of Greater Madani Locality

The region has a semi-arid climate, with hot summers, moderate winters, and heavy seasonal rainfall [2]. Its topography is generally flat, with a slight structural slope from the southeast to the northwest. The plain is intersected by seasonal wadi systems and an extensive network of artificial canals associated with the Gezira Irrigation Scheme. Surface water from these channels contributes to the replenishment of groundwater in low-lying areas by seeping downwards [3, 11].

The region is underlain by Quaternary Gezira alluvial deposits, which are structurally composed of interbedded layers of clay, silt, sand, and gravel. These highly non-homogeneous deposits create variable aquifer conditions, ranging from confined to unconfined systems depending on the localized presence of upper clay layers [7]. The surface soils are predominantly black clay layers, which have very low vertical permeability but large water storage capacity.

As a result, the Greater Madani region is an important laboratory for groundwater extraction research because of its central location, its rapidly expanding population, and its total reliance on continuous groundwater extraction [3]. It is essential to have a solid understanding of the hydrogeological structure to design sustainable plans for the management of water resources, which will guarantee the safe utilization of water [6].

B. Sampling and analysis

To provide a comprehensive, integrated, and systematic assessment of groundwater and hydrogeological characteristics in the Greater Madani area, an integrated sampling and data collection program was implemented in collaboration with the Gezira State Water Corporation.

The process began with the selection and identification of sampling points. Thirty-seven (37) active and productive wells were chosen as sampling points to cover the entire study area (Greater Madani Locality). The selection of these wells was based on several criteria, primarily spatial coverage. These wells were selected using a grid-based sampling method to minimize spatial bias and ensure a comprehensive distribution across the study area. Additionally, data availability was considered, prioritizing wells with complete data records, including lithological records, construction details, and full discharge rates.

Finally, socioeconomic importance was considered, prioritizing high-capacity production wells, which are the primary sources of domestic and agricultural water for local communities. The precise geographic coordinates (latitude and longitude) of each of the selected wells were recorded and verified during field visits using the Gezira State Water Corporation's GPS device [5], in addition to using Google Earth software as shown in Fig. 2.

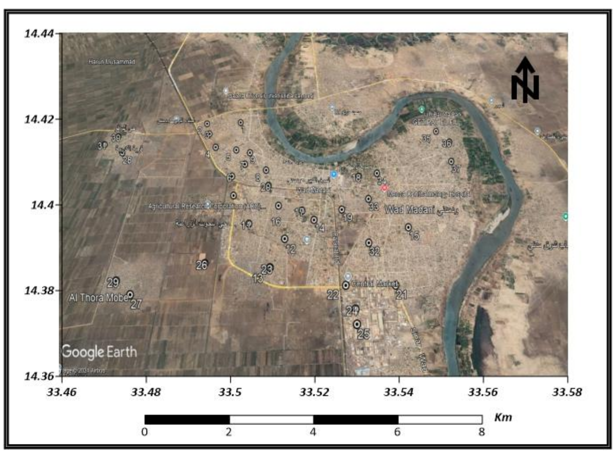

Fig. 2. Map of Greater Madani Locality

Next, the characteristics of the wells and the basics of disinfection for each well were determined. All the wells studied were deep tube wells drilled into Quaternary sedimentary aquifers and Nubian sandstone layers, at depths ranging from approximately 60 to 150 meters. To ensure that the collected groundwater samples accurately represented the surrounding aquifer and were not simply stagnant water from the well casing, each well was continuously pumped for at least 45 to 60 minutes before sampling. The stability of physical parameters (such as pH, electrical conductivity, and temperature) was monitored in situ during the disinfection process; sampling only commenced after these parameters had stabilized within a margin of error of ±10% over three consecutive readings. At each site, samples were collected in accordance with the standard methods for the examination of water [9]; containers were prepared, and samples were prepared for analysis. Environmentally sensitive physical and chemical parameters (Temperature, pH, and Electrical conductivity) were measured on-site immediately after sample collection from the wellhead. Samples were then preserved in accordance with standard methods [9] at room temperature and transported to ensure quality after collection. Each sample was uniquely labeled with the date, time, and well name, and the site data sheet was updated.

