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EXPERIMENTAL INVESTIGATIONS OF THE EFFECT OF CONDUIT CONNECTIVITY ON FLOW EXCHANGE IN KARST AQUIFERS

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ABSTRACT

A 3D physical model (3.00×0.60×0.60m) was constructed using pipe-matrix coupling concept to investigate the effect of conduit connectivity on flow exchange between conduit network and matrix domain resembling karst aquifers. The conduit network was simulated by two horizontally connected perforated pipes, allowing the connection to be either enabled or disabled based on the specific experiment, through diverter valves. The conduit diameter was 0.50 inches, with a perforation ratio of 30%. Sandy soil was used to simulate the matrix domain. Four experiments were conducted to examine different cases: (1) a single flowing conduit unconnected non-flowing conduit, (2) a single flowing conduit connected to non-flowing conduit, (3) two unconnected flowing conduits, and (4) two connected flowing conduits. The matrix head was higher than the conduits in all experiments. Results indicated that the flow is from matrix to conduit in all cases with higher flow exchange in cases of connected conduits compared to the cases where the conduits are unconnected.

KEYWORDS: Karst aquifer, Karst flow, Experimental model, Matrix-conduit exchange.

دراسة معملية حول تأثير اتصال القنوات على تبادل التدفق فى الخزنات الجوفية ذات الشقوق والتكهفات

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الملخص

لمحاكاة طبقات المياه الجوفية ذات الشقوق والتكهفات، ولفهم أكثر تعمقاً لدراسة تأثير إتصال تلك الشقوق والتكهفات ببعضها على التدفق المتبادل بينها وبين الوسط المحيط لها، فقد تم إنشاء نموذج معملى ثلاثي الأبعاد بمقاسات (3.00 × 0.60 × 0.60 م) بإستخدام مفهوم الإرتباط بين مصفوفة التربة والقنوات الموجودة بها. ولتحقيق ذلك فقد تم إجراء أربعة تجارب، لمحاكاة شبكة

القنوات التى تمثل الشقوق أو التكهفات بواسطة أنبوبتين مثقوبتين أفقيتين بقطر نصف بوصة ونسبة تثقيب 30%، حيث يتم التحكم في اتصالهما طبقا للتجربة المراد اجراؤها باستخدام محابس تحكم بينهما، بينما تم استخدام الرمال لمحاكاة الوسط المسامي المحيط . تم اجراء أربعة تجارب الأولى لسريان المياه في أنبوبة واحدة فقط غير متصلة بالأنبوبة الأخرى. أما التجربة الثانية فهي لسريان المياه في أنبوبة واحدة متصلة بأخرى، وكانت التجربة الثالثة لسريان المياه في أنبوبتين غير متصلتين ببعضهما، فى حين كانت التجربة الرابعة لسريان المياه في أنبوبتين متصلتين معاً. وقد تمت جميع التجارب تحت ظروف حدودية واحدة وهى أن الضاغط الهيدروليكى للماء في الوسط الرملى الذى يمثل الوسط المسامي أعلي من الضاغط الهيدروليكى للمياه في الأنابيب والتى تمثل الشقوق. وقد أسفرت النتائج عن أن التدفق المتبادل من الوسط المسامي للقنوات يزداد فى حالة القنوات المتصلة عنه في القنوات غير المتصلة.

الكلمات المفتاحية : الطبقات ذات الكهوف والتشققات، تدفق الطبقات ذات الكهوف والتشققات، نموذج معملى، التدفق المتبادل بين الوسط المسامي للتربة والتشققات.

1. Introduction

Karst aquifers occupy around 15% of the world's land surface [1]–[4]. Karst aquifers have highly productive conduits that allow rapid recharge and flow of groundwater but provide little natural water storage. Approximately a quarter of the global population relies on water from karst aquifers [4]. Proper management of karst aquifers is important for sustainable water. The dual nature of groundwater flow in karst aquifers, characterized by both rapid flows dominated by conduits and slow flow through the matrix media [5] possessing various types of porosity and permeability [6].Conduits presence leads to a unique flow system marked by concentrated, high-velocity groundwater flow. The flow within these conduits can exhibit either laminar or turbulent characteristics[7].

Understanding and modeling groundwater flow in Karst aquifers present unique challenges for hydrologists due to the heterogeneous nature of karst, traditional investigation techniques often fail to characterize features controlling subsurface flows [8]. Rapid groundwater velocities through conduits also pose problems for monitoring-based characterization methods [9]. These complexities introduce uncertainties that hydrologic models struggle to reproduce, hindering management of these vulnerable but vital groundwater stores [10].

