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Developing Design Curves to Determine Recharge Wells Influence Zones under Various Soil Characteristics

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ABSTRACT

Accurate assessment of hydraulic elements in hydraulic engineering and irrigation is crucial. The effectiveness of recharge wells for recharging groundwater aquifers is influenced by factors such as well design, aquifer properties, and recharge methods. Experimental models play a vital role in gaining insights into the complex hydraulic behavior of various aquifer types. This research was conducted at the Fluid Mechanics and Hydraulics Laboratory of the Faculty of Engineering, Al-Azhar University, where an experimental model was designed and implemented to simulate the hydraulic dynamics of various recharge well configurations. The primary objective of this research is to better understand the diverse impact mechanisms associated with different types of injection wells and their performance in recharging aquifers. The model, simulating real-world conditions, incorporates variables such as well geometries, recharge rates, and aquifer properties. The research analyzes hydraulic performance under controlled conditions, aiming to provide valuable data for designing efficient recharge well systems and optimizing groundwater recharge processes. The study is expected to contribute to sustainable groundwater management and inform decisions on recharge well design. In conclusion, the research elucidates complex hydraulic behavior, offering findings with theoretical and practical implications in hydraulic engineering and groundwater management. The detailed curve analysis aims to identify influential factors, holding significance in developing accurate predictive models and empowering specialists to make informed decisions in groundwater management..

KEYWORDS: Recharge wells, Groundwater Recharge, Well Configurations, Soil types.

تطوير منحنيات التصميم لتحديد مناطق تأثير آبار التغذية تحت تأثيرخصائص التربة المختلفة

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الملخص

يعد التقييم الدقيق للعناصرالهيدروليكية في الهندسة الهيدروليكية والري أمرًا بالغ الأهمية.حيث تتأثر فعالية إعادة شحن الطبقة الجوفيه بآبار إعادة الضخ بعوامل عديده مثل تصميم الآبار، وخصائص طبقة المياه الجوفية، وطرق إعادة التغذية. تلعب النماذج التجريبية دورًا حيويًا في الحصول على نظرة ثاقبة للسلوك الهيدروليكي المعقد لأنواع طبقات المياه الجوفية المختلفة. أجري هذا البحث بمعمل ميكانيكا الموائع والهيدروليكا بكلية الهندسة جامعة الأزهر، حيث تم تصميم وتنفيذ نموذج تجريبي لمحاكاة الديناميكية الهيدروليكية لآبارالشحن. الهدف الأساسي من هذا البحث هو فهم آليات التأثير المتنوعة المرتبطة بأنواع مختلفة من آبار الحقن

وأدائها في إعادة شحن طبقات المياه الجوفية بشكل أفضل. يتضمن النموذج، متغيرات مثل هندسة الآبار، ومعدلات التغذية، وخصائص طبقة المياه الجوفية. يقوم البحث بتحليل الأداء الهيدروليكي في ظل ظروف خاضعة للتدقيق، بهدف توفير بيانات قيمة لتصميم أنظمة إعادة تغذية الآبار الفعالة وتحسين عمليات إعادة تغذية المياه الجوفية. ومن المتوقع أن تساهم الدراسة في الإدارة المستدامة للمياه الجوفية واتخاذ قرارات مستنيرة بشأن تصميم آبار التغذية. وفي الختام، يوضح البحث السلوك الهيدروليكي المعقد، ويقدم نتائج ذات آثار نظرية وعملية في الهندسة الهيدروليكية وإدارة المياه الجوفية. ويهدف تحليل المنحنى التفصيلي إلى تحديد العوامل المؤثرة، والتي لها أهمية في تطوير نماذج تنبؤية دقيقة وتمكين المتخصصين من اتخاذ قرارات مستنيرة في إدارة المياه الجوفية.

الكلمات المفتاحية : آباراعاده الضخ، المياه الجوفيه، خصائص آبارالضخ ، خصائص التربة .

1. INTRODUCTION

In the domain of groundwater recharge methodologies, a plethora of studies has significantly enriched our comprehension and methodologies. James (1981) [1] conducted a thorough review of model applications, emphasizing the pivotal role of parameter estimation techniques in refining initial estimates. However, a caveat was issued against the inadvertent misuse of models, particularly concerning the assumption of inappropriate grid sizes for 3D flow, thereby incurring additional efforts and costs.

Rao and Sharma (1981) delved into the nuanced realm of groundwater mounds formation arising from finite aquifer recharge. Their numerical solution offered a compelling visualization of water field responses, notably superior in finite aquifers compared to infinite counterparts [2].

Viswanathan (1983) introduced a distinctive approach by employing the recursive least squares method to modify a linear model for daily water level estimation. The results underscored the temporal dependence of soil parameters, introducing a "forgetting factor" to enhance current rainfall level tracking [3].

Huston (1993) meticulously explored the Kabwe well field in Zambia, employing linear regression models to simulate water level fluctuations. While acknowledging their forecasting capabilities for groundwater systems, he acknowledged the inherent limitations necessitating extensive data collection over prolonged periods [4].

Arif Ismail (2018) directed attention towards the determination of the optimal number of recharge wells, delving into sustainable scenarios over a decade and illuminating the nuanced impact of cargo layer characteristics [5].

Edy Susilo et al. (2018) shed light on the intricacies of well recharge, elucidating its direct proportionality to cross-sectional area and soil permeability. They underscored the adverse effects of improperly perforated well screens on recharging rates[6].

Roger A. Luyun Jr. (2019) embarked on experimental simulations of artificial recharge in the Philippines, unveiling a discernible decrease in recharge rates with extended injection periods at high rates [7].

