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Experimental Comparison of Single and Dual Conduit Connectivity in Karst Aquifers

Amr. A. Ashour*[1], Ahmed E. Hassan[2], Mostafa A. Abdel-Aal[1] and Mohamed A. Abd-Elmegeed[2]

[1] Civil Engineering Department, Faculty of Engineering, Al-Azhar University, Nasr City, 11884, Cairo, Egypt.
[2] Irrigation and Hydraulics Department, Faculty of Engineering, Cairo University. Giza, Egypt.
*Correspondence: amr.ashour@azhar.edu.eg

الملخص : لدراسة ديناميكية تدفقات المياه الجوفية بين الكهوف والوسط المسامي المحيط بها، تم تطوير نموذج فيزيائي بأبعاد 3.00 متر × 0.60 متر × 0.60 متر لمحاكاة شبكة من تلك التكهفات الجوفية باستخدام أنابيب بقطر 0.5 بوصة ونسبة تثقيب 30%، وهذه الشبكة مكونة من أنبوبين مزدوجين متصلين بشكل يسمح بتعديل الاتصال من خلال استخدام صمامات تحويل على مسافات 0.80 متر و1.20 متر مقاسة من منبع تغذية النموذج. هذا التصميم يسمح بالتحكم المنهجي في الترابط بين القنوات مع الحفاظ على ظروف حدودية متسقة. وقد تمت محاكاة الوسط المسامي المحيط باستخدام تربة رملية، مما ساعد على انشاء بيئة مضبوطة لفحص التفاعلات الهيدروليكية بين نطاقات التدفق المنفصلة والمستمرة. وقد تم إجراء تجربتين لدراسة تأثير الاتصال، بحيث تضمنت التجربة الأولى أنبوبة واحدة مفتوحة من كلا طرفيها ومتصلة عبر صمامات تحويل بأنبوبة أخرى مثقبة ومغلقة من كلا الطرفين. في المقابل، تم تنفيذ التجربة الثانية باستخدام أنبوبين يعملان في آن واحد ومفتوحين من كلا الطرفين ومتصلين عبر نفس الصمامات. وقد أجريت كلتا التجربتين في ظروف كان فيها منسوب المياه في الأنابيب أعلى من الوسط المسامي عند منبع التغذية والمصب بمقدار 9 سم و1.1 سم على التوالي. وقد كشفت نتائج النموذج المعملي عن أن مسافة القرب بين الأنابيب في التجربة الثانية لم يكن لها تأثير على معدلات التدفق الخارج من القنوات، حيث تضاعفت معدلات التدفق في الأنابيب المزدوجة مقارنة بالأنابيب المفردة. وبالمثل، تضاعف تدفق التبادل تقريباً بنسبة 98%

Abstract. To investigate the hydrodynamics between conduit networks and matrix domains in karst aquifers, a physical model was developed with dimensions of 3.00 m × 0.60 m × 0.60 m. The model featured a configurable dual-conduit system composed of 0.5 inches in diameter perforated conduit and a 30% perforation ratio with adjustable connectivity controlled through diverter valves at distances of 0.80 m and 1.20 m measured from the model upstream. This design allowed for systematic manipulation of conduit interconnectivity while maintaining consistent boundary conditions. The surrounding matrix medium was simulated using sandy soil, creating a controlled environment for examining the hydraulic interactions between discrete and continuous flow domains.
Two experiments were conducted to investigate the effect of connectivity. The first experiment involved a single conduit open at both ends and connected via diverter valves to another perforated conduit sealed at both ends. In contrast, the second experiment used dual conduits operating simultaneously and connected through identical valves. Both experiments were conducted under conditions where the conduit head was higher than the matrix upstream and downstream of the model by 9 cm and 1.1 cm, respectively. Results revealed that the proximity distance between the conduits in the second experiment had no effect on the outflow rates from the conduits, as the flow rates in the dual conduit were doubled by 100% compared to the single conduit. Similarly, the exchange flow nearly doubled with a ratio of 98%.

Keywords: Karst aquifer, Experimental model, Flow exchange and Conduits connectivity.