Experimental models play a crucial role in advancing our understanding of flow exchange dynamics within karst aquifers. These models enable scientists to simulate various hydrological conditions of karst aquifers and study the complex interactions that occur in them. A comprehensive laboratory and numerical investigation was conducted focusing on saline intrusion in fractured coastal aquifers [11]. Also, a laboratory analog and numerical study was offered to explore groundwater flow and solute transport in a karst aquifer [5]. The karst groundwater model with and without discrete conduit flow was compared by [6]. The water exchange, mixing, and transient storage was determined between a saturated karstic conduit and the surrounding aquifer [12].To investigate the spatio-temporal variability of water exchange between fissures and conduits in a karstic aquifer a laboratory and numerical simulations was conducted [13]. To get better understanding of karst aquifers, a comprehensive review of laboratory-scale models was conducted, providing an overview of different approaches and similitude considerations [14]. A 3D laboratory model was constructed to study the matrix-conduit exchange and the response of the aquifer to groundwater pumping. The results highlighted the influence of head difference, conduit size, and hydraulic gradient on matrix-conduit exchange [1].

The effect of conduits connectivity on flow exchange is still a challenging reach topic which has not been fully studied experimentally. The main objective of the current research is to build 3D physical model simulating karst aquifer to investigate the effect of conduits connectivity on flow exchange between matrix and conduit domains.

2. Experimental Work And Procedures

2.1. Model description

A 3D physical model with dimensions 3.00×0.60×0.60m was constructed in Irrigation and Hydraulics laboratory at Faculty of Engineering, Al-Azhar University, Egypt to simulate karst aquifer. **Fig. 1** presents a schematic of the laboratory model setup.

The model is built from acrylic Plexiglas and consists of 5 parts. The two separate left parts are the inlet flow reservoirs to both matrix and conduit domains. The intermediate part represents the karst aquifer, and the two separate right parts are the outlet reservoirs for matrix and conduit domains. The inlet and the outlet reservoirs have overflow pipes to control water levels upstream and downstream in each domain acting as a specified head boundary.

The conduit network is simulated using two parallel horizontal perforated PVC pipes which are placed along the longitudinal direction of the model and located at 0.20 m heigh above the model bottom. The conduits which occupy one and two-thirds of the model width are 0.50-inch in diameter with 30% perforation ratio. Geotextile was used to cover the conduits to prevent the infiltration of fine materials of the porous medium into the conduits. Two blinded pipes, equipped with diverter valves, were installed between the conduits at distances of 0.80 m and 1.20 m to simulate conduit connectivity, and the connection can be enabled or disabled depending on the experiment. The matrix media is represented by sand. Stainless-steel mesh, sealed with a geotextile membrane, was installed between the matrix and the matrix inlet and outlet reservoirs to prevent any movement of sand particles. **Fig. 2** shows a photograph of the laboratory model setup.

