

Deep Injection Wells for Flood Prevention and Groundwater Management

Mohammad R. Jafari, Francois G. Bernardeau

Abstract—With its arid climate, Qatar experiences low annual rainfall, intense storms, and high evaporation rates. However, the fast-paced rate of infrastructure development in the capital city of Doha has led to recurring instances of surface water flooding as well as rising groundwater levels. Public Work Authority (PWA/ASHGHAL) has implemented an approach to collect and discharge the flood water into a) positive gravity systems; b) Emergency Flooding Area (EFA) – Evaporation, Infiltration or Storage off-site using tankers; and c) Discharge to deep injection wells. As part of the flood prevention scheme, 21 deep injection wells have been constructed to discharge the collected surface and groundwater table in Doha city. These injection wells function as an alternative in localities that do not possess either positive gravity systems or downstream networks that can accommodate additional loads. These injection wells are 400-m deep and are constructed in a complex karstic subsurface condition with large cavities. The injection well system will discharge collected groundwater and storm surface runoff into the permeable Umm Er Radhuma Formation, which is an aquifer present throughout the Persian Gulf Region. The Umm Er Radhuma formation contains saline water that is not being used for water supply. The injection zone is separated by an impervious gypsum formation which acts as a barrier between upper and lower aquifer. State of the art drilling, grouting, and geophysical techniques have been implemented in construction of the wells to assure that the shallow aquifer would not be contaminated and impacted by injected water. Injection and pumping tests were performed to evaluate injection well functionality (injectability). The results of these tests indicated that majority of the wells can accept injection rate of 200 to 300 m³/h (56 to 83 l/s) under gravity with average value of 250 m³/h (70 l/s) compared to design value of 50 l/s. This paper presents design and construction process and issues associated with these injection wells, performing injection/pumping tests to determine capacity and effectiveness of the injection wells, the detailed design of collection system and conveying system into the injection wells, and the operation and maintenance process. This system is completed now and is under operation, and therefore, construction of injection wells is an effective option for flood control.

Keywords—Deep injection well, wellhead assembly system, emergency flood area, flood prevention scheme, geophysical tests, pumping and injection tests, Qatar geology.

I. INTRODUCTION

IN recent years, the incidents of surface water flooding and rising groundwater level have increased in Qatar, and specifically in capital city of Doha. These increases are related to the ongoing and rapid urbanization taking place across the State of Qatar (see Fig. 1).

All reported flooding incidents are reported to and

continuously monitored by the PWA/ASHGHAL Operation and Maintenance (O&M) Department. The PWA O&M Department developed a database that is continually being updated to incorporate all incoming reported flooding complaints – each of which is given a unique identifier Flooding Hotspot reference. Current number of hotspots in the database reached 863.



Fig. 1 Flash flood in capital city of Doha

In November/December 2016 PWA was tasked with undertaking a root and branch review of 247 of the reported flooding hotspots and preparing a Flood Prevention Scheme (FPS) program to identify, design, and construct a solution to address each flooding hotspot.

For each flooding hotspot case, the primary aim of the program of works was to:

- Assess existing ongoing and upcoming planned construction projects to establish if such projects can deliver a resolution to the flooding hotspot problem;
- Review existing design proposals (pre-tender) that if constructed and implemented would resolve the flooding hotspot issue;
- In the absence of a solution from the previous two bullet points to resolve the flooding hotspot problem to develop an emergency interim solution that can be fully implemented and constructed.

For this reason, the design philosophy has been prepared to set the overall context for the program of works then to explore the technical issues and finally to support the final flooding hotspots mitigation recommendations. Technical solutions considered:

- 1) The existence of high ground water that will affect the design solution;
- 2) The type of system discharge outlet employed in the final design and whether it is a recommended temporary or permanent design solution. Examples of system discharge

M. R. Jafari is with CDM Smith Inc, Doha, Qatar (phone: +974-3369-10181; fax: +974-4436-2882; e-mail: jafarimr@cdmsmith.com).

