Geotechnical Challenges for Underground Infrastructure in Qatar: Hydrogeological Assessment for Dewatering and Deep Excavation Works: South of Wakrah Pumping Station and Outfall (SWPSO) Project

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Abstract

The evaluation of hydrogeological conditions and groundwater inflows, as part of the geotechnical risk assessment, poses one of the key challenges during the design and construction of major infrastructure projects and underground works. This paper presents an example of a recently developed geotechnical and hydrogeological investigation program for the Pre-Tender design of the South of Wakrah Pumping Station and Outfall project in Qatar, where a comprehensive hydrogeological study was carried out to characterize heterogeneous hydrogeological conditions along the project area and to determine potential impacts on the groundwater levels drawdown and groundwater inflows during excavation and dewatering activities. The results of the hydrogeological evaluation concluded that a proper groundwater management approach and mitigation measures are required at an early stage of the project to minimize the impact on dewatering, groundwater inflows and groundwater levels drawdown for construction works. A similar approach can be adopted for future infrastructure projects to support the geotechnical risk assessment and to minimize the impact of construction activities on the environment.

Keywords: Hydrogeological assessment; Permeability; Dewatering; Deep excavations; Groundwater management

1 Introduction

In Qatar, the Vision for efficient mass transit and resilient urban drainage infrastructure, with recent rapid urbanization and extreme weather events, motivated a massive increase in the construction of underground infrastructure projects in a short span of time. Given unknown ground conditions, the pioneering tunnelling and underground projects like the Doha Metro, the Inner Doha Resewerage Implementation Strategy (IDRIS) and most recently the Doha South Terminal Pumping Station (DSTPS) and the Musaimeer Pumping Station and Outfall (MPSO) faced challenges to identify and quantify the geotechnical risks and to develop an appropriate risk mitigation approach for underground works, to guarantee the completion of the projects on time and within budget.

Although the extensive experience gained during the execution of these major infrastructure projects in Qatar has led to a better understanding of the geotechnical risks, the role of hydrogeological conditions in geotechnical risk assessment is still one of the key challenges during engineering design and construction stages. The assessment of karst environment and associated groundwater inflows and dewatering requirements for the construction of deep underground works require a considerable amount of time and resources against the tight schedules of the projects.

Thus, it is of paramount importance to carry out a detailed hydrogeological risk evaluation during the early stages of the project to minimize the impact of unknown ground and groundwater conditions. This paper presents an example of a recently developed geotechnical investigation program for the pre-tender design of the South of Wakrah Tunnels, Pumping Station and Outfall project, where a comprehensive hydrogeological study was carried out to characterize heterogeneous hydrogeological conditions along the tunnel, shafts and pumping station areas and to be able to determine potential impacts on: (1) the environment (e.g., expected groundwater levels drawdown, barrier effect and groundwater resources discharge), and (2) the project (groundwater inflows, dewatering, ground improvement requirements). As a result, we assessed the mitigation measures for the future excavation of pumping station and screening shafts and propose a groundwater management approach to support the geotechnical risk assessment and to minimize the impact of construction activities for future infrastructure projects.

2 Project Background

2.1 Ground Investigations

The South of Wakrah Pumping Station and Outfall project is one of the key capital projects in the State of Qatar, whose major goal is to provide a long-term optimum strategic drainage system for stormwater and groundwater in the catchment area. Most of the project challenges come from the construction of deep underground structures (i.e., tunnels and shafts), with variable groundwater conditions and presence of karstic deposits.

The geology of the project area comprises thin Quaternary deposits (<2m thick), followed by a sequence of horizontally layered sedimentary rocks with Simsima Limestone, Midra Shale and Rus Formations reaching the full depth of the projected civil works. The main geotechnical hazards identified for the construction of the underground works are: (i) the presence of karstification, cavities and caverns and (ii) shallow groundwater levels, presence of underground channels and potential high groundwater inflows.

Due to the large size of the underground works (i.e., pumping station of approximately 80 metres diameter and 60 metres depth and tunnel diameters ranging from 4.5 to 8.5metres ID), with the associated risks, it was required to carry out a comprehensive hydrogeological assessment to quantify the expected groundwater inflows for dewatering requirements and to evaluate the impact of potential groundwater levels drawdown during construction activities. The executed ground investigation works for the pumping station area included the drilling of 33 boreholes (60-80metres deep), together with 120 packer permeability tests and a pumping test tomography to test both shallow and deep aquifers. In addition, 12 observation wells and 6 standpipe piezometers were utilized to monitor groundwater levels during the execution of the in-situ testing program.