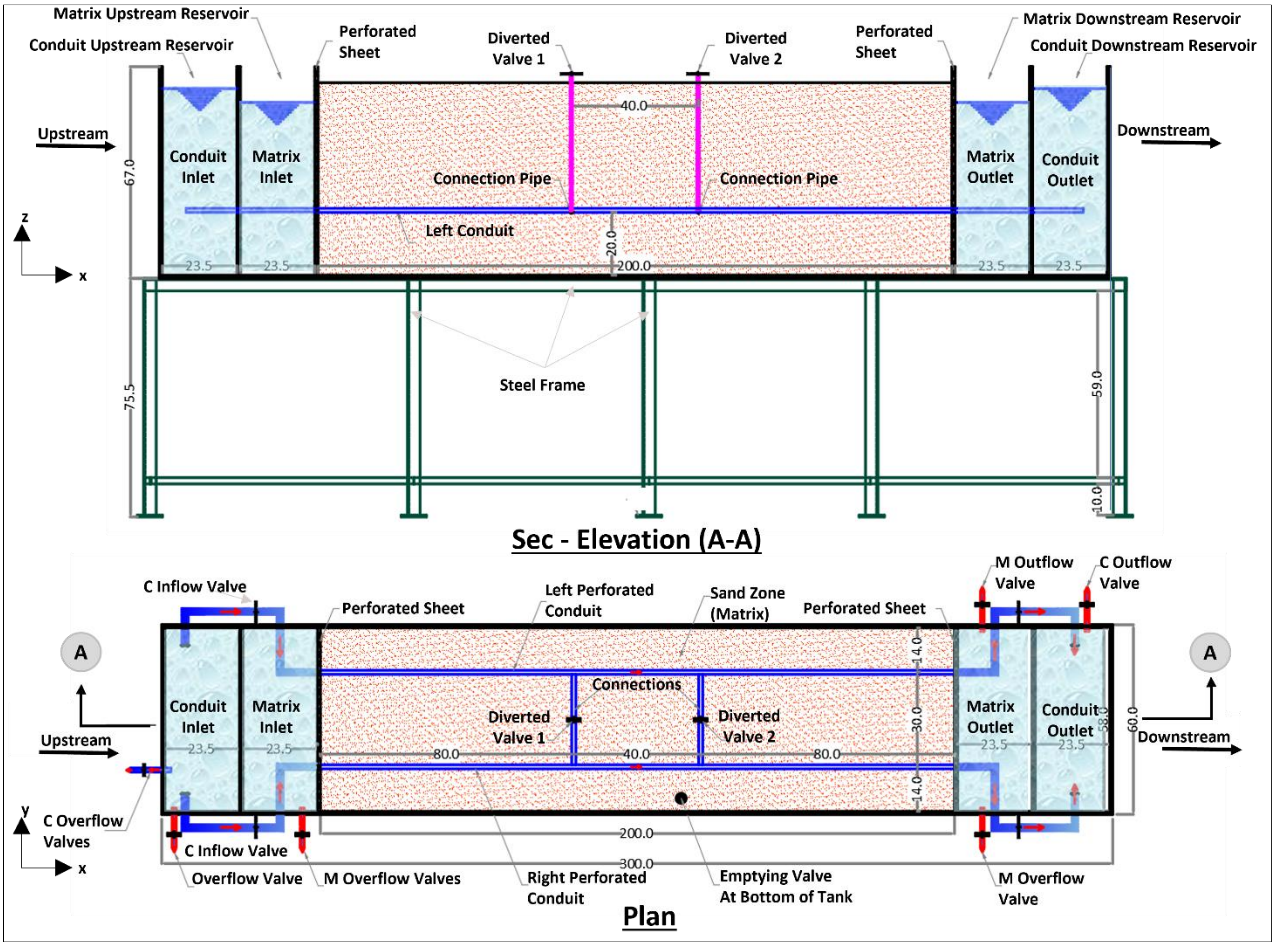

Fig. 1. Schematic of the laboratory model setup (Dimensions are in centimeters).

Fig. 1. Photograph of the laboratory model setup.

Pressure heads are measured using 65 piezometers, 8 piezometers are placed in the two conduits and 57 piezometers are placed in the matrix at four levels. Twenty-four (24

) piezometers are distributed 3 cm from the model base. Eleven (11) piezometers are distributed 15 cm from the model base. The third level contains 11 piezometers at 20 cm from the model base and the last 11 piezometers are placed at 45 cm from the model base. **Fig. 3** illustrates piezometers distribution along the experimental model.