F. G. Bernardeau is with CDM Smith Inc, Doha, Qatar (phone: +974-6618-0675; fax: +974-4436-2882; e-mail: bernardeaufg@cdmsmith.com).

outlets include:

- i. Discharge into downstream positive gravity systems.
- ii. Emergency Flooding Area (EFA/pond) – Evaporation, infiltration or storage with tankering.
- iii. Discharge to deep injection wells under gravity.

The disposal of storm water and shallow groundwater using deep injection wells may have both positive and negative impacts on the environment. On the positive side, it is environmentally attractive because:

- i. Storm water runoff is permanently removed from the biosphere, when the technology is properly applied. Successful deep injection well systems do not adversely impact the environment or human health.
- ii. Injection well systems have a minimal surface footprint and once constructed do not significantly impact local environments.
- iii. Deep injection wells are not aesthetically objectionable. Deep injection wells are not visually intrusive, do not generate noise, and do not have odor or dust issues.

On the negative side, migration of the injected water out of the injection zone could adversely impact groundwater resources and other groundwater users. Another potential issue could be the effects of the storm water interacting with the formation in the injection zone that may, on the long run, result in a level of dissolution of the formation's minerals affecting the well integrity.

II. PROJECT DESCRIPTION

A. FPS – Network Details

During early stage of FPS program, it was discovered that some of the drainage networks could not be connected to existing positive (gravity) system due to the lack of such system or risk of overloading downstream networks and creating flooding elsewhere. The optimal interim drainage solution for these areas is to discharge into the deep injection wells. These wells were identified in Al Wakrah, Al Khor and across Doha in Meibaireek, Muaither South, Nuaija, Al Duhail South and Al Dayeen. A typical layout of such network is presented in the Fig. 2. In Fig. 2, the red line presents the drainage network which collects the surface storm water and the groundwater and discharge it to the injection wells. The shown example network will provide surface and groundwater drainage in Meibaireek for a catchment of approximately 2 km².

A typical section of a drainage system is shown in Fig. 3. Along the network perforated drainage pipe and granular trench fill will cater for two distinctive inflows to the system:

- i. A nominal sustained base flow of groundwater during dry season,
- ii. Combined baseflow (groundwater) and peak storm water runoff,
- iii. Perforated pipe will act as a soakaway system if the pipe is full and groundwater table is below the perforated pipe.

Storm runoff will be diverted from impermeable surfaces (asphalt, walkways etc.) into the underground network through

road gullies, catch pits and manholes. The coarse suspended fractions carried by the runoff will be captured by GRP baskets suspended inside of every gully.

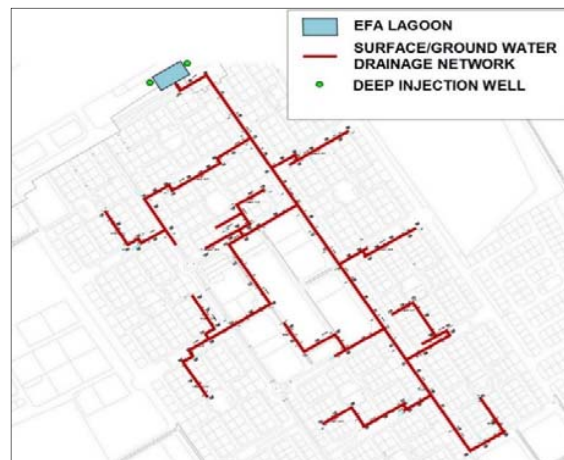


Fig. 2 FPS project in Meibaireek, Doha (FPS09)

1. Flow Assessment

Injection wells will be used to discharge groundwater from networks of perforated pipes throughout the year and rainfall events during the rainy season into the injection wells under gravity.

Based on drainage design models established for the FPS projects and the findings of the Drainage Master Plan Study, it is estimated that for the great majority of time in any given year a groundwater will be discharged into the deep injection wells with a small duration of storm runoff (up to 48h discharge). It means that, for 99.5% of time, more than 95% of total flow volume will come from the groundwater and only 0.5% of the time from surface runoff. The percentage breakdown is shown in Table I.