S. Purwantara (2019) probed artificial shipping wells in Yogyakarta, Indonesia, uncovering their pivotal role in water preservation and flood risk reduction [8].

Fiaz Hussain (2019) delved into the potential of rainwater harvesting in Lahore, utilizing modeling for artificial recharge to circumvent rainwater-wastewater mixing [9].

J. H. van Lopik (2019) proposed a pragmatic solution for urban inundation and artificial recharge in Lahore, showcasing the potential of rainwater harvesting using recharge wells [10].

J. H. van Lopik (2020) extended his research to determine the requisite number of recharge wells in Bandung, Indonesia, simulating them as drainage wells for soil stability [11].

Mostafa Ali Abdelaal (2020) accentuated the importance of studying well spacing during simulations, offering insights into mutual well interference and presenting a curve for predicting spacing. He also underscored the significance of calibrating screen perforations to ensure precise results, particularly in laboratory settings.to make sure that it will give the required rate, because the type, thickness, material, and the quality of perforation have a significant impact on the recharge rates[12].

Mohamed Abdelaziz, (2023) Investigated the impact of well-based groundwater recharge on soil properties. Experiments on sandy and clayey soils revealed enhanced tensile and compressive strength, reduced compressibility, and increased soil water content, contributing to higher pollutant concentrations in groundwater [13].

Ahmed Abdelhamid, (2023) Explored the feasibility of using wells for groundwater recharge in urban settings. The study, conducted in a Cairo residential area, concluded that well-based groundwater recharge effectively raises groundwater levels and safeguards against pollution [14].

Mahmoud Abdullah, (2023) Provided design guidelines for wells intended for groundwater recharge. The study emphasizes considering groundwater properties, soil characteristics, and the specific needs of the targeted area [15].

Zeinab Abdelaziz, (2023): Assessed the impact of wells on groundwater quality. Based on an agricultural area in Fayoum Governorate, the study found that wells can negatively impact groundwater quality, leading to increased pollutant concentrations[16].

Nature Sustainability a recent study from the University of California, Berkeley, December (2023) emphasizes the need for careful design and regulation of recharge wells to ensure their effectiveness and groundwater safety. Further research is recommended to improve operational aspects. Despite supporting evidence for recharge wells, challenges like high costs and environmental impact must be addressed for safe and sustainable implementation[17].

In conclusion, while the mentioned studies offer valuable scientific contributions to the understanding of groundwater recharge, there is a notable gap in the investigation of various well screen lengths across different types of charging layers. Our upcoming research aims to address this gap by exploring the influence of well screen lengths on recharge wells, particularly focusing on generating informative curves for inferring impact circles in the presence of diverse soil types. This approach will contribute to a more comprehensive understanding of the factors influencing the effectiveness of recharge wells and provide insights for practical applications in different hydrogeological contexts.

THEORETICAL APPROACH

A comprehensive understanding of the interdependencies among all parameters influencing the recharge well has been achieved. This comprehension is elucidated through the application of Buckingham's π-theorem, utilizing the dimensional analysis technique. The methodology of dimensional analysis is grounded in the principle of dimensional homogeneity, asserting that any equation articulating the relationship between physical quantities must exhibit dimensionally homogenous characteristics. This fundamental principle underscores the significance of maintaining dimensional consistency in expressions delineating the intricate relationships within the context of recharge well dynamics.

Where:

B1 = Length of sand tank model.
B2 = Width of sand tank model.
H = Height of water column.
h1 = Height of recharge layer.
h2 = Height of above layer.
X = The maximum effective distance of recharging well.
Q = Discharge of well.
G = Gravitational acceleration.
ρ = Mass density of fluid.
μ = Dynamic viscosity.
K_1= Hydraulic conductivity for the soil number 1
K_2= Hydraulic conductivity for the soil number 2.
K_3= Hydraulic conductivity for the soil number 3.
Ls = Length of screen.
D = Diameter of well screen.

When:

According to Buckingham's π -theorem, the general form of the relationship between these variables is as follows:

$$\frac{q}{\sqrt{g}*h^{5/2}} = f\left(\frac{B_1}{B_2}, \frac{h_1}{H_2}, \frac{h_2}{h_w}, \frac{h_t}{H}, \frac{X}{Y}, \frac{\mu_1}{\rho\sqrt{g}*H^{3/2}}, \frac{k_{1x}}{k_{2x}}, \frac{k_{1y}}{k_{2y}}, \frac{k_{1z}}{k_{2z}}, \frac{L_s}{X}, \frac{D}{d}\right) \qquad \text{Eq. (1)}$$

EXPERIMENTAL WORK

3.1 Tank Design and Simulation:

A specialized tank has been intricately designed to replicate the study area, encompassing both the soil designated for water recharge and the recharge wells. **Photo 1.**

The meticulous craftsmanship of the tank ensures a close emulation of natural conditions.

Photo. 1. Sand Tank Model.

3.2 No-Flow Boundary Simulation:

Perforated pipes have been strategically installed around the tank's perimeter to replicate the no-flow boundary conditions commonly observed in natural settings. **Photo 2**

In addition to installing several piezometers in a specific location.

Photo. 2. Perforated Pipes and Gravel Filter For Drinage.

3.3 Wells Preparation and Testing:

The wells have undergone perforation and rigorous testing to guarantee uniform conditions, aiming for a higher degree of precision in the obtained results.

3.4 Clogging Prevention Measures:

To prevent potential well clogging caused by fluctuations in water levels within the recharge layer, a gravel filter and a plastic mesh have been specifically designed and implemented. **Photo 3**

Photo. 3. Perforated Pipes and Gravel Filter For Wells.