2.2 Geological Model

The geotechnical and hydrogeological model was prepared based on the findings of the ground investigations program. The following general geological sequence and main description has been defined for the 3D geological model (Figure 1):

- Quaternary Deposits (QD): Superficial layers of sand fill with material as light brown silty, gravelly to very gravelly, fine to medium sand.
- Simsima Limestone (SL): In the conceptual model corresponds to the Upper aquifer, typically described as a buff to pale brown chalky crystalline limestone with siltstone inclusions, variably dolomitic.
- Midra Shale (MS): Aquitard unit, typically described as yellow-brown laminated occasionally fissile shale, fossiliferous with limonite and phosphatic nodules, with thin bands of limestone. Its lateral continuity is variable, and its thickness is considerably reduced in some areas of the domain.
- RUS Limestone (RL): Lower aquifer, cyclic deposition of weak carbonate marls, siltstones, thin limestones and chalk.
- RUS Gypsum (RG): Lower Aquifer, typically described as anhydrite and gypsum with marl and thin limestone

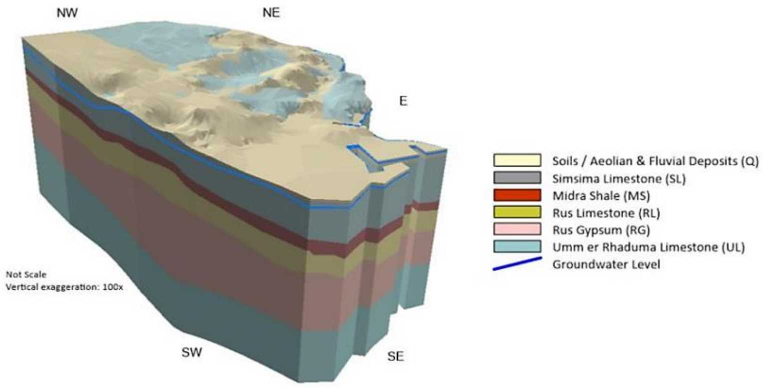


Fig. 1: 3D Geological Model South of Wakrah Project Area

3 Results and Project Implementation

3.1 Hydrogeological Modelling Strategies

Based on the compilation of previous information, and the new geological and geotechnical data, we defined the hydrogeological conceptual model (CM) of the study area. This CM consist of a saturated medium, which considers the groundwater level variations in the aquifers of South Al Wakrah, due to natural processes and the drawdowns induced by pumping in the industrial sector and the dewatering preformed during the construction of tunnels and pumping stations. Various sources of information have been consulted for the development of technical reports and the groundwater numerical model proposal. Once the CM is defined, it is possible to develop Numerical Models (NM) capable of quantifying the hydrogeological processes of interest. To define the expected models it is necessary, to have a proper assessment of the hydrogeological conditions of the area of study, by adopting the following methodology:

- Conduct a desktop survey of the project’s available data; collect background geological and hydrogeological information outlining the characteristics of the major aquifers and aquitards, existing groundwater levels and permeability values, to establish an initial 3D hydrogeological CM.

- Design the packer permeability and pumping tests at each location of interest (i.e., location, depth, flowrates).
- Technical review of the permeability tests and procedures implemented during drilling, collation, and processing of the pumping test data to derive the aquifers' parameters, required as input data for the dewatering modelling.
- Assessment of local and catchment Hydrogeological NM at each location of interest followed by the calibration of the models with the available short-term data.
- Complete the simulations of the various dewatering scenarios, provide conceptual groundwater control measures, provide estimates of groundwater inflows and surrounding impacts, and produce a dewatering schedule for design and construction purposes.

In order to implement the proposed methodology, three different kinds of modelling procedures are required: (1) to process the pumping test data to derive the aquifers' parameters, required as input data for the dewatering modelling; (2) to quantify the dewatering requirements and predict the characteristics of the drawdown (estimate pumping flow rate, maximum drawdown, radius of influence, etc.); and (3), to simulate the various dewatering scenarios for shafts and tunnels (both, during the construction and in their final stage), providing conceptual groundwater control measures, estimates of groundwater inflows and surrounding impacts, and developing a dewatering schedule for design and construction purposes.

3.2 Numerical Models for Processing the Pumping Test Data

Pumping tests design: To design an effective drainage system, it is essential to know the permeability (hydraulic conductivity) and storage coefficient of the different geological layers involved. This requires the execution and later interpretation of pumping tests. The interpretation of the pumping tests is based on monitoring the evolution of the piezometric level (drawdown) produced by a determined pumping flow rate. Various methods of quantification of hydraulic parameters can be used depending on the type of test and the heterogeneity of the terrain. If the terrain is homogeneous and the well and piezometers are totally penetrating the hydrological units, conventional analytical formulas can be applied (i.e.: Theis or Jacobmethods) using common pumping test interpretation software. By contrast, when the terrain is heterogeneous and the wells or piezometers are partially penetrating, the analytical formulas are not applicable, and it is necessary to use numerical flow models to calibrate and estimate the values of the parameters.

In the area of South Wakrah Pumping Station, the terrain has a high degree of heterogeneity. This largely determines the specific design of the drainage system. Thus, it is necessary to establish the specific design elements required for the execution of pumping tests (number of pumping wells and observation piezometers), their specific characteristics, and a proposal of activities to measure piezometric levels in wells and piezometers, as well as pumping rates. In this project, the pumping tests general proposal consist of one or two pumping wells, and six to nine piezometers to measure the evolution of the drawdown and recovery of the piezometric levels. An example of the pumping test configuration at the pumping station area is presented in Figure 2.