To ensure the accuracy of laboratory analysis procedures, a robust quality assurance and monitoring framework was implemented. Empty deionized water samples were transported alongside well samples to monitor for any potential contamination during transport. Field issues during implementation were overcome. Power failures frequently affected production well operations. To solve this, the field sampling schedule was dynamically changed to match local backup generator running cycles. Also, high summer temperatures hindered sample preservation.

C. Methods of analysis

To scientifically assess groundwater potential and the hydrodynamic behavior of the aquifer in the Greater Madani area, an analytical framework was applied to pumping test data from 37 selected production wells. The hydraulic variables—hydraulic conductivity (K), transmissivity (T), storage coefficient (S), and specific capacity (SC)—are important measurements for determining the efficiency of local wells and evaluating the long-term sustainability of the aquifer [3]. Water table decline over time and residual recovery data, obtained during field pumping phases, were interpreted using three internationally recognized standard analytical formulas for solving hydrodynamic groundwater flow equations under specific conditions [2, 12]:

- The Cooper-Jacob Straight-Line Method: which is applied to time-drawdown data collected during the constant-rate pumping phase. [2, 8].
- Theis's recovery method: Analysis of residual water level decrease curves immediately after pumping is done using this method. This analytical approach theoretically negates operational errors induced by well water storage, damage to well casing, and tiny flow rate changes during active pumping, resulting in extremely dependable hydrodynamic characteristics [8].
- Theis-Hantush Method: This method is used to analyze drawdown behavior in production wells with leaky semi-confined boundaries within complex Quaternary sedimentary layers and underlying Cretaceous sequences. This analytical model accounts for vertical hydraulic connectivity and leakage through low-permeability upper or lower confining mudstone sheets [3, 8], as summarized in Fig. 3.

Specific capacity (SC) and well productivity metrics were calculated to present well efficiency. These physical parameters serve as hydrodynamic indicators for characterizing well performance, well design, and spatial variations in aquifer yield capacity across the region [4, 5].

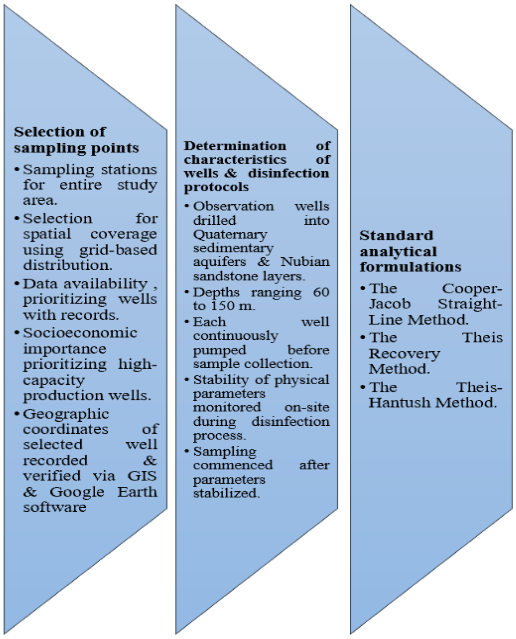

Fig .3. Sampling and methodology.

To ensure the accuracy of the hydraulic parameters used, a specific system of hydrogeological verification and data filtering was implemented before analytical calculations. All well data (including time, flow rates, and dynamic drawdown depths) underwent a thorough audit. Data sets exhibiting inaccurate data, unrecorded intermittent pumping interruptions, or significant flow rate variations were corrected or excluded to maintain structural data integrity.

Analytical optimization of the pumping test sites was performed using specialized hydrogeological verification platforms, including Aquifer Test and Surfer software. To assess the regional spatial distribution and structural variations of the calculated hydraulic conductivity (K), transmissivity (T), storage coefficient (S), and specific capacity (SC), Spatial statistical modeling and surface interpolation were performed using the Surfer mapping software [5, 13].