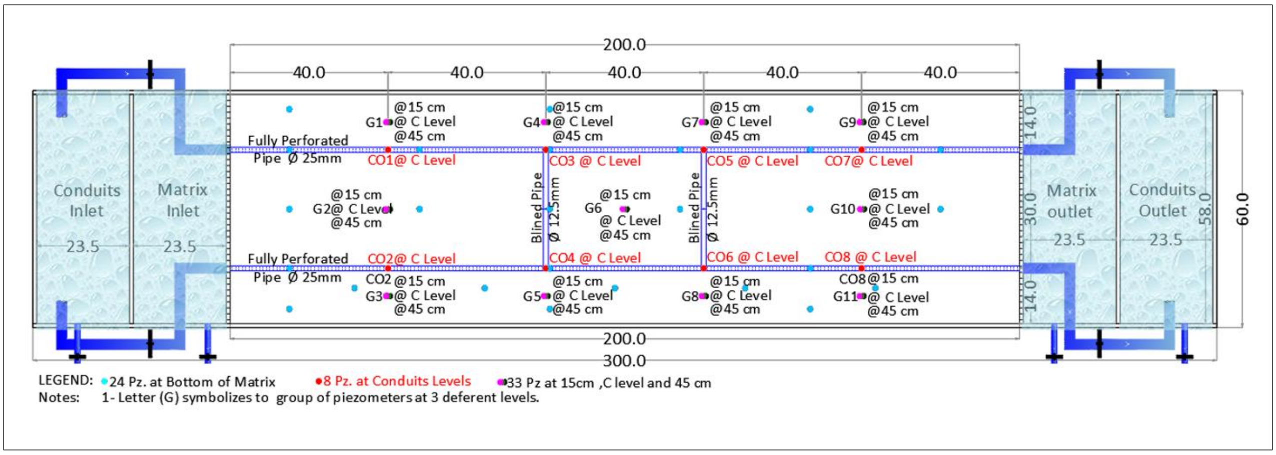

Fig. 3. Distribution of piezometers levels along the experimental model**.**

2.2. Experimental Tests

Four experiments are conducted to investigate the effect of conduit connectivity on flow exchange between conduit network and matrix domain resembling karst aquifers. Experiment 01 is conducted using a single flowing conduit (1) unconnected to non-flowing conduit (2) where conduit (2) is closed at its both ends, and the diverter valves are closed. The second experiment was identical to the first one but the diverter valves between the two conduits are opened to simulate connectivity in case of single flowing a single conduit. Experiment 03 simulates two flowing unconnected conduits to study the effect of conduit network connectivity. The fourth experiment differs from experiment 03 by connecting the two conduits to investigate connectivity through the conduits network. For all experimental tests, the upstream and downstream matrix and conduits heads are maintained constant so that the matrix head was higher than the conduit head.

3. Results and Discussion

To investigate the effect of conduit connectivity on the matrix-conduit flow exchange, hydraulic head contours are interpolated using both matrix and conduit head values to shows flow directions clearly. **Fig. 4** shows the hydraulic head distributions at a horizontal section along the conduits for the four conducted experiments. The horizontal X-axis and Y-axis represent the longitudinal and transverse directions of the model, respectively. measures are in centimeters. The left edge represents the upstream boundary, and the right edge represents the downstream boundary. The black and red lines represent conduit (1) and conduit (2), respectively.

It could be seen from the figure that the flow exchange is from matrix to conduit in all cases. By comparing **Fig.4.A** and **Fig.4.B.**, which presents the hydraulic head distributions in cases of single flowing conduit, one can see a similar pattern with almost a similar hydraulic head distribution. The same behavior is noted by comparing **Fig.4.C** and **Fig.7.D.**, which presents the hydraulic head distributions in cases of double flowing conduit.

To determine the flow exchange between conduits and matrix in studied cases, the inflow and outflow for the matrix and conduits domains are measured. Table (1) presents the values of inflow and the outflow discharges for both domains and the flow exchange of each experiment. The measures shows that the inflow to both matrix and conduits domain increases by increased the number of flowing conduits and the same behavior is observed in the outflow of both domains.

For single flowing conduit, it is observed that the flow exchange is found to be 0.10 L/s and 0.11L/s for experiments 1 and 2, respectively with 9.1% increasing value due to the connectivity between the flowing and non-flowing conduits. In the case of dual flowing conduits, the flow exchange is found to be 0.13L/s and 0.15L/s for experiments 3 and 4, respectively with 13.3% increasing value due to the connectivity between the two flowing conduits. Results of conducted experiments indicate that conduits connectivity increase the flow exchange from the matrix domain to the conduit.

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

Parameter / Experiment	**Experiment 01**		**Experiment 02**		**Experiment 03**		**Experiment 04**	
Flowing Conduit	Conduit No.1	Conduit No.2	Conduit No.1	Conduit No.2	Conduit No.1	Conduit No.2	Conduit No.1	Conduit No.2
	☑	☒	☑	☒	☑	☑	☑	☑
Matrix inflow (L/s)	0.31		0.31		0.37		0.35	
Matrix outflow (L/s)	0.20		0.21		0.22		0.22	
Conduits inflow (L/s)	0.03		0.02		0.05		0.04	
Conduits outflow (L/s)	0.14		0.12		0.20		0.17	
Flow exchange (L/s) (M to C)	0.10		0.11		0.13		0.15	