From the six piezometers, two of them will be open (slotted sections) in Simsima Limestone

Formation, two in Rus Formation, two in Rus Gypsum Formation, and the other two all along their length, in the same way, that their corresponding pumping well. It is important to define a clear protocol that reflects the important tasks to be carried out before, during, and after the test, as well as the solution to possible problems that may arise during the pumping test. Despite some additional tests (i.e. Step Drawdown Test), the pumping test will consist of three days of pumping and, at least, the same period for recovery. Measuring the groundwater heads and the flow measurements are crucial in the interpretation of the pumping test, at an acceptable frequency defined in the protocol. All these measurements are performed by, both, manual and data logger procedures in order to have a highly consistent and error-free measurements data set. Three different areas were selected for the pumping test deployment in order to be representative of the whole study area. These areas are (1) inland; (2) pumping station; and (3) coastal area.

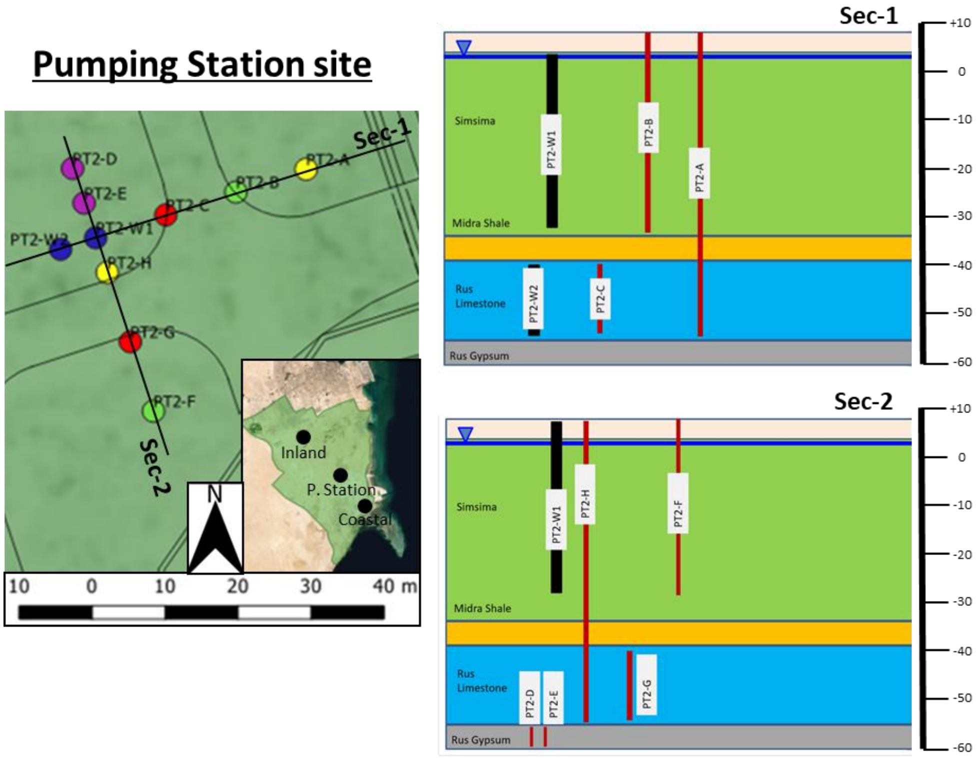


Fig. 2: Pumping test design at Pumping Station site

Pumping test interpretations: The aquifer characteristics which are evaluated by most aquifer tests are: Permeability; Specific storage or Storativity; and transmissivity. Additional aquifer characteristics are sometimes evaluated, depending on the type of aquifer, including: Specific yield; Leakage coefficient and the presence of aquifer boundaries. In this case, as a general procedures in each pumping test interpretation, it was necessary to provide: (1) Conceptual Model (CM): CM definition and constrains in each aquifer test site previous to perform Pumping Test (PT) interpretation; (2) Methods: The use of the selected pumping test interpretation methods, and its related assumptions, has to be properly justified and documented; and (3) Results: Once the interpretation is finished all information related the pumping test interpretation results have to be clearly provided.

Within the framework of this project and to have great guarantees that the results are of high quality and representative of the properties of the site, various methods have been applied for pumping test interpretation with respect to each parameter:

1. The following analytical methods were utilized to provide the Equivalent Hydraulic parameters of all hydrogeological sections:
   - Conventional Jacob adjustment method: applied to constant rate pumping test.
   - Pumping test software interpretation: applied to constant rate pumping test and step pumping test.
2. The following three numerical models were performed to provide the specific Hydrogeological Unit Hydraulic parameters:
   - Multilayer plan view model (Constant Rate Pumping test).
   - 2D axisymmetric model (Constant Rate Pumping test).
   - 2D axisymmetric model (Step Pumping test).

The hydraulic parameters obtained by the four pumping test in the three sites are consistent, with significant differences, as summarized in Table 1.