IV. Results

A. Hydraulic conductivity

Three methods were used to determine hydraulic conductivity: the Jacob method, the Theis recovery method, and the Theis-Hantush method [3], as shown in Fig. 4. The results of these analyses revealed significant spatial variation across the study area, reflecting clear differences in aquifer material properties, particle-size distribution, and sediment sorting. The values ranged from 1.78 to 21.08 m/day, with an overall average of 7.20 m/day across the 37 wells studied in Greater Madani Locality. Table 1 presents the average, minimum, and maximum values for the three methods. Hydraulic conductivity (k) is an important property for understanding groundwater flow and aquifer behavior. Calculating hydraulic conductivity using the equation enables assessment of aquifer permeability, designing appropriate wells, and modeling groundwater systems, as shown in Fig. 4.

Table I
The Hydraulic Conductivity (K) Values by Three Methods

Method	Overall Mean (m/day)	Minimum (m/day)	Maximum (m/day)
Jacob	6.68	1.78	21.08
Theis Recovery	7.01	1.84	21.80
Theis & Hantush	7.91	2.01	18.68
Overall Average for 37 Wells	7.20	-	-

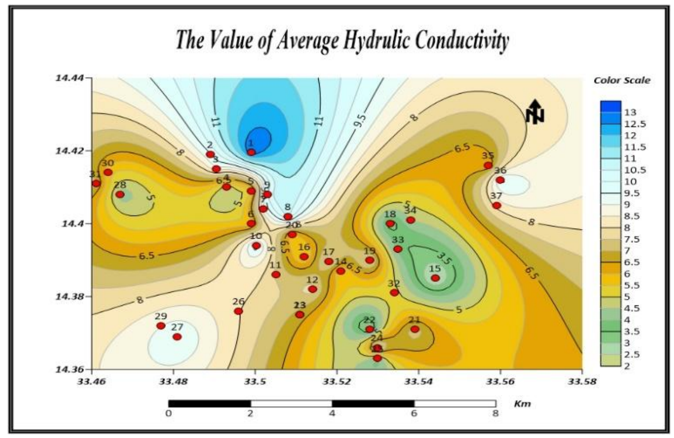

Fig. 4.The Hydraulic Conductivity (K) Values by Three Methods

B. Transmissivity

Transmissivity (T) is one of the hydrodynamic properties in hydrogeology, used to quantify an aquifer's capacity to transmit groundwater through its entire saturated thickness under a unit hydraulic gradient. Characterizing transmissivity configurations is critical for regional groundwater flow modeling and pumping-test investigations, as it directly presents well-field drawdown behavior and physical safe-yield limitations under continuous pumping stress [13, 14]. The calculated transmissivity values present substantial spatial variation across the Greater Madani Locality, reflecting the combined structural effects of hydraulic conductivity (K) and changes in saturated aquifer thickness (b) across the sedimentary basin. The Transmissivity ranges from a minimum of 82.09 m²/day to a maximum of 843.32 m²/day, with an average of 295 m²/day. This variation is controlled by the alluvial depositional architecture of the Quaternary sequences [7]. The statistical distributions, including the minimum, maximum, and average transmissivity values, present from each of the three analytical pumping-test frameworks. The comparative evaluation is presented in Table 2.

In a saturated aquifer with a thickness (b) of approximately 90 meters, the calculated transmissivity (T) values exceeded 500 m²/day, exactly in the central and northern segments of the study area, as shown in Fig. 5. This configuration indicates a high capacity for groundwater transport, suggesting high physical productivity and hydraulic efficiency across these productive zones.

TABLE I I
Transmissivity (T) Values by Three Methods

Method	Overall Mean (m²/day)	Minimum (m²/day)	Maximum (m²/day)
Jacob	274.44	82.09	843.32
Theis Recovery	287.95	84.50	872.16
Theis & Hantush	322.66	92.50	805.70
Overall Average for 37 Wells	**295.02**	-	-

On the other hand, transmissivity values falling below 150 m²/day are directly associated with thin saturated aquifer sections and a predominant distribution of fine-grained alluvial materials, present in the southern sectors of the study area. These highly constrained zones require intensive physical management and regulated pumping tests to prevent drawdown, rapid water-table depletion, and reductions in the efficiency of a well [10], as shown in Fig. 5.