1. Introduction

Karst aquifers are crucial water resources that supply an estimated quarter of the global population [1] and occupy approximately 15% of the Earth's landmass [1], [2], [3]. These aquifers feature a unique dual groundwater flow regime characterized by highly conductive conduits facilitating rapid recharge alongside slower flow through the matrix media [4]. The conduit system creates distinct flow patterns with concentrated, high-velocity transport that can be either laminar or turbulent [5], while the matrix component exhibits heterogeneous permeability and porosity [6]. Despite their significance, these aquifers have limited intrinsic storage potential, necessitating careful management practices to ensure water supply sustainability.

The inherent heterogeneous nature of karst aquifers presents substantial obstacles in modeling and comprehending groundwater movement. Traditional aquifer characterization techniques frequently fail to identify the key features that control underground flow patterns in these complex systems[7] . Additionally, the swift groundwater movement through karst conduits creates challenges for monitoring methods, which often cannot adequately capture these rapid flow dynamics [8]. Such challenges result in considerable uncertainties within hydrological modeling efforts, compromising the accurate representation of flow patterns. Consequently, these limitations impede effectively managing these essential but sensitive groundwater resources [9].

Physical modeling provides a fundamental approach to understanding the complex flow dynamics within karst aquifers. Researchers can simulate and analyze various hydrological conditions through these experimental setups to better understand groundwater movement patterns. Several significant studies have advanced our knowledge in this field. [2] developed a three-dimensional laboratory model that revealed the critical role of head difference, hydraulic gradient, and conduit dimensions in controlling matrix-conduit water exchange during groundwater pumping. [6] evaluated the impact of discrete conduit flow through comparative modeling studies. Further research [10] utilized an integrated laboratory and numerical methodology to examine saltwater intrusion in fractured coastal aquifers. At the same time, similar combined approaches were employed [11] to study groundwater flow and solute transport mechanisms. Additional investigations focused on specific aspects: the interaction between saturated karst conduits and surrounding aquifers [12], the temporal and spatial variations in fissure-conduit flow exchange [12] [13], and comprehensive analysis of laboratory model construction techniques [14].

Unlike previous studies that primarily focused on numerical modeling, this study employs a physical model to directly observe the interactions between conduits and the matrix resulting from conduit connectivity. This research experimentally investigates the influence of conduit connectivity due to the rising water head in the conduit inflow rather than the matrix inflow, providing insights that can enhance water resource management in karst regions, which are critical for sustainable development in areas reliant on groundwater.

2. Experimental Work And Procedures

2.1. Model Description

To simulate a karst aquifer using a laboratory scale, a three-dimensional physical model measuring 3.00 m long, 0.60 m wide, and 0.60 m deep was constructed at the Irrigation and Hydraulics Laboratory, Faculty of Engineering, Al-Azhar University, Egypt. **Fig. 1** shows a photograph of the laboratory model setup, while **fig.2** illustrates it in 3D.

The physical model was constructed from acrylic Plexiglas and comprised of five interconnected parts. Two separated left compartments served as inflow reservoirs, one for the matrix domain and another for the conduit domain. The central section represented the karst aquifer itself. Finally, the two rightmost compartments functioned as outflow reservoirs for the matrix and conduit domains. The inlet and outlet reservoirs have incorporated overflow pipes. These pipes facilitated control of upstream and downstream water levels within each domain, mimicking a specified head boundary condition.

Sandy soil was selected to simulate the matrix domain due to its hydraulic properties, which closely mimic natural conditions in karst aquifers. The soil was classified using sieve and hydrometer tests. The tests revealed that the soil sample was predominantly sandy (98.31%), with minimal gravel (0.34%) and negligible silt and clay content, as shown in **fig. 3**. The particle size distribution analysis yielded D10 = 0.2231 mm, D30 = 0.3063 mm, and D60 = 0.5263 mm. With a Coefficient of Uniformity (Cu) of 2.359 and a Coefficient of Curvature (Cc) of 0.7989, both outside optimal ranges, the soil was classified as poorly graded sand (SP) under the Unified Soil Classification System. The hydraulic conductivity of the matrix was 0.03 cm/s, determined through a constant head permeability test. A stainless-steel mesh, lined with a geotextile membrane, was installed at the interface to prevent sand movement from the matrix into the inlet and outlet reservoirs.