Table 1: HU hydrogeological parameters at each pumping test site

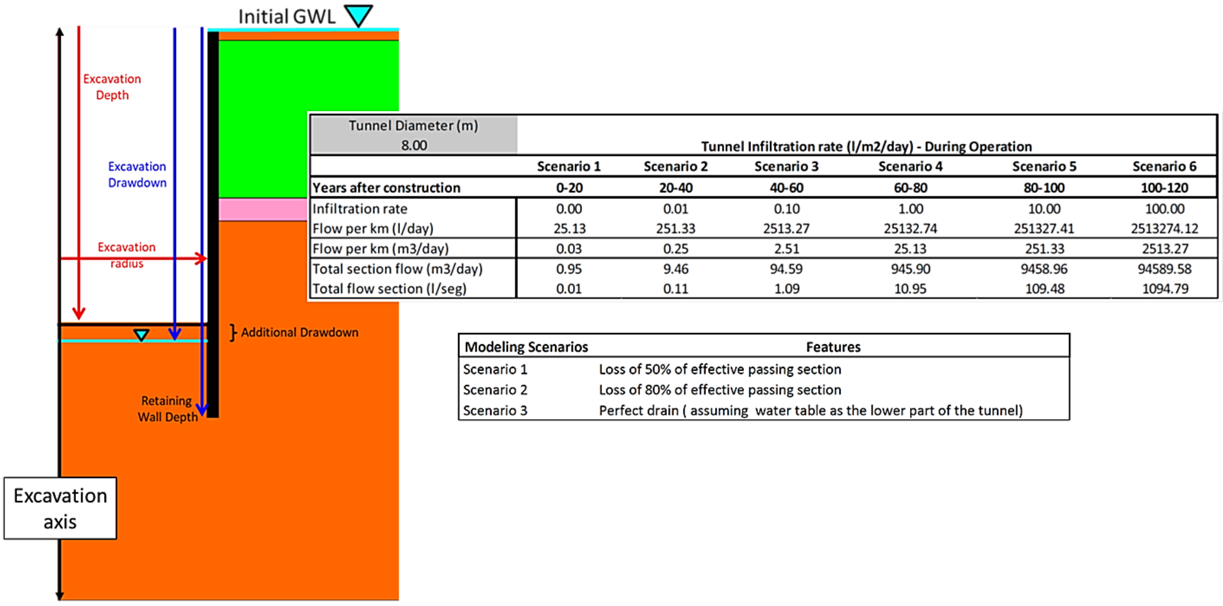
	Permeability - K(m/d)			**Storativity - S**		
Hydrogeological Units (HU)	**Inland PT**	**Pumping Station PT (x2 tests)**	**Coastal PT**	**Inland PT**	**Pumping Station PT (x2 tests)**	**Coastal PT**
QUATERNARY			2.73			4.00E-02
W. SIMSIMA			0.76			3.80E-05
SIMSIMA	8.4	155	44	0.017	0.045	2.78E-05
MIDRA	0.0014	1.7	0.24	9.20E-06	4.40E-03	3.32E-05
RUS	0.034	1.9	0.3	5.54E-06	3.70E-04	4.05E-05
RUS GYPSUM		0.008			2.85E-06	

The models' results provided by different methods and models in each site are very consistent. Adjustments results statistics and validation indicators are very good. The results provide confident parameters. Simsima Unit is the most permeable HU in the three sites (44-155 m/d) and constitutes the main aquifer. Midra, Rus and Rus gypsum have very low permeability (0.001 - 2 m/d) and both are considered aquitards. The less permeable area is the inland site; the most permeable (2 orders of magnitude higher) is the pumping station area. These results are consistent with the observed intense karstic development in the Pumping Station area. This intense karst development was identified by means of a comprehensive geological and geophysical works carried out in this area.

3.3 Numerical Models to Quantify the Dewatering Requirements

For the execution of the shafts of South Wakrah Pumping Station and Outfall, it is planned to excavate below the groundwater table. Excavation needs to be done in safe and drained conditions. To design an effective dewatering system, it is essential to know the permeability, storativity and boundary conditions of the different geological layers involved. Once these parameters are appropriately quantified by means of pumping test interpretation, it is possible to quantify the groundwater flow rates required for the shaft dewatering purposes and the groundwater level drawdown (magnitude and extension) caused by the dewatering pumping rates. The objective is to quantify the dewatering requirements and predict the characteristics of the drawdown (estimate pumping flow rate, maximum drawdown, radius of influence, etc.). This requires adequate simulation and dewatering quantification in each required shaft by means of groundwater modeling. Various dewatering simulations have been performed related to the selected examples: Inland Shaft; Pumping Station screen and pumping Shafts; and a Coastal Shaft.

Two different dewatering modelling procedures are performed: (1) Multilayer Plan View model and (2) Cross Section models. In both cases, aquifers are considered isotropic (Kv=Kh) and anisotropic (Kv=10·Kh) for the different hydrogeological units. All these models are based on those performed for pumping test interpretations and include all layers defined in each site, with their corresponding geometry, depth, thickness, hydraulic properties, etc. Additionally, we apply design conditions for dewatering quantification as; (1) Excavation depth; (2) Shaft Diameter; (3) Retaining walls; etc. The basic design parameters are summarized in Figure 3.