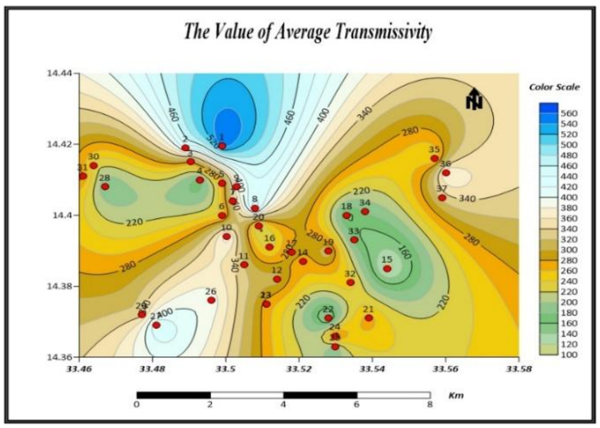

Fig .5.The Transmissivity (T) Values by Three Methods

Transmissivity is an important parameter that presents an aquifer's ability to transmit groundwater through its saturated thickness. This property depends on the hydraulic conductivity and saturated thickness. Transmissivity can be accurately measured through pumping tests and analytical equations.

C. Storage Coefficient

The storage coefficient (S) represents the volume of water that a porous aquifer matrix releases from or takes into storage per unit surface area per unit change in hydraulic head. This coefficient is subject to the rigidity of the aquifer's structure and the expansion potential of the groundwater matrices under pressure changes.

Determining the spatial distribution of the storage coefficient is important for mapping the structural groundwater movement and behavior of the aquifer under pressure. In the Greater Madani Locality, the calculated storage coefficient values range from 0.007 to 0.8460, with a mean of 0.1034. This large variability indicates high degrees of hydraulic confinement across the network of multiple aquifers.

The low-flow storage coefficient ($S < 0.01$) observed in the selected well indicates locally confined to semi-confined aquifer dynamics, structurally controlled by interconnected upper clay layers [8].

The high storage coefficient values ($S > 0.2$) recorded in adjacent well groups indicate unconfined groundwater level conditions. The general statistical distributions, including minimum, maximum, and average storage coefficients derived from the three analytical pumping test techniques, were structured for comparative evaluation and are presented in Table 3.

TABLE III
The Storage Coefficient (S) Values by Three Methods

Method	Overall Mean	Minimum	Maximum
Jacob	0.0132	0.0069	0.0353
Theis Recovery	0.2680	0.0470	0.8460
Theis & Hantush	0.0290	0.0070	0.0650
Overall Average for 37 Wells	0.1034	-	-

The Spatial distribution shows higher values in the northern parts and lower values in the central and southern parts of the study area. Based on the average storage coefficient value, concluded that the aquifer in the study area is classified as semi-confined or unconfined, with high storage capacity, as shown in Fig. 6.