3.5 Encapsulation and Enhanced Fluidity:

The wells have been encapsulated, and their design emphasizes improved fluidity by incorporating an innovative water-sealing tool beneath them.

This design feature allows for controlled management of the rise and fall of the recharge well water level.

Photo. 4. water-sealing tool.

3.6 Water Resourse

Two tanks have been designed, with the first serving as a water source used during the experiment. The second tank, positioned above, simulates the ground surface for the recharge well. It is controlled based on the water level above the well surface through the operation of a structure at the center of this tank.

Photo. 5. Source Tank and Upper Tank.

3.7 METHODOLOGY OF WATER SUPPLY

The pump facilitates the transfer of water from the lower tank to the four entry points of the upper tank. It is imperative to maintain consistent flow rates across all valves, accomplished by adjusting the weir to achieve the desired water level. Any surplus water is efficiently regulated, ensuring a controlled return to the lower tank. This meticulous approach guarantees uniform water levels across all wells, thereby facilitating equitable discharge rates. The process involves a systematic introduction of water into the wells, initiated by the pumping of water into the upper tank. **Photo. 6**

Photo. 6. All experimental set-up components.

NUMERICAL INVESTIGATION

The GMS software employed a numerical model, calibrated by comparing results with the physical model's observations. Specifically, groundwater levels within the recharge layer were monitored through dedicated wells in the experimental model. Notably, the Child Model (CM) function was integrated to simulate phenomena requiring a finer grid than the Parent Model (PM) grid. This finer grid is essential for accurately representing sharp changes in hydraulic gradient or hydraulic properties. The CM utilized the boundary conditions provided by the coarser PM to ensure optimal resolution, preventing loss of detail that might occur with a coarser parent grid implementation. **Fig. 1.**

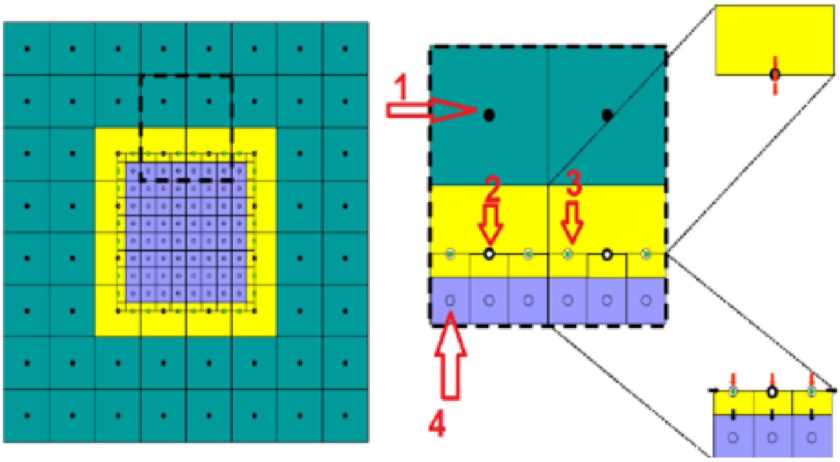

Fig. 1. CM interface.

Where:

1: PM node.

2: PM-CM shared node .

3: CM specified-head boundary node obtained by interpolation from PM parent solution at shared nodes.

4: Area (with unit width and length) of net recharge .

4.1 MODEL CALIBRATION

4.1.1 Simulation of 100 % well screen length form recharge layer

The piezometers, configured as observation wells in the experimental model, were introduced. Experimental data obtained from the laboratory test was incorporated, enhancing the sensitivity of the monitoring wells for improved real-world simulation accuracy. The impact of the dimensions of the grid cell containing the well was observed. Notably, when aligning the cell dimensions with those of the recharge well in reality, the results were unsatisfactory. **Fig. 2**

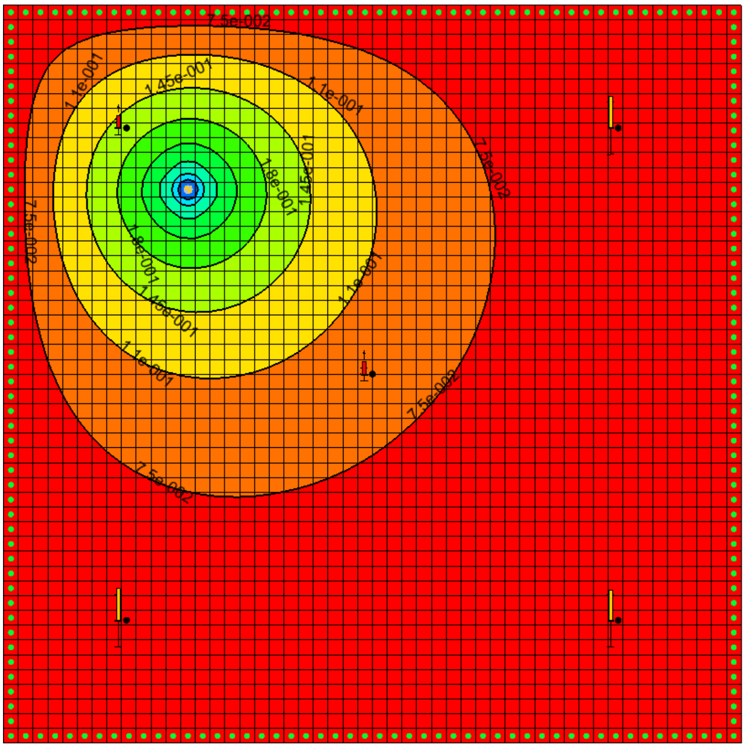

Fig. 2. Observation well results with equal cell dimensions and well diameter with Ls=100 %.