Tunnel Diameter (m) 8.00	Tunnel Infiltration rate (l/m2/day) - During Operation					
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Years after construction	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**100-120**
Infiltration rate	0.00	0.01	0.10	1.00	10.00	100.00
Flow per km (l/day)	25.13	251.33	2513.27	25132.74	251327.41	2513274.12
Flow per km (m3/day)	0.03	0.25	2.51	25.13	251.33	2513.27
Total section flow (m3/day)	0.95	9.46	94.59	945.90	9458.96	94589.58
Total flow section (l/seg)	0.01	0.11	1.09	10.95	109.48	1094.79

Modeling Scenarios	Features
Scenario 1	Loss of 50% of effective passing section
Scenario 2	Loss of 80% of effective passing section
Scenario 3	Perfect drain (assuming water table as the lower part of the tunnel)

Fig. 3: Basic design parameters for dewatering simulations modelling – Top table: Simulation scenarios for different infiltration rates. Bottom Table: Simulation scenarios for barrier effect

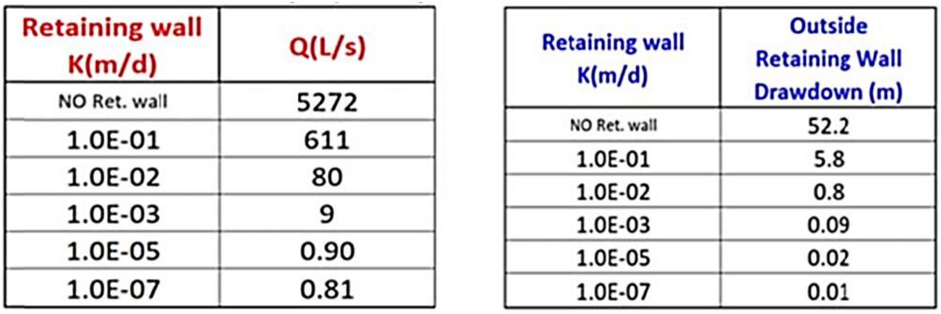
Note that for Retaining walls design, some considerations and challenges could arise. In this case, it is recommended the use of cut-off walls, mostly without any load-bearing function, that basically consist of a vertical slurry wall with very low water permeability to minimize the groundwater flow. In this regard, the following cut-off wall types can be implemented: (1) Cut-off walls constructed using diaphragm wall techniques; (2) Secant pile walls from concrete of slurry; (3) Thin slurry walls; (4) Grout Injection walls; and (5) Freezing walls. As these last details are not defined in this stage of the project, here the quantification of the dewatering flow rate and related effects are performed taking into consideration a wide range of possibilities. These different scenarios correspond to:

- No Retaining walls.
- Moderate permeability Retaining walls (equivalent permeability: 0.1 to 0.01 m/d).
- Low permeability Retaining walls (equivalent permeability 0.001 to 0.00001 m/d).
- Very low permeability Retaining walls equivalent permeability < 10e-7 m/d).

“Equivalent permeability (K)” refers to the final permeability of the Cut-off wall once it is implemented. This means the integrated permeability includes: construction method, materials, width, execution quality (joints, defects, etc.). During the implementation of the projects a design equivalent permeability must be guaranteed, which must be defined according to the dewatering requirements.

In the performed scenarios the necessary pumping rates and the impact of the drawdown have been calculated based on the “equivalent permeability”, and 6 different scenarios have been simulated in each case. As a result, the relationship between the equivalents K of the retaining walls related the required flow rate can be defined according to a graphic function. The application of all this modelling methods shows that the differences between Plan View and X-Section models are very little and are caused by the slight differences between the models. Furthermore, differences between isotropic and anisotropic results are also very few. In the case of anisotropic model, flow rate results are slightly lower. This is due that in the bottom of the shaft the flow is essentially vertical. In Table 2 it is possible to observe the relationship between the equivalents K of the retaining walls related the required flow rate corresponding Pumping Station Shaft. This function will be useful for assigning the “equivalent permeability” requirements in the project. Furthermore, the expected drawdown produced by the dewatering in the entire domain of the model has been calculated. As an example, the Table 2 summarizes the drawdown calculated on the outside of the Cut-off wall corresponding Pumping Station Shaft site. In all cases the implementation of Cut-off walls greatly reduces the drawdown outside the excavation.

Table 2: Dewatering scenarios in the Pumping Station Shaft.
Left: dewatering pumping rates. Right: Outside Cut-off wall drawdown



Retaining wall K(m/d)	Q(L/s)
NO Ret. wall	5272
1.0E-01	611
1.0E-02	80
1.0E-03	9
1.0E-05	0.90
1.0E-07	0.81

Retaining wall K(m/d)	Outside Retaining Wall Drawdown (m)
NO Ret. wall	52.2
1.0E-01	5.8
1.0E-02	0.8
1.0E-03	0.09
1.0E-05	0.02
1.0E-07	0.01

According to the results presented in Table 2, it is important to highlight that:

- Inland Access shat pumping rates are low (< 60 L/s). It is possible to dewater the shaft without considering cut-off walls.
- In the Pumping Station area (Screen Shaft and Pumping Shaft) very high flow rates are expected. It will be very difficult to dewater these shafts without considering cut-off walls.
- In the Coastal Area high flow rates are expected. It will be difficult to dewater these shafts without considering cut-off walls. The moderate permeability of the bottom of the excavation (Rus Unit) produces considerable up flow to the dewatering excavation bottom. Significant both, pumping rates and drawdown, will be produced, even considering low permeability retaining wall values.