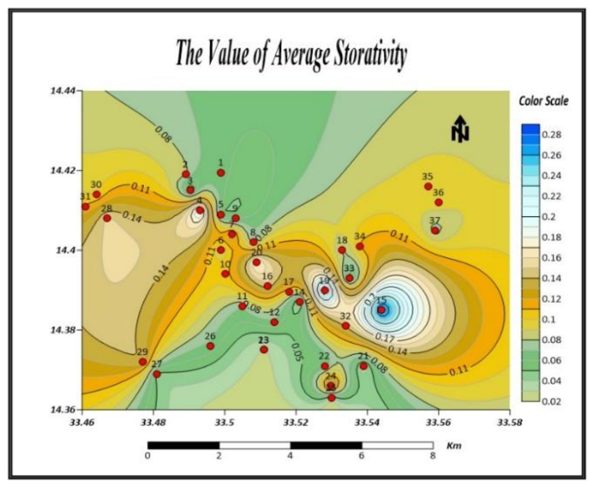

Fig 6. The Storage Coefficient (S) Values by Three Methods

D. Specific Capacity

Specific capacity (SC) is a parameter in groundwater hydrology and well hydraulics used to evaluate a production well's water-yield efficiency and overall operational performance [8]. This indicator serves as a primary indicator of design well efficiency, especially in semi-arid regions that depend on continuous groundwater extraction for domestic and agricultural purposes. In the study area, calculated specific capacity values range from a minimum of 67.29 m³\day\m to a maximum of 691.53 m³\day\m. The highest configurations were systematically documented within the high-Transmissivity of alluvial formations occupying the northern and central sectors of the Greater Madani Locality.

Specific capacity calculation, as responses reaching 691.53 m³/day/m, directly indicates a physical capacity of the well-aquifer to transmit high discharge volumes per unit depth of water-level drawdown [13]. On the other hand, a depressed specific capacity to a minimum of 67.29 m³/day/m indicates that greater drawdown is required to achieve a given operational flow rate. These lower-yielding zones present localized hydraulic constraints where well development and regulated pumping rates are important to minimize structural efficiency losses, as shown in Fig. 7.

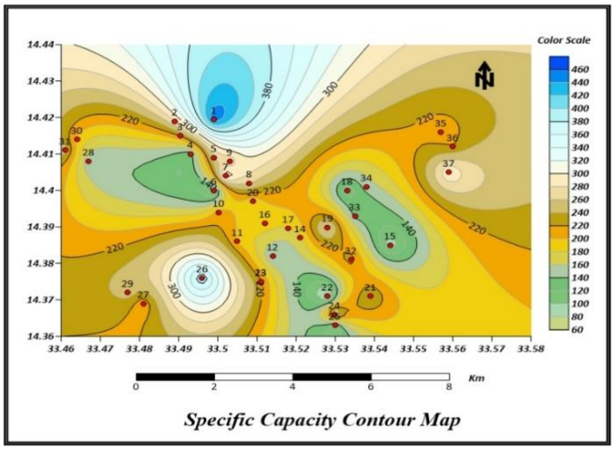

Fig. 7. Specific Capacity Contour Map

Regular, time-dependent declines in specific capacity are a key hydrodynamic diagnostic indicator of localized well degradation, filter sediment buildup, or gravel biocontamination, thus identifying critical periods for operational maintenance. Spatial mapping of specific capacity allows hydrogeologists to identify high-yield, optimized target areas and to mathematically determine suitable locations for drilling potential production wells.

TABLE IV

Statistical summary and spatial variability analysis.

Parameter	Minimum	Maximum	Mean	Stander Deviation	Coefficient of Variation (CV %)	Spatial Variability Level
Hydraulic conductivity	1.78	21.08	7.20	3.28	45.56%	Moderate to High
Transmissivity	82.09	843.32	295.02	134.12	45.46%	Moderate to High
Storage coefficient	0.007	0.8460	0.1034	0.0631	61.03%	High
Specific Capacity	67.29	691.53	225.96	114.73	50.77%	High

Specific capacity provides a practical, field-proven measure of the relationship between the pumping discharge rate (Q) and the groundwater level decline (s) [8]. Ensuring accurate experimental measurement of SC through performed pumping tests, along with a structural understanding of the hydrodynamic and lithological factors affecting well performance, remains essential to improving subsurface resource extraction and reducing wellfield efficiency losses throughout the Greater Madani Locality. Table IV presents the summary and spatial variability analysis of hydrogeological parameters for 37 wells.