In comparison, the conduit domain consisted of two parallel horizontal perforated pipes with a diameter of 0.50 inches and a 30% perforation ratio. These pipes were located at one and two-thirds of the model and 0.20 m above the base. A geotextile membrane enveloped the conduits to impede the infiltration of fine particles from the surrounding porous media. Two connector pipes, equipped with control valves, were installed between the conduits in the middle of the model at distances of 0.80 m and 1.20 m to investigate the connectivity effect between conduits due to the various flow scenarios during experiments.

A network of 65 piezometers monitored pressure heads throughout the system. 8 piezometers were installed inside the two conduits. At the same time, the remaining 57 were strategically placed within the matrix across four distinct elevation levels. At the lowest level (3 cm from the model base), 24 piezometers captured pressure data. The second level (15 cm from the base) housed 11 piezometers. Eleven additional piezometers were installed at the third level (20 cm), with the final 11 at the highest level (45 cm from the base). **Fig. 4** illustrates piezometer distribution along the experimental model.

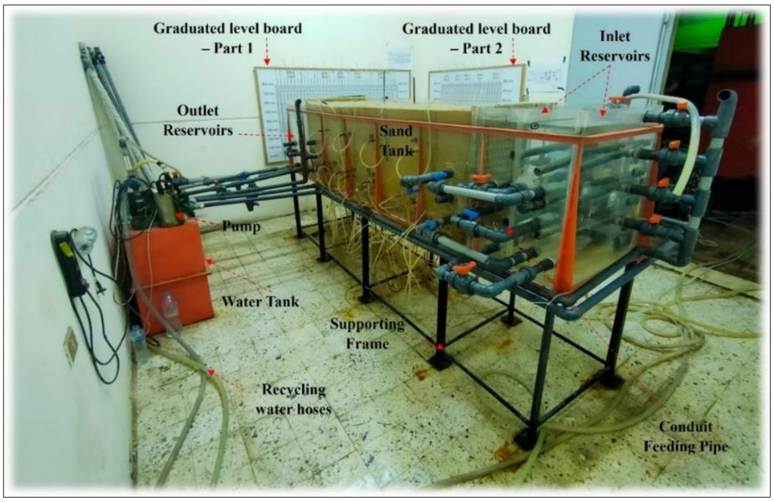

Fig. 1. A Photograph Depicting the Experimental Setup.