Due to the fast track nature of the entire FPS program and non-existence of the networks, it was not be possible to establish credible flow volumes from the catchments to the deep injection wells. Preliminary assumptions for expected average and peak injection volumes are 4500 m³/day and 9500 m³/day, respectively and will need to be verified after the first 12 months of the operation of the injection wells. Each deep injection well will be fitted with an electromagnetic flowmeter which will record injected volumes versus time.

B. Project Locations

As part of the FPS, a total of 21 deep injection wells, 14 shallow and 12 deep monitoring wells were implemented in 12 sites in different urban areas of greater Doha City in Qatar.

Drainage network connections to the injection wells are implemented only for 10 sites (Site 1, 2, 3, 4, 5, 8, 9, 10, 12, 14) in the current program phase. Drainage systems will be installed in the remaining sites (Site 6,11) at a later stage.

Fig. 4 provides an overview of the site locations for the current project.

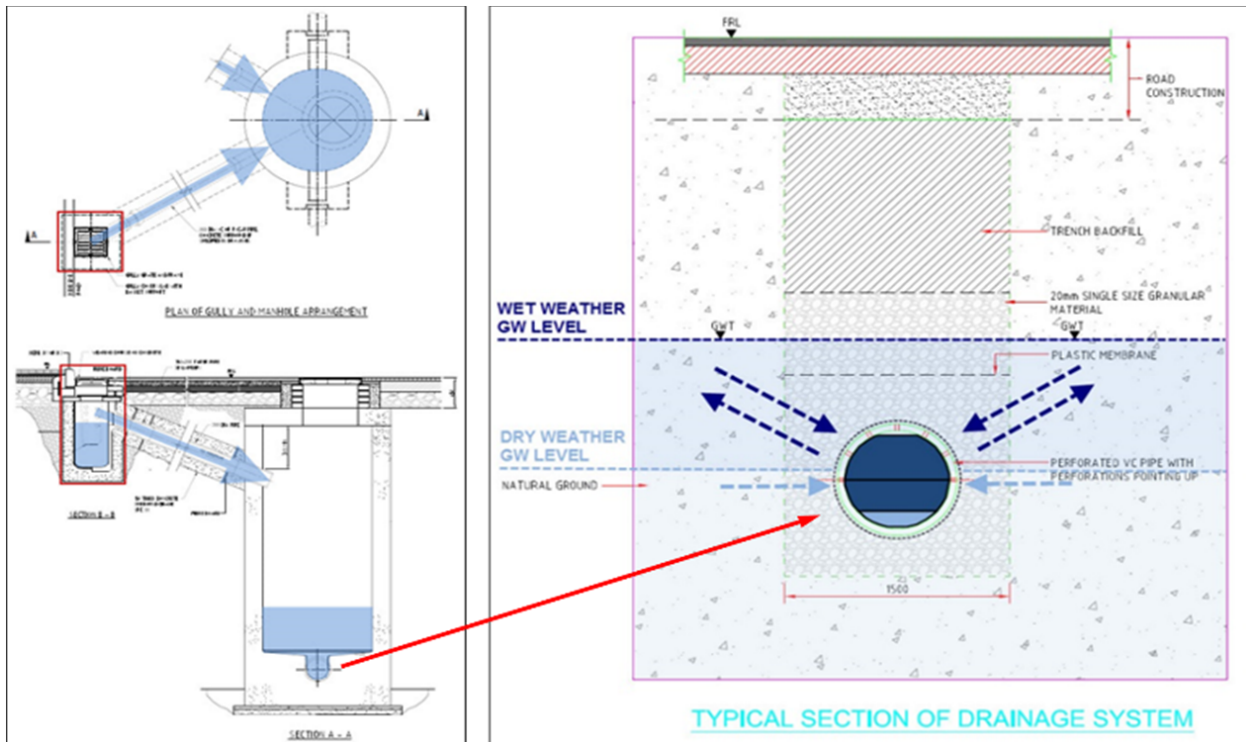


Fig. 3 Typical plan and section of road gullies and perforated drainage pipe

Table II provides the number of wells proposed for each location.