Through several attempts using the Child Model CM function, the cell dimensions were adjusted to achieve good results that closely match those in the experimental model. After several trials **Figs. 3&4**, the best results were obtained when reaching cell dimensions equivalent to 0.67 of the well diameter in reality upon achieving this result, the numerical model became calibrated and reliable. **Fig. 5**

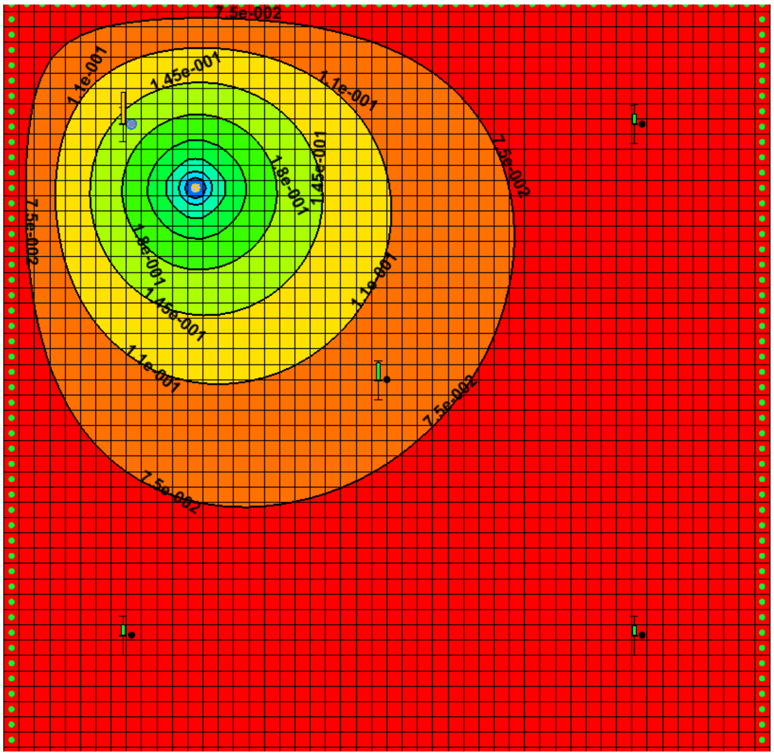

Fig. 3. Observation well results with cell dimensions equal 90% well diameter.

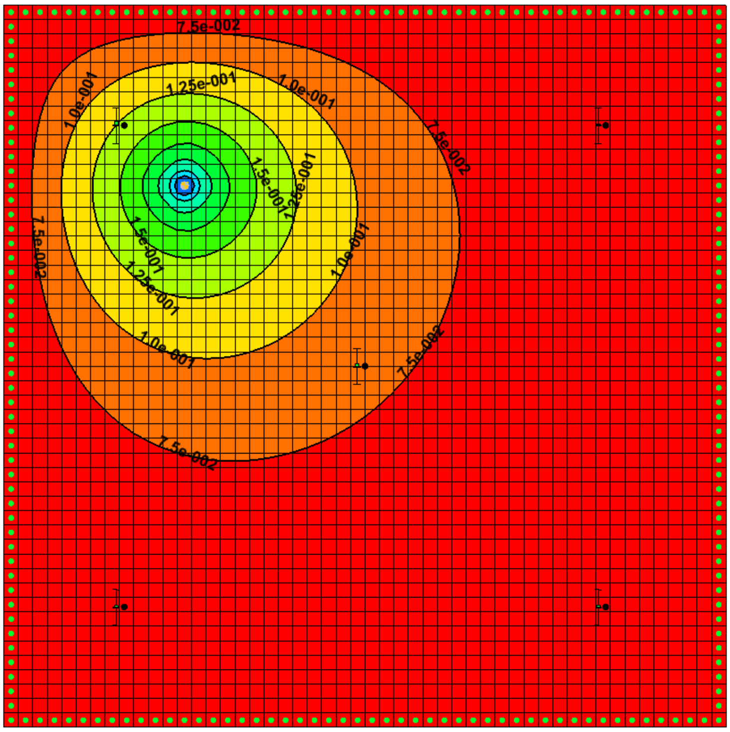

Fig. 4. Observation well results with cell dimensions equal 80% well diameter with Ls=100 %.

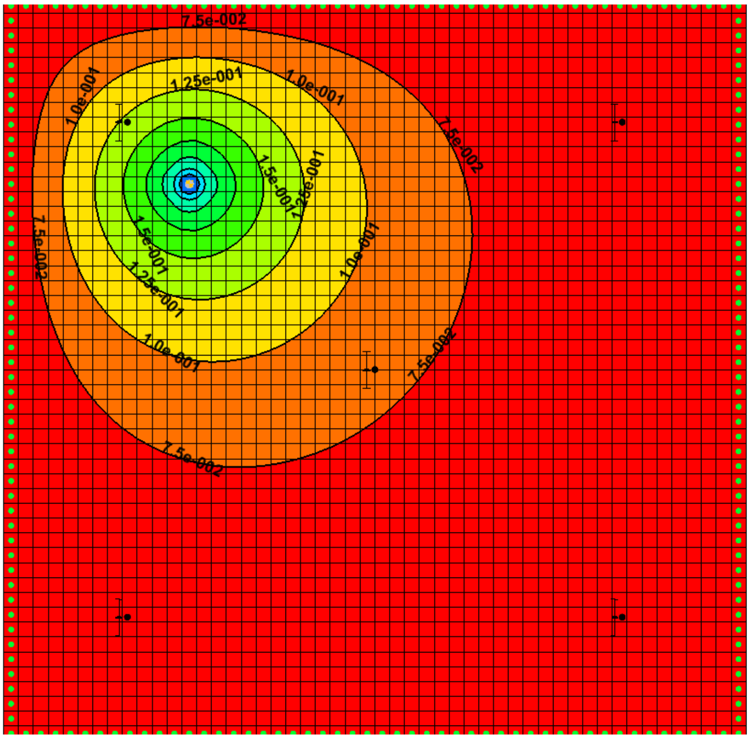

Fig. 5. Observation well results with cell dimensions equal %67 well diameter with Ls=100 %.