3.4 Numerical Models to Determine Potential Impacts

For the execution of the shafts of South Wakrah Pumping Station and the construction of the tunnel, it is planned to excavate below the groundwater table. These actions could modify the original geological settings of the layers, causing possible impacts on the distribution of the water table and flow direction. The main objective of these numerical models is to understand the steady-state and transitory conditions of the aquifers in the area to help assess the construction of the South Wakrah Pumping Station and Sea Outfall Project.

This Project is located in the southern sector of Al Wakrah (Qatar), and the model area covers a total area of 552 square kilometres. The area is limited to the East by the sea and to the west by a groundwater contour line. The North and South limits are defined by the flow directions lines. As mentioned before, the limits of the domain have been defined considering the project area and according to hydrogeological criteria, the reason why the final area of the model is greater than the one initially defined in the project (Figure 4). The numerical model was built using the finite element code FEFLOW v.7.4, which solves the flow equation in a saturated underground medium. FEFLOW allows the adaptation to complex geometries and the incorporation of geological structures through unstructured meshing.

Discretization involves dividing the modelling domain into a series of individual elements. The finite element method solves the groundwater flow equation at the vertices of mentioned elements and/or within each of them. The limits of the domain of the numerical model are conditioned by the geometry and extension of the aquifers, so its discretization must be adapted to these characteristics and to the existing singular elements. To achieve optimal discretization, it is especially important to consider the areas that are most sensitive to flow and those areas in which the greatest hydraulic gradients are expected, since only with a good distribution of elements can they be reproduced mathematically with a minimum error. The 3D domain has been divided into 371,810 elements and 223,818 nodes (Figure 4). The different hydrogeological units (UH) are represented by using five layers in the model, which have been described in the previous sections (Figures1 and 4):

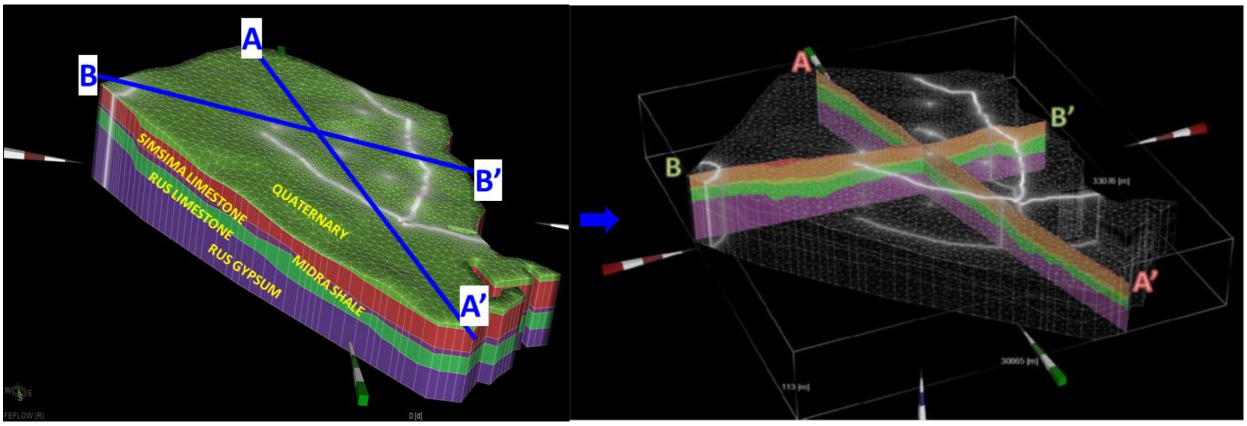


Fig. 4: 3D hydrogeological model domain, discretisation and cross sections examples

The hydrogeological **parameters** assigned to the aquifer units are considered as a basis for the calibration process. The interpretation of these pumping tests provided information on permeability and storativity, these values oscillate considerably depending on their geographic positions due to the high grade of heterogeneity and karstification features. For the reason mentioned before, an approximation was made to obtain the general value for the different layers, with the objective of representing the general distribution of the water levels in the model.