TABLE I
TIME AND VOLUME COMPARISON FOR PROJECT FPS09

FPS 09	Groundwater Baseflow	Groundwater & Storm Water Runoff (%)
Time	99.5 %	0.5 %
	363 days	2 days
	>95	<5%
Volume	620,000 m ³ /y*	27,000 m ³ /y**
	*Recharge rate 0.31 m/m ² /y (2062)	
	* Storm 1 in 10 y 24 hours	

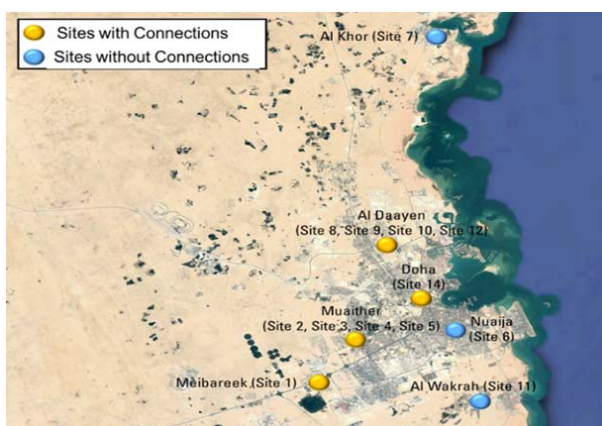


Fig. 4 Overview of the project sites in Doha City

C. Deep-Well Injection of Storm Water and Shallow Groundwater

TABLE II
PROJECT WELLS AND SITES

Site Name	Injection Wells	Deep Monitoring Wells	Shallow Monitoring Wells
FPS 09_Site 1	2	1	2
FPS10 A_Site 2	2	1	1
FPS10 B_Site 3	2	1	1
FPS10 C_Site 4	2	1	2
FPS10 D_Site 5	1	1	1
FPS11_Site 6	2	1	1
FPS14 A_Site 8	2	1	1
FPS14 B_Site 9	1	1	1
FPS14 C_Site 10	2	1	1
FPS14 D_Site 12	1	1	1
FPS 19_Site 11	2	1	1
FPS 16_Site 14	2	1	1
Total	21	14	12

Sites with network connections implemented.
Sites without network connections implemented.

Injection wells are used throughout the world for water and wastes disposal. Injection wells, as broadly defined, range from shallow cesspits and dry wells to deep wells that may be completed over 1,000 m below ground surface. Deep injection wells, such as those constructed in the past around the City of Doha, inject excess water into confined aquifers with the intention of permanently isolate it from the surface biosphere.

A properly designed and functioning deep injection well system will discharge collected groundwater and storm surface

runoff into a permeable zone that is separated from overlying aquifers and surface environments by essentially impermeable confining unit. The injection zones for deep injection well systems typically contain saline water that is not being used for water supply. The groundwater in the deep storage zones has stagnant or very slow groundwater movement and long retention times.

Injection wells are widely used and have been intensely scrutinized in the United States. The United States Environmental Protection Agency (USEPA) concluded that underground injection reduces human exposure to organic and inorganic chemicals, and heavy metals by removing them from the environment. However, while deep well injection is not inherently dangerous, and can contribute to the protection of human health and the environment, it will only be safe if constructed properly [1]. The critical technical issue is the effectiveness of the confining strata above the injection zone to prevent upwards migration of the injected fluids into overlying aquifers.

III. GENERAL GEOLOGY AND HYDROGEOLOGY

A. General Geology

Information on the geology and hydrogeology of the 13 injection well sites was obtained based on existing drilling and literature. The sequence of the geology in the Qatar Peninsula can be summarized as in Table III.