4.1.2 simulation of 75 % well screen length form recharge layer.

The child function was utilized to simulate the recharge well screen length penetrating the recharge layer. The previous parameters were utilized, where they designated the importance of the recharge well screen length, in terms of the cell width containing recharge well.

Primarily, the cell dimension was equal to recharge well diameter, where this indicated unreasonable readings of the observation wells **Fig. 6.** Several attempts followed, from which it was clear that the appropriate cell dimension was equal to 1.15 recharge well diameter **Fig. 7.**

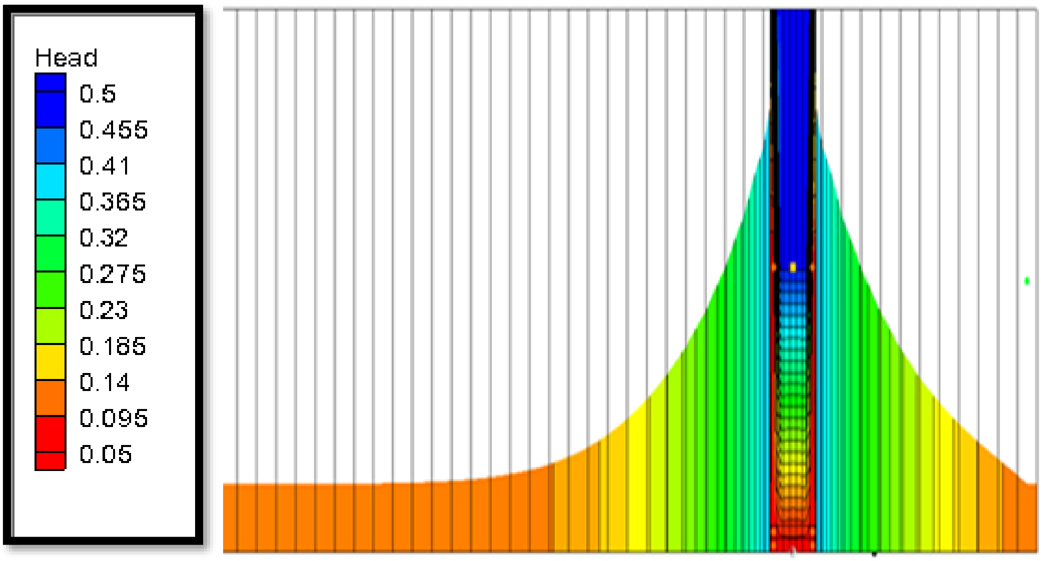

Fig. 6. Cell dimension equals recharge well diameter, at Ls=75% .

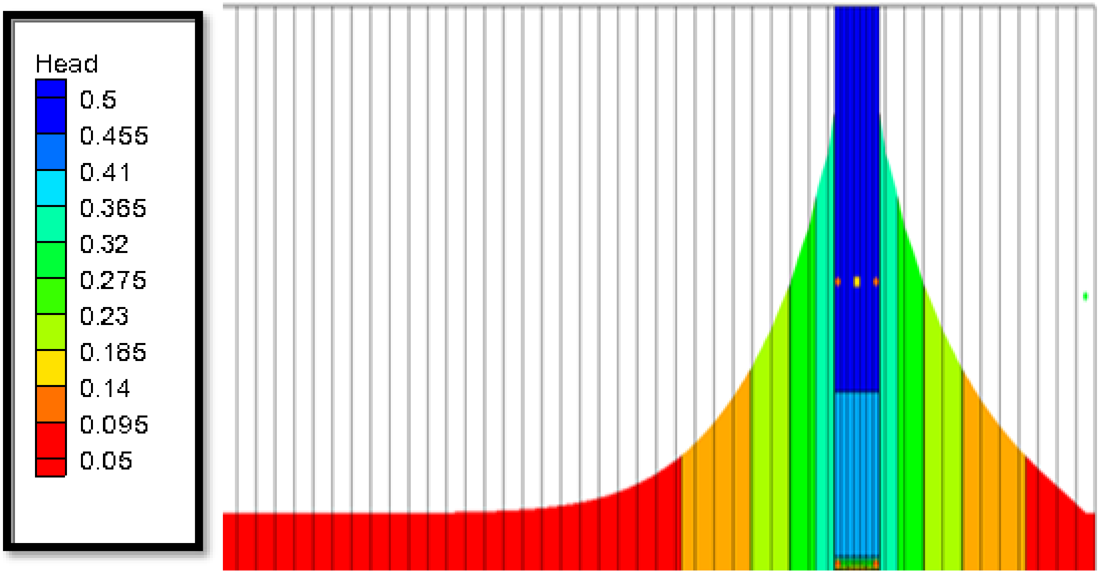

Fig. 7. Cell dimension equals 1.15 from recharge well diameter, at Ls=75%.

4.1.3 simulation of 50% well screen length form recharge layer.

The child function controlled the screen length that penetrates recharge layer, where the parameters that indicated the length and width of the cell containing the recharge well were implemented **Fig. 8.**

Initially, the cell dimensions were equal to the recharge well diameter. This provided false readings results of the monitoring wells .