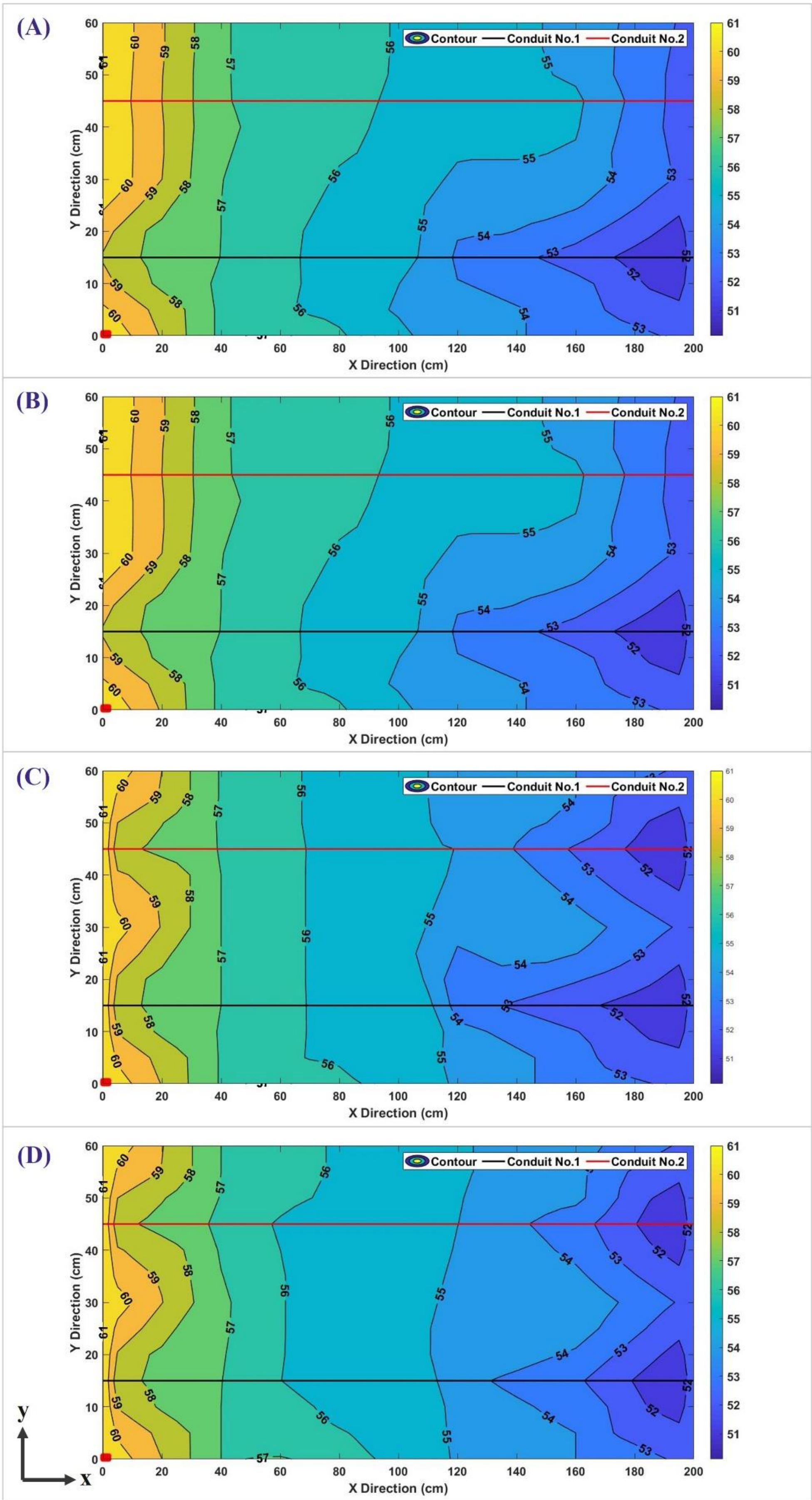

Fig. 4. Hydraulic heads distribution in a horizontal section at the conduits level for A) Experiment 01; B) Experiment 02; C) Experiment 03, and D) Experiment 04.

4. Conclusion

A 3D physical model with dimensions 3.00×0.60×0.60m was constructed to simulate karst aquifer. The conduit network is simulated using two parallel horizontal perforated PVC pipes which are placed along the longitudinal direction of the model. The matrix media is represented by sand. Four experiments are conducted to investigate the effect of conduit connectivity on flow exchange between conduit network and matrix domain resembling karst aquifers. For all experimental tests, the upstream and downstream matrix and conduits heads are maintained constant so that the matrix head was higher than the conduit head.