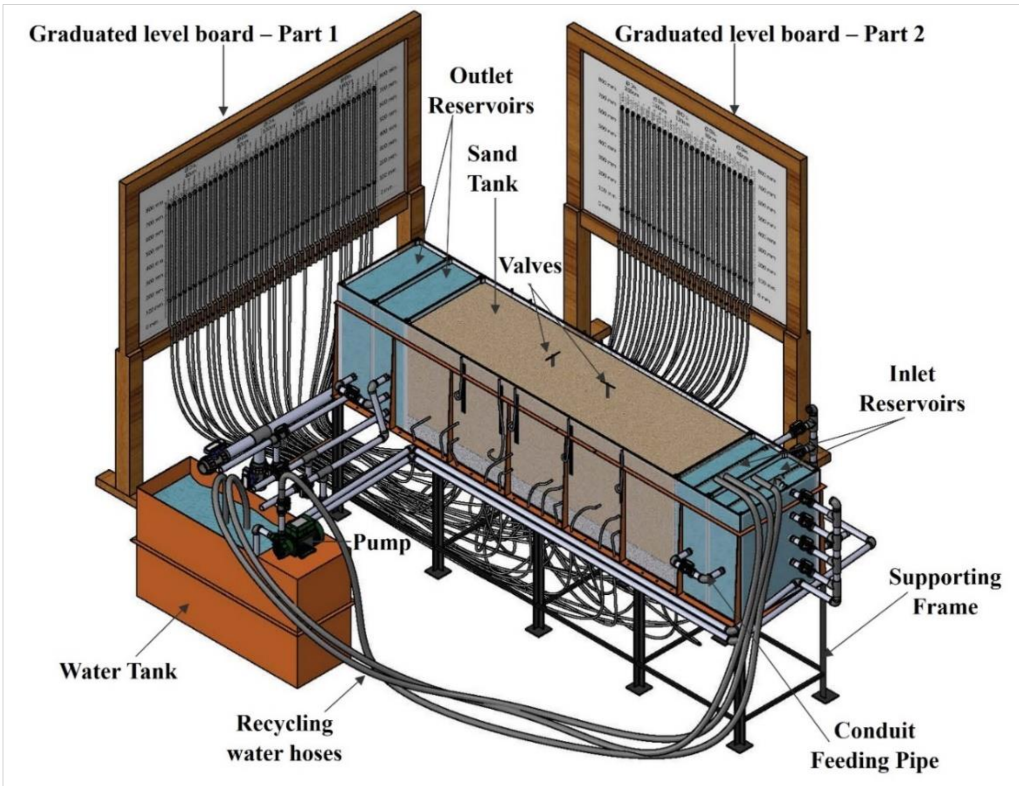

Fig. 2. Conceptual Model of the Experimental Setup in the 3D View.