Several attempts were achieved with different cells dimensions; from which it was clear that the appropriate cell dimension is 1.45 times recharge well diameter **Fig. 9.**

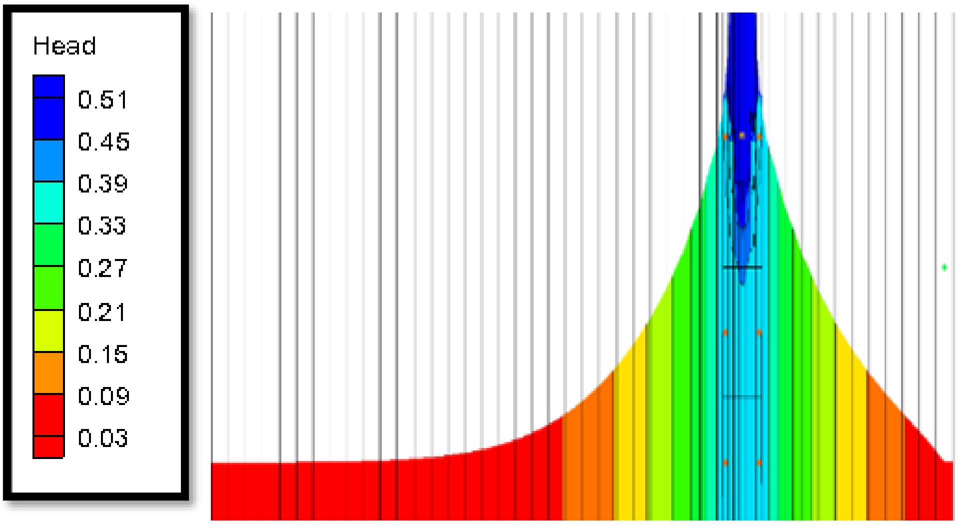

Fig. 8. Cell dimension equals recharge well diameter, at Ls=50% .

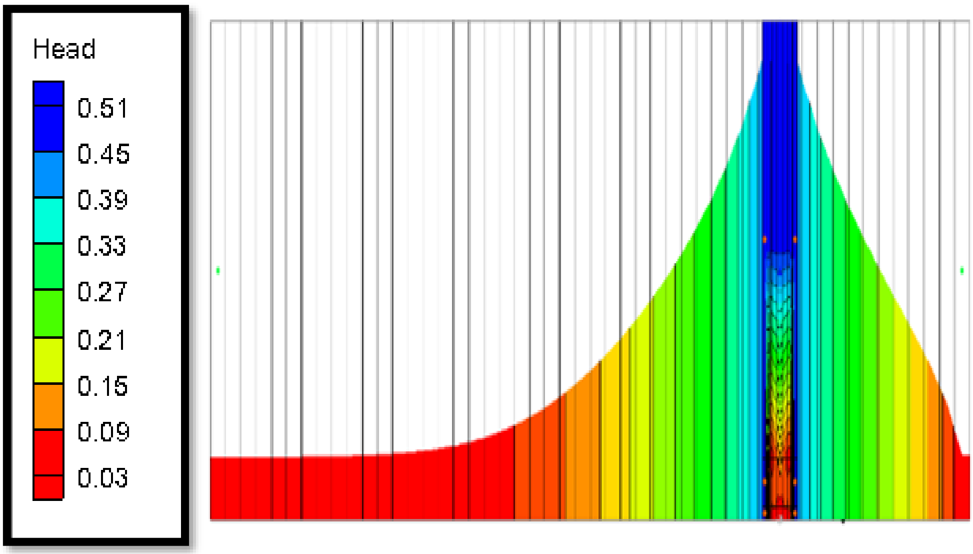

Fig. 9. Cell dimension equals 1.45 from recharge well diameter, at Ls=50%.

ANALYTICAL INVESTIGATION

After calibrating the numerical model to replicate the experimental model, we are now able to explore various scenarios. Given that the primary objective of the research was to obtain results beneficial for groundwater developers, the hydraulic conductivity was adjusted. This parameter is crucial, especially in the groundwater recharge process through recharge wells.

The experiments were conducted on the numerical model with variations in recharge rates, which were 80, 60, 50, and 35 cubic meters per hour.

The hydraulic conductivity value for the soil was selected based on actual measurements in the experimental model, which amounted to 35 meters/day. This precise determination reflects the real conditions of the study and enhances the numerical model's alignment with practical outcomes.

A value of 250 meters/day was chosen for the hydraulic conductivity to represent silty sandy soil, providing an accurate representation of its water characteristics.

A value of 5 was selected for the hydraulic conductivity to represent clayey soil, making it closer to pure clay and mimicking the standard conditions.

In the following, curves are shown that illustrate the relationship between different discharge rates and the variation in well screen length **Figs. 10,11&12.**