TABLE III
GEOLOGICAL SEQUENCE OF THE QATAR PENINSULA

Hydrogeologic Unit	Geologic Formation	Approximate Thickness	Description
Shallow Aquifer	Dammam Formation	45 to 50 m	Interbedded and intermixed limestone, dolomite, gypsum, and anhydrite
Gypsum Unit	Rus Formation	40 to 60 m	Predominantly gypsum and minor anhydrite and dolomite
Injection Zone	Umm er Radhuma Formation	> 250 m	Predominantly dolomite, minor gypsum and anhydrite

The shallow aquifer consists of limestone, dolomite, gypsum, and anhydrite, which are part of the Lower to Middle Eocene-aged Dammam Formation. The upper part of the Dammam Formation at the injection well sites consists predominantly of limestones and dolomitic limestones.

The lower part of the Dammam Formation is more lithologically diverse and contains interbedded limestones, silty limestones, gypsum, dolomitic limestone, and chert. The Dammam Formation strata encountered at most of the deep injection well sites appear to belong (from top down) to the Umm Bab Member (aka. Simsima Member), Durkham Member, and Midra Shale Member [2].

The Rus Formation consists of a series of gypsum beds, one to six meters thick, that are separated by interbedded dolomitic beds with varying limestone (calcite) and clay contents. The

presence of beds of evaporite minerals (gypsum with minor anhydrite) can be readily detected in geophysical logs. This gypsum unit separates the shallow aquifer from the deeper injection zone. Depending upon its hydraulic properties, the gypsum unit may be a confining or semi-confining (very low to low permeability) unit between the injection zone and shallow aquifer.

The formation, which outcrops in the core of the Qatar central arch, as well as in the Dukhan anticline, varies in thickness from 20 – 110 m and is dominated by soft dolomite limestone with occasional layers of intercalated green/brown attapulgite clay.

A feature of the Rus formation is the occurrence of evaporites, mainly gypsum with minor anhydrite. Continuous gypsum beds are not present in the Rus formation in the northern part of Qatar, as shown in Fig. 4, reflecting a syndepositional control rather than subsequent dissolution [3].

Qatar is divided into a Northern Province of the Rus formation characterized by the depositional carbonate to residual sulphates facies (without evidence of gypsum confining unit), and a Southern Province characterized by mainly depositional sulphate facies consisting of anhydrite and gypsum.

Both layers create an isolation layer or aquitard between the Umm Er Radhuma (UER) deep aquifer and the surface aquifers. Exploratory drilling in the Al Khor area for other projects identified a non-permeable formation (i.e. chert and compact dolomite) between approximately 75 – 85 m below ground level (bgl), which provides substantially similar hydraulic isolation for the proposed injection conditions.

The UER Formation is an aquifer present throughout the Gulf Region [4]. The UER Formation consists of a thick succession of carbonates (white/grey/brown vesicular dolomite, dolomite limestone, and limestone) over calcareous shales at the base, which acts as a hydraulic barrier to the Aruma formation below it. There are siliceous parts of the sequence comprised of chert and silicified limestone; however, the formation is remarkably uniform in the State of Qatar.

Argillaceous and gypsiferous deposits occur with limited extent, predominantly at the base of the formation. This formation is present throughout Qatar and borehole data from deep groundwater exploration boreholes have proven thicknesses in the range from 270 m to 330 m.

Tectonic and regional halokinetic processes contributed to the fracturing, folding and uplift, resulting in fracturing, enhanced storage capacity and effective yield. An important feature of this formation is the loss of circulation encountered while drilling, due to the high transmissivity of the fractured and karstified vesicular dolomite segments.

Returns of cuttings were nearly absent throughout drilling of the formation, therefore characterization of the stratigraphy through the cuttings was minimal in this formation and is reliant on the significant historical data from other boreholes.