Different **boundary conditions** were implemented (Figure 5): The no flux condition is intended to impose an impervious boundary. It has been considered null flow in all those contours of the model in which there is no exchange of water between the modelled domain and the outside (or is negligible). This condition has been considered for (1) the basal surface: represents the lower limit, the contact between the aquifer unit with the basement is considered hydraulically impervious; and (2) the lateral contours: the south and north limits are defined and determined by the flow direction, where the northern limit corresponds to a watershed and on the other hand the southern limit corresponds to a line parallel to the flow direction. The prescribed level condition corresponds to levels that are well known during the modeled period. Based on this, two prescribed level limits were defined: (1) Sea: This boundary condition is defined throughout the eastern limit and corresponds to the coastline; and (2) Sinkholes: It is applied to the westernmost part of the model and corresponds to the average of the water table in the sinkhole. The prescribed flux boundary conditions are implemented to represent the piezometric dynamics and water level distribution in the numerical model due to the anthropic effects, example; the effects of the drawdowns produced by the pumping wells and infiltration rates of the tunnel: (1) Current extraction wells and their pumping rates were defined based on previous studies of the area; (2) Tunnel drain rate: The tunnel drain rate is related with the surface of the tunnel and their infiltration rates, the infiltration rates increase as the years pass, according to the design, the life of the tunnel is 120 years. The drain rate was calculated for the whole tunnel section.

After reviewing and filtering the last updated database of observed hydraulic heads we have selected a total of 138 **observation points** that have been used to calibrate the model in a stationary state and to estimate the general hydraulic parameters (Figure 5). Once the model is calibrated, it is possible to implement the various simulation scenarios

The modelling of the **simulation's scenarios** consisted of (1) a steady-state model to determine the initial conditions and previous hydrogeological conditions before the construction works; and (2) quantifying tunnel hydrogeological impacts under different scenarios, including, both, tunnel infiltration and barrier effect simulations.

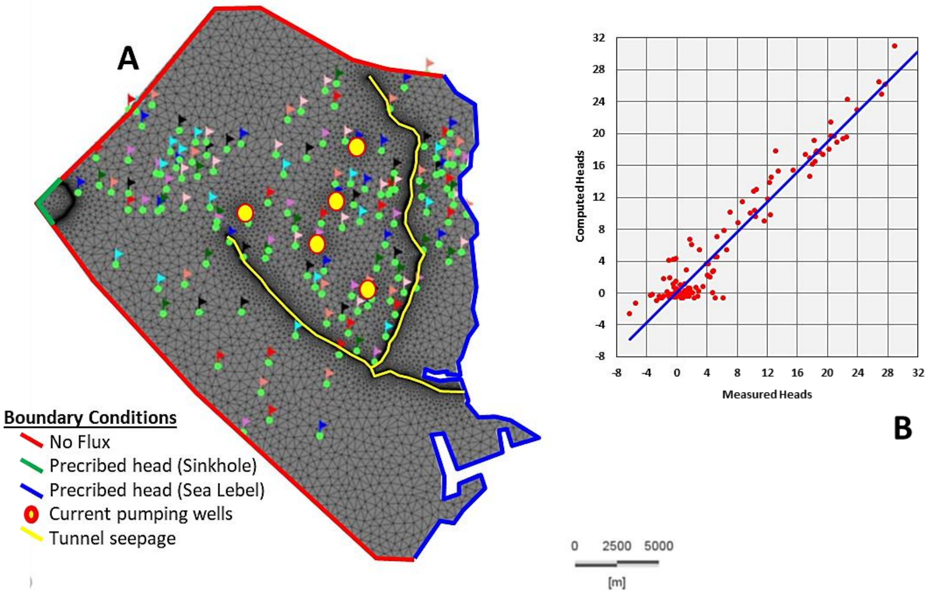
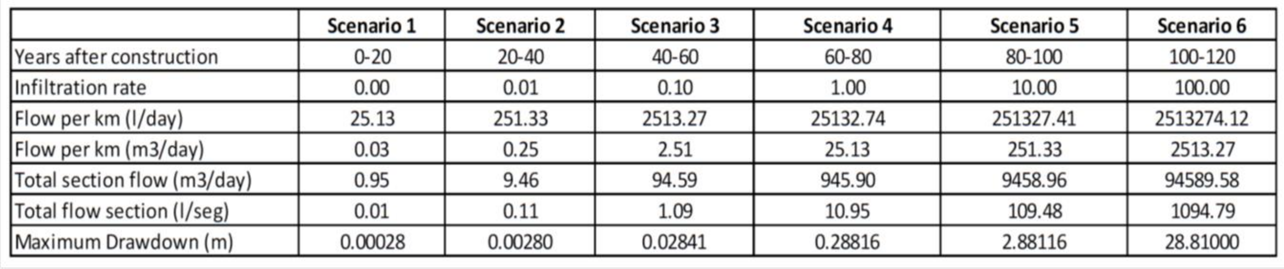


Fig. 5: A: Plan view of geographical location of the boundary conditions for the Simulations models. B: Stationary Model calibration results, observed vs. simulated levels