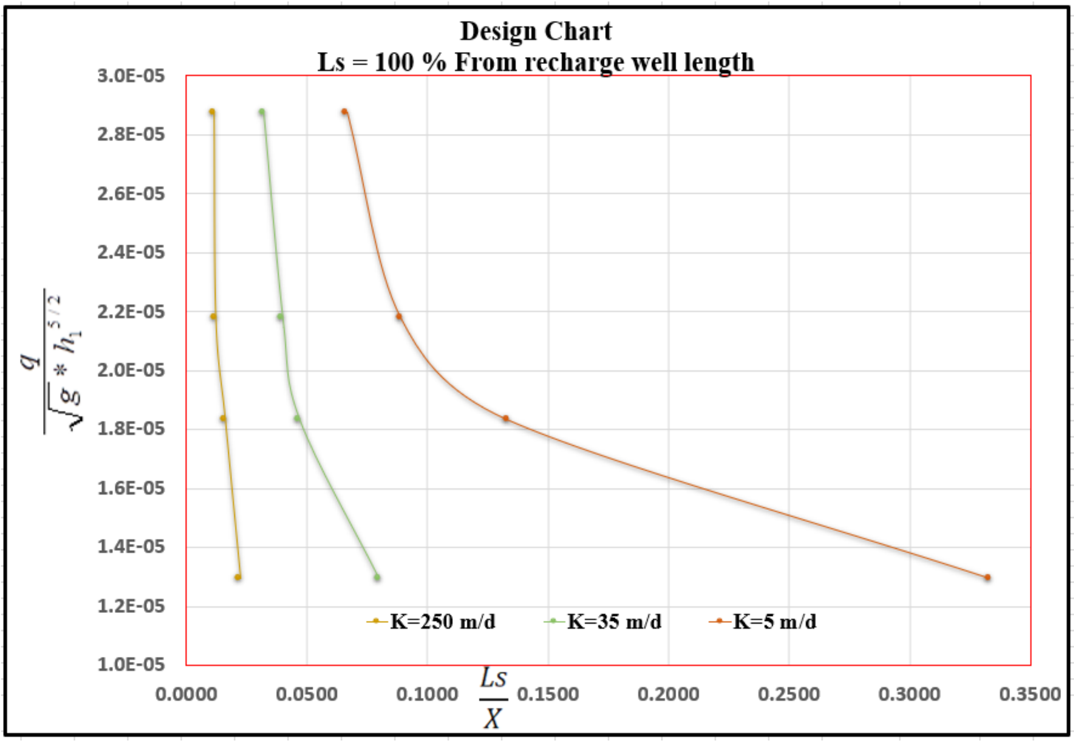

Fig. 10. Well influence zone design curve with Ls=100%.

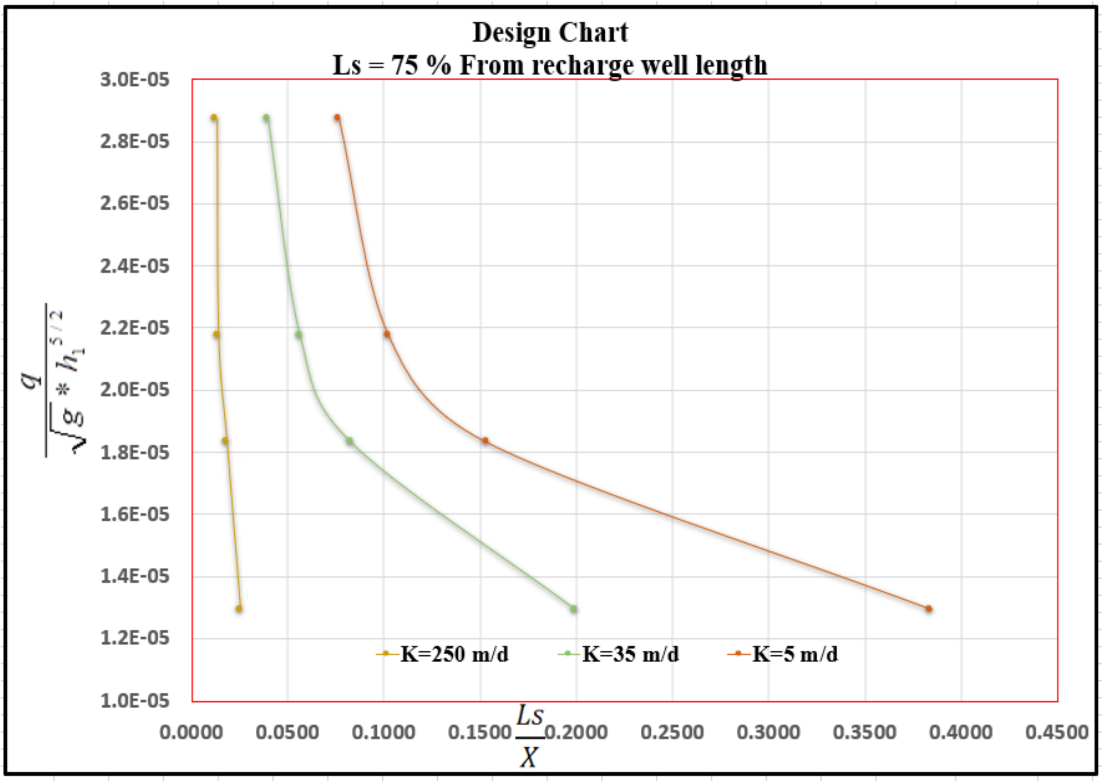

Fig. 11. Well influence zone design curve with Ls=75%.