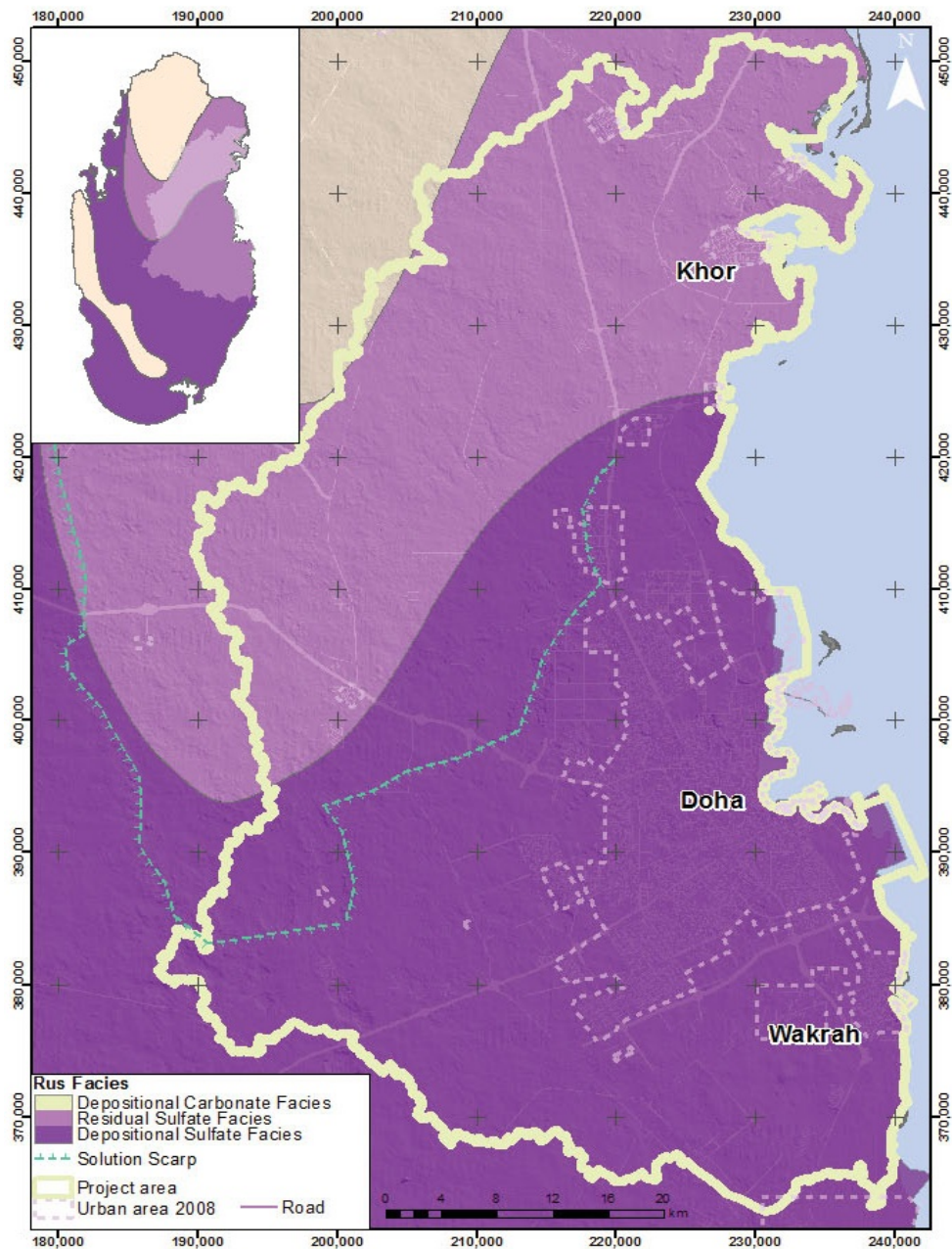


Fig. 5 Area of gypsum confinement in Doha Area [5]

B. Hydrological Assessment

To understand the hydrogeological units at the various sites, the groundwater level (Table IV) in each deep injection well of each site was assessed. The results indicated that, at most sites where flood water management is required