V. Discussion

The Hydraulic conductivities (K: 1.78–21.08m/day, mean 7.20 m/day) and Transmissivities (T: 82.09–843.32 m^2\day, mean 295.02 m^2/day) calculated in the study area, with hydrogeological evaluations across central Sudanese basins, show big differences. The results present a high Spatial Variability Level (CV > 45%), resulting in high transmissivity (T > 500m^2\day), which is constrained in northern and central paleo channels where saturated aquifer thickness (b) reaches up to 90 meters. Similar structural parameter variability has been documented in semi-arid alluvial aquifers globally [8], where silt/clay intercalations cause variations in hydraulic parameters. The storage coefficient (S: 0.0070–0.8460, mean 0.1034) confirms dynamic transitions from semi-confined conditions under thick black clays to unconfined conditions where the clay thins, corroborating the multi-layered recharge mechanisms. By applying a multi-model analytical approach (Cooper-Jacob, Theis Recovery, and Theis- Hantush), this research successfully isolated vertical leaky recharge seeping through semi-confining clay layers from primary horizontal inflow, resolving ambiguities inherent in single-model estimations.

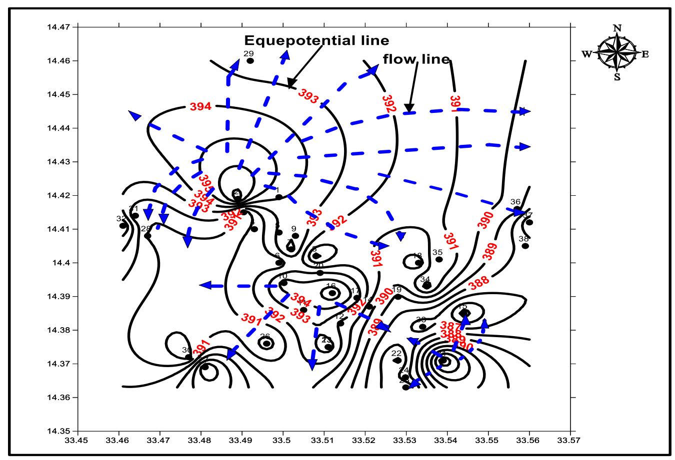

Fig. 8 . Groundwater flow Contour Map

The specific capacity (SC: 67.29–691.53 m^3/day/m) is controlled by the depositional environments. Northern and central areas with high-yield present high-energy alluvial channel deposits dominated by well-sorted gravels and coarse sand, acting as a subsurface layer helping in groundwater flow. The hydraulic limitations present in the southern and south-eastern locations (T < 150m^2/day and K < 3.5m/day) are low floodplain deposits dominated by fine-grained silt, mudstone, and silicified sandstone barriers that prevent the flow. Groundwater flow maps in Fig. 8 indicate good movement from northwest to southeast, driven by lateral feeding from the Blue Nile.

VI. Conclusion

This study assessed the Greater Madani Locality groundwater aquifer system, bridging estimates and scientific data. The basic hydrogeological findings showed a dynamic, multi-layered aquifer network that transitioned between semi-confined and unconfined conditions. Spatial maps show a continuous northwest-to-southeast flow of groundwater, supported by active lateral recharge from the Blue Nile.

Practical guidelines for groundwater management in Gezira State were derived from these results, as follows:

- Ensure high-capacity production wells are located only in northern and central permeability channels ($T > 500$ m²/day). Extractions in low-permeability southern locations ($T < 150$ m²/day) should be limited to wells with modest discharge rates to avoid interference. Pumping in semi-confined areas with low specific capacity ($SC < 100$ m³/day/m) and low storage coefficients ($S < 0.01$) must be regulated through timed, periodic extraction plans to mitigate dynamic pressure drops and mud compaction
- Continuous monitoring of dynamic specific capacity relative to baseline (average 225.96 m³/day/m) should be enforced as an early warning diagnostic tool to differentiate between physical well degradation (e.g., siltation in the filter) and depletion of the regional aquifer.
- The multi-model analytical methodology accounts for vertical leakage and recharge, providing a solid platform for long-term municipal water supply planning and sustainable governance in Al-Jazirah State.

Acknowledgements

The authors would like to express their sincere gratitude to the Faculty of Graduate Studies and the Department of Water Resources, College of Water and Environmental Engineering of Sudan University of Science and Technology for their continuous support and guidance. This paper is prepared to fulfill the requirements for the Ph.D. degree in Water Resources.

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