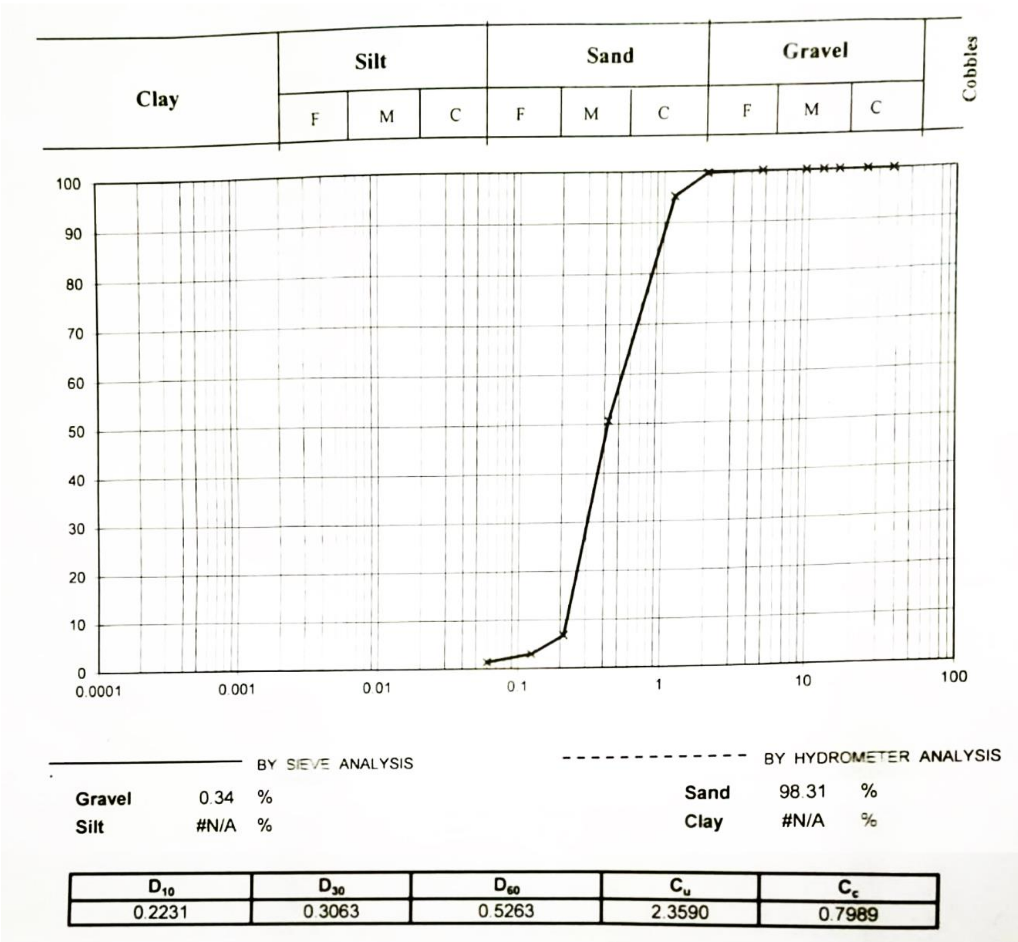

Fig. 3. The Matrix Medium's Particle Size Distribution (PSD) Curve.

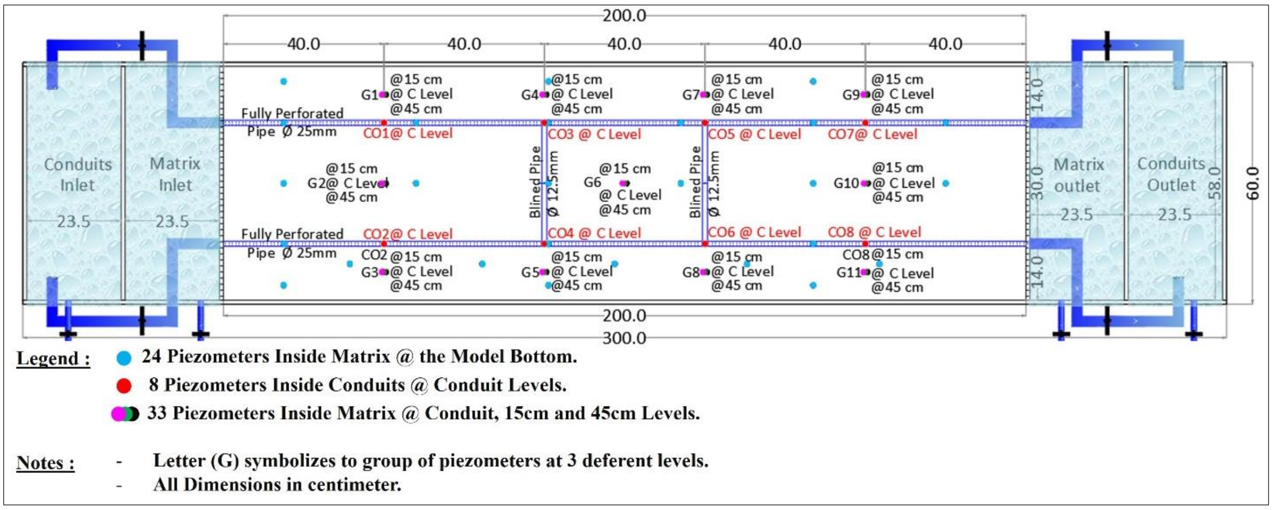

Fig. 4. Spatial distribution of piezometers throughout the experimental model in the plan view.

2.2. Experimental Tests

Two experiments were conducted to investigate the influence of conduit conductivity on flow exchange in a karst aquifer using an identical setup of hydraulic heads at both the upstream and downstream ends of the experimental model for either conduit feeding or matrix feeding. Two diverter valves at 0.80 and 1.20 from the upstream side were opened to connect the conduits and surrounding matrix fully. The experiments were performed when the hydraulic head of the conduits was higher than that of the matrix. The specified upstream heads for the conduit and matrix were 61.0 cm and 51.0 cm, respectively, while the specified downstream heads were 47.5 cm for the conduit and 46.4 cm for the matrix.

3. Results and Discussion

This study examines the impact of conduit connectivity on the flow exchange between the conduit and matrix domains when the conduit head is higher than the matrix head in both model directions. Hydraulic head contours have been interpolated from matrix and conduit head values to illustrate flow directions clearly. Comparing the hydraulic heads in **fig. 5** and **fig. 6** reveal identical behavior, showing that the proximity of the two conduits in Run 02 does not influence the results under the established laboratory settings relative to Run 01. In the single conduit scenario, the hydraulic heads remain stationary relative to the dual conduit situation, indicating that two conduits operating as drains enhance efficiency, as evidenced in the first and final thirds of the laboratory model. This observation corroborates the results of [4] experiment, affirming the validity of the laboratory experiments.

The inflows recorded from the conduits source into the laboratory model were 324 l/hr in Run 01 and 864 l/hr in Run 02, indicating a 267% increase in the dual conduit's scenario. The outflows from the conduits were 72 l/hr in Run 01 and 144 l/hr in Run 02, thereby twice the value observed in the dual conduits experiment. The inflows from the matrix source into the laboratory model were 576 l/hr in Run 01 and 36 l/hr in Run 02, indicating a 1600% increase in the single-conduit experiment. The matrix fluxes were the same in both scenarios at l/hr. **Table 1** summarizes the observed and determined parameters in both experiments.

Table 1. Measured and determined parameters of the experimental tests.

<table>
<tr><th rowspan="2">Run Series</th><th colspan="2">Matrix Heads (cm)</th><th colspan="2">Conduits Heads (cm)</th><th colspan="2">Matrix Flows (L/hr.)</th><th colspan="2">Conduits Flows (L/hr.)</th><th rowspan="2">Matrix Exchange (L/hr.) (C to M)</th></tr>
<tr><th>US Head</th><th>DS Head</th><th>US Head</th><th>DS Head</th><th>Inflow</th><th>Outflow</th><th>Inflow</th><th>Outflow</th></tr>
<tr><td>Run 01 (Single conduit)</td><td rowspan="2">52</td><td rowspan="2">46.4</td><td rowspan="2">61</td><td rowspan="2">47.5</td><td>576</td><td>792</td><td>324</td><td>72</td><td>446.40</td></tr>
<tr><td>Run 02 (Dual Conduit)</td><td>36</td><td>792</td><td>864</td><td>144</td><td>884.20</td></tr>
</table>