Measures of inflows and outflows for both matrix and conduits domains show that the flow exchange is from matrix to conduit in all cases, the inflow to both matrix and conduits domain increases by increasing the number of flowing conduits and the same behavior is observed in the outflow of both domains. For single flowing conduit, it is observed that the flow exchange is increased by 9.1% due to the connectivity between the flowing and non-flowing conduits. In the case of dual flowing conduits, an increase of 13.3% in flow exchange is observed due to the connection between the two flowing conduits.

5. Reference

[1] E. H. Amin, "Experimental study of hydrodynamics of groundwater flow in karst aquifers under stressed and unstressed conditions," MSc thesis, Cairo University, 2021.

[2] N. Goldscheider et al., "Global distribution of carbonate rocks and karst water resources," Hydrogeol. J., vol. 28, no. 5, pp. 1661–1677, Aug. 2020, doi: 10.1007/s10040-020-02139-5.

[3] B. Andreo, "Introductory editorial: Advances in karst hydrogeology," Environmental Earth Sciences, vol. 65, no. 8. pp. 2219–2220, Apr. 2012. doi: 10.1007/s12665-012-1621-3.

[4] D. Ford and P. Williams, Karst Hydrogeology and Geomorphology. Book, New York: Chichester, Wiley, 2013. doi: 10.1002/9781118684986.

[5] J. Faulkner, B. X. Hu, S. Kish, and F. Hua, "Laboratory analog and numerical study of groundwater flow and solute transport in a karst aquifer with conduit and matrix domains," J. Contam. Hydrol., vol. 110, no. 1–2, pp. 34–44, 2009, doi: 10.1016/j.jconhyd.2009.08.004.

[6] S. P. Saller, M. J. Ronayne, and A. J. Long, "Comparison of a karst groundwater model with and without discrete conduit flow," Hydrogeol. J., vol. 21, no. 7, pp. 1555–1566, 2013, doi: 10.1007/s10040-013-1036-6.

[7] S. Bauer, R. Liedl, and M. Sauter, "Modeling of karst aquifer genesis: Influence of exchange flow," Water Resour. Res., vol. 39, no. 10, 2003, doi: 10.1029/2003WR002218.

[8] N. Goldscheider and D. Drew, Methods in karst hydrogeology: IAH: International Contributions to Hydrogeology, 26. Crc Press, 2014.

[9] B. R. Scanlon and A. Dutton, "Groundwater Recharge in Texas," Bur. Econ. Geol., no. March, pp. 1–62, 2002, [Online]. Available: http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=pubmed&cmd=Retrieve&dopt=AbstractPlus&list_uids=7020174552600114951related:54vl9icRvgkJ

[10] A. Hartmann, M. Mudarra, B. Andreo, A. Marin, T. Wagener, and J. Lange, "Modeling spatiotemporal impacts of hydroclimatic extremes on groundwater recharge at a Mediterranean karst aquifer," Water Resour. Res., vol. 50, no. 8, pp. 6507–6521, 2014.

[11] G. Etsias et al., "Laboratory and numerical investigation of saline intrusion in fractured coastal aquifers," Adv. Water Resour., vol. 149, no. July 2020, p. 103866, 2021, doi: 10.1016/j.advwatres.2021.103866.

[12] S. Binet, E. Joigneaux, H. Pauwels, P. Albéric, C. Fléhoc, and A. Bruand, "Water exchange, mixing and transient storage between a saturated karstic conduit and the surrounding aquifer:

Groundwater flow modeling and inputs from stable water isotopes," J. Hydrol., vol. 544, pp. 278–289, Jan. 2017, doi: 10.1016/j.jhydrol.2016.11.042.

[13] L. Shu, Z. Zou, F. Li, P. Wu, H. Chen, and Z. Xu, "Laboratory and numerical simulations of spatio-temporal variability of water exchange between the fissures and conduits in a karstic aquifer," J. Hydrol., vol. 590, no. May, p. 125219, 2020, doi: 10.1016/j.jhydrol.2020.125219.

[14] Z. Mohammadi, W. A. Illman, and M. Field, "Review of Laboratory Scale Models of Karst Aquifers: Approaches, Similitude, and Requirements," Groundwater, vol. 59, no. 2. Blackwell Publishing Ltd, pp. 163–174, Mar. 01, 2021. doi: 10.1111/gwat.13052.