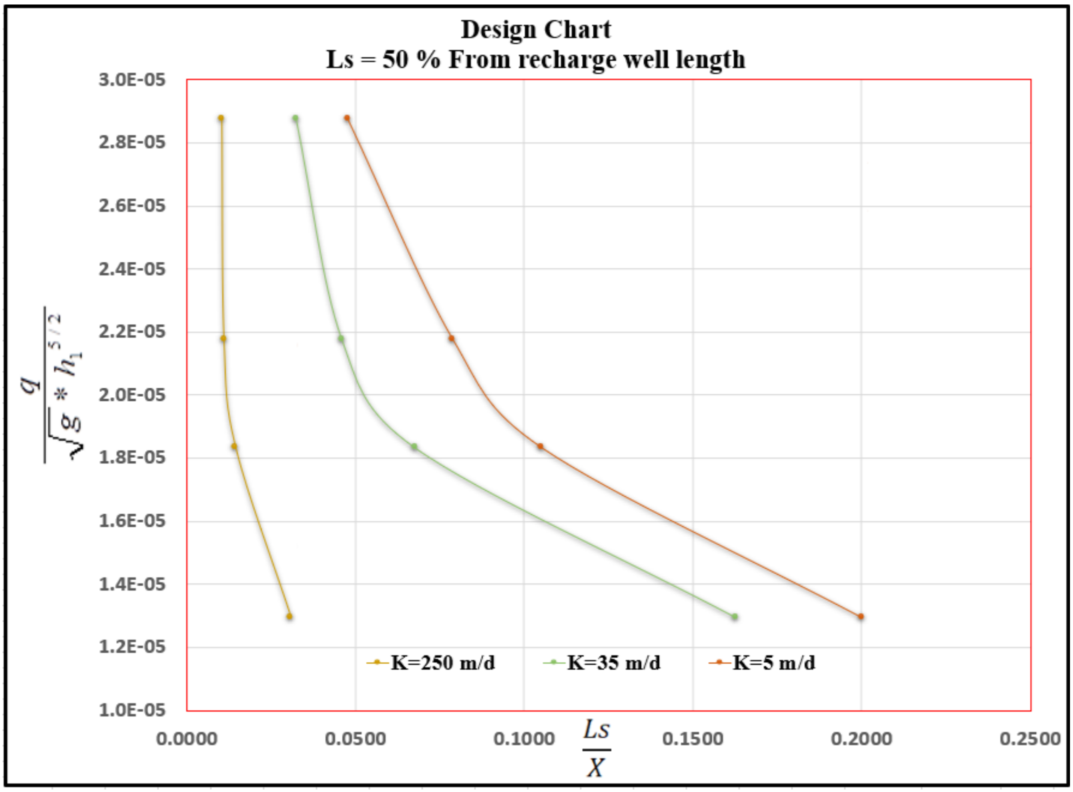

Fig. 12. Well influence zone design curve with Ls=50%.

Conclusions

- Simulation conducted for various well screen lengths using GMS software, highlighting the significance of cell dimensions and their impact on well representation.
- Optimal cell dimensions for representing a well screen length equal to the thickness of the aquifer layer determined to be 67% of the well diameter.
- Best cell dimensions for representing a well screen length of 75% of the aquifer layer depth identified as 1.15 times the well diameter.
- Optimal cell dimensions for representing a well screen length of 50% of the aquifer layer depth established at 1.45 times the well diameter.
- Design curves developed to assist groundwater developers and well design engineers in determining well influence zones under various soil properties, particularly hydraulic conductivity.

Recommendations

- Enhancing comprehension of numerical models like GMS involves effective methods, with calibration through a practical model simulating natural conditions being a key approach.
- Conduct additional simulations to investigate the impact of other factors, such as aquifer geometry and heterogeneity, on well representation and influence zones.
- Develop more comprehensive design curves that incorporate a wider range of soil properties and well configurations.
- Develop and disseminate guidelines for groundwater developers and well design engineers on the proper application of the research findings and design curves.

References

[1] James, I. G. (1981). A review of the applications of groundwater models. Journal of Hydrology, 50(1-2), 153-178.

[2] Rao, P. S., & Sharma, M. L. (1981). Finite aquifer recharge from wells in multi-layered systems. Journal of Hydrology, 52(3-4), 347-361.

[3] Viswanathan, M. N. (1983). Groundwater level estimation by recursive least squares. Journal of Hydrology, 65(1-3), 83-94.

[4] Huston, J. M. (1993). Simulation of groundwater level fluctuations at the Kabwe well field, Zambia. Journal of Hydrology, 143(1-2), 133-154.

[5] Ismail, A. (2018). Determination of optimal number of recharge wells for sustainable groundwater management. Journal of Water Resources Management, 32(14), 4803-4816.

[6] Susilo, E., Danoedoro, P., & Sutopo, B. (2018). The effect of soil permeability and well screen perforation on well recharge performance. Journal of Engineering Science and Technology, 13(4), 2277-2288.

[7] Luyun Jr., R. A. (2019). Experimental simulation of artificial recharge in the Philippines. Water Science and Technology: Water Supply, 19(2), 637-643.

[8] Purwantara, S. (2019). The effectiveness of artificial recharge wells in water preservation and flood risk reduction in Yogyakarta, Indonesia. Journal of Environmental Science and Technology, 11(1), 59-67.

[9] Hussain, F. (2019). Rainwater harvesting potential and artificial recharge for groundwater management in Lahore, Pakistan. Water Resources Management, 33(12), 4195-4209.

[10] van Lopik, J. H. (2019). Urban inundation and artificial recharge solutions for Lahore, Pakistan. Journal of Hydrology, _575, 116-129.

[11] van Lopik, J. H. (2020). Determining the optimal number of recharge wells in Bandung, Indonesia, through simulation of drainage wells for soil stability. Journal of Sustainable Water Resources Management, 6(1), 1-12.

[12] Abdelaal, M. A. (2020). Studying the effect of well spacing on well interference in artificial recharge. Journal of Hydroinformatics, 22(4).

[13] Abdelaziz, M. (2023). The effects of groundwater recharge by wells on soil properties. Journal of Civil Engineering, Cairo University, 100(1).

[14] Abdelhamid, A. (2023). The use of wells for recharging groundwater in urban areas. Journal of Water Resources, Mansoura University.

[15] Abdullah, M. (2023). The design of wells for groundwater recharge. Journal of Environmental Engineering, Alexandria University, 300(1), 1-10.

[16] Abdelaziz, Z. (2023). Assessment of the impact of wells on groundwater quality. Journal of Environmental Sciences, Ain Shams University.

[17] Nature Sustainability. (2023, December). Recharge wells need careful design and regulation, study finds. Nature Sustainability, 1-4.