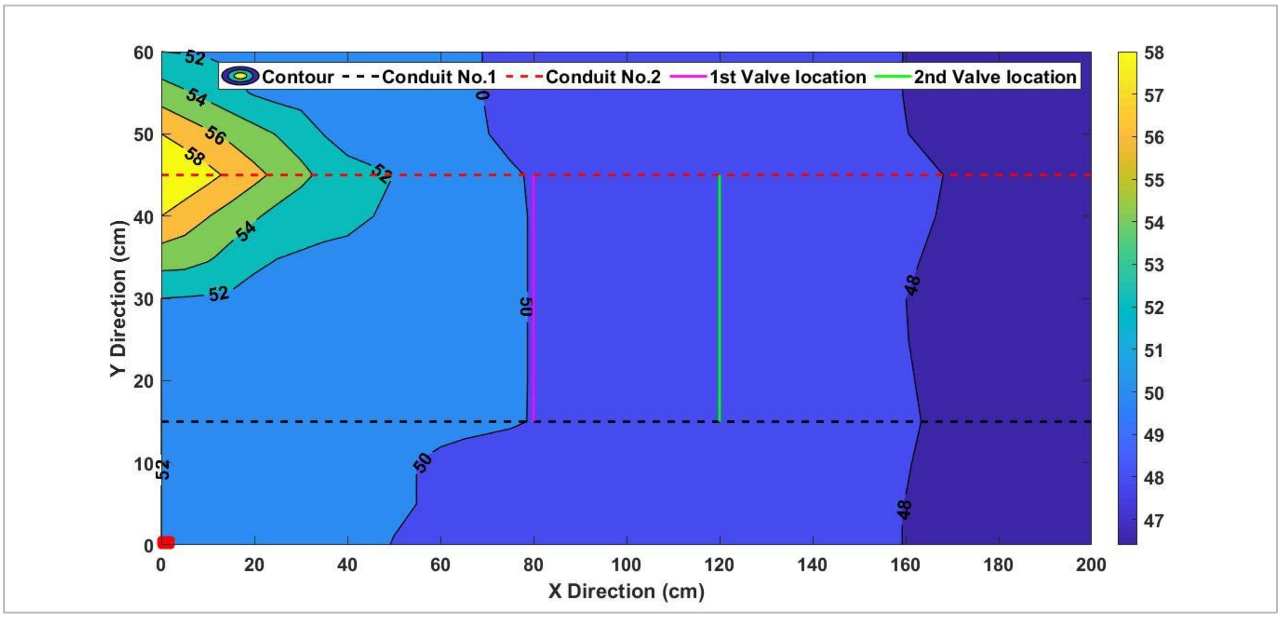

Fig. 5. Hydraulic Head Distribution at Single Conduit Level in Run 01.

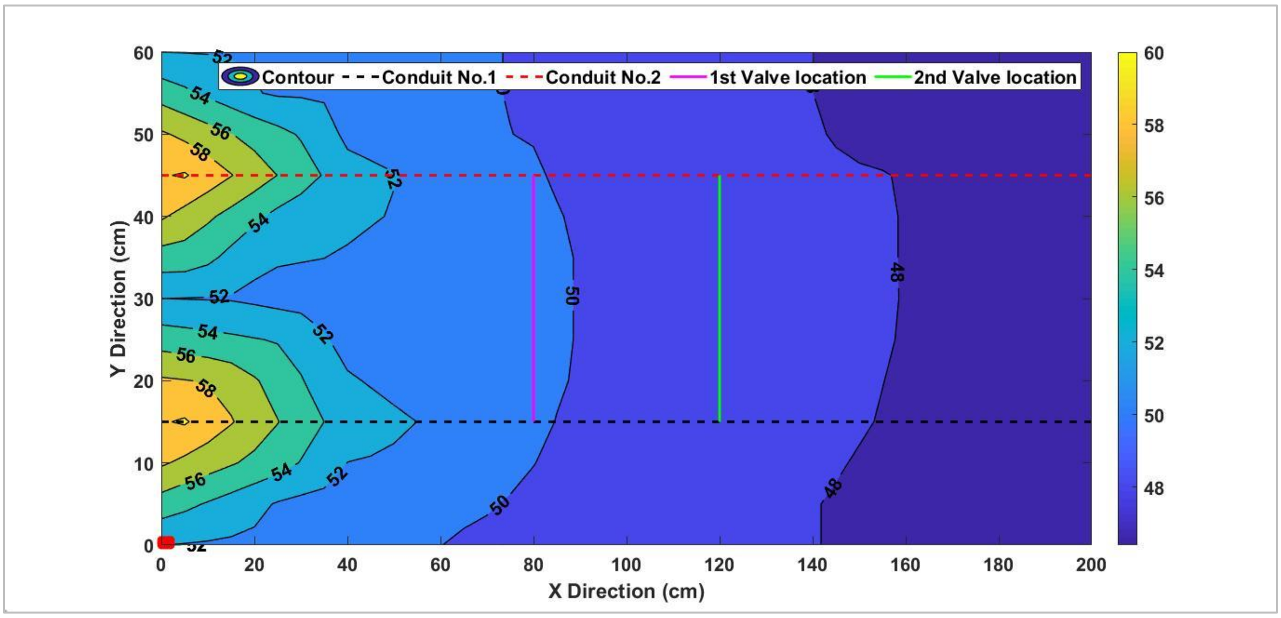

Fig. 6. Hydraulic Head Distribution at Dual Conduits Level in Run 02.

4. Conclusion

A physical scale model was constructed to simulate karst aquifer behavior, focusing on the role of conduit connectivity in flow exchange dynamics. This study addresses the lack of experimental evidence in this domain, providing new insights that emphasize the importance of dual-conduit systems. The results demonstrated a 100% increase in discharge rates and a 98% enhancement in flow exchange efficiency compared to single-conduit configurations. Maintaining steady hydraulic conditions ensured reliable comparisons, and the spatial distribution of hydraulic heads revealed consistent flow patterns from the conduits to the matrix. These findings can inform the design of groundwater management strategies and serve as a foundation for future research exploring variable conduit geometries and matrix conditions.

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