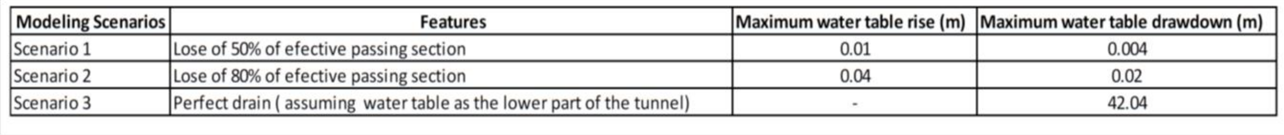
Tunnel infiltration simulations: Given that the construction level of the tunnel is below the water table, there is the possibility that this structure acts as a drain. Considering that the tunnel will be a precast segmental lining and that there will be an increase in infiltration rates as the years pass (design life is 120 years), the following infiltration rates scenarios for a tunnel of 8 metres of diameter are suggested (Figure 6, Table 4):

Barrier effect simulations: As a result of the construction of the tunnel, there is a loss of the effective passage section for groundwater, which will result in a rise or fall of the water table in the vicinity of the tunnel. The possible ascent/descent will be proportional to the loss of the effective passage section as well as to the direction of the flow. To represent the possible barrier effect different scenarios are proposed (Figure 6, Table 3).

Table 3: Calculated Flow Rates and Drawdowns corresponding the simulated scenarios



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Years after construction	0-20	20-40	40-60	60-80	80-100	100-120
Infiltration rate	0.00	0.01	0.10	1.00	10.00	100.00
Flow per km (l/day)	25.13	251.33	2513.27	25132.74	251327.41	2513274.12
Flow per km (m3/day)	0.03	0.25	2.51	25.13	251.33	2513.27
Total section flow (m3/day)	0.95	9.46	94.59	945.90	9458.96	94589.58
Total flow section (l/seg)	0.01	0.11	1.09	10.95	109.48	1094.79
Maximum Drawdown (m)	0.00028	0.00280	0.02841	0.28816	2.88116	28.81000



Modeling Scenarios	Features	Maximum water table rise (m)	Maximum water table drawdown (m)
Scenario 1	Lose of 50% of efective passing section	0.01	0.004
Scenario 2	Lose of 80% of efective passing section	0.04	0.02
Scenario 3	Perfect drain (assuming water table as the lower part of the tunnel)	-	42.04

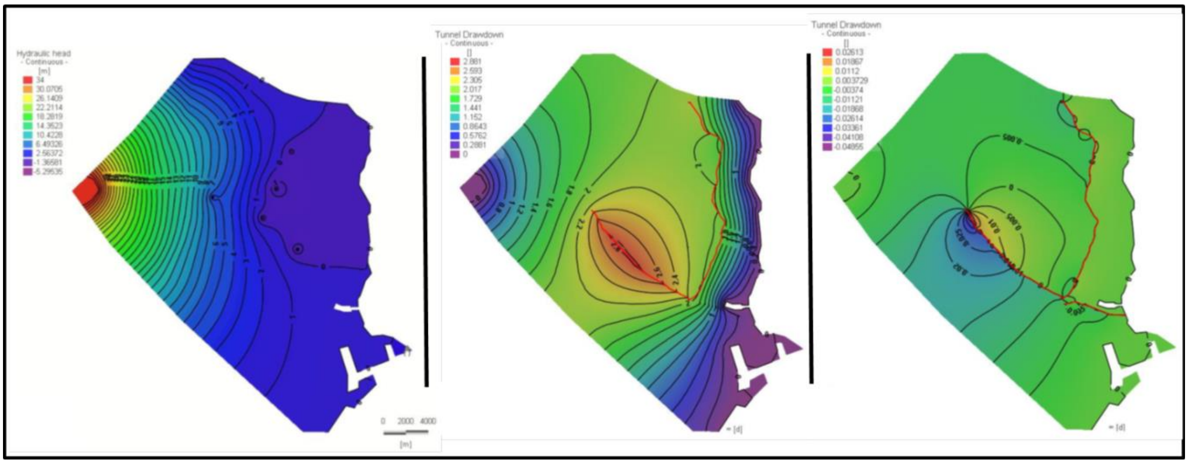


Fig. 6: Model results corresponding to: **(a)** current steady state piezometry; **(b)** tunnel infiltration scenario 5; **(c)** tunnel barrier effect scenario 2

4 Conclusion

This paper presents an example of a recently developed geotechnical investigation program for the pre-tender design of the South of Wakrah Pumping Station and Outfall project. A comprehensive hydrogeological study was carried out to characterize heterogeneous hydrogeological conditions along the project area and to be able to determine potential impacts on the environment and on the project. Complete geological and geotechnical data has been utilized to define the hydrogeological conceptual model of the study area, which made it possible to develop numerical models capable to quantify the hydrogeological processes of interest.

Three different kinds of modelling procedures were required: (1) for processing of the pumping test data to derive the aquifers' parameters, required as input data for the dewatering modelling; (2) to quantify the dewatering requirements and predict the characteristics of the drawdown; and (3), simulations of the various dewatering scenarios related shafts and tunnels.

As a result, we assessed the mitigation measures for future excavation of pumping station and screening shafts and propose a groundwater management approach to support the geotechnical risk assessment and to minimize the impact of construction activities for future infrastructure projects. In consequence, we propose a groundwater management approach to support the geotechnical risk assessment and to minimize the impact of construction activities for future infrastructure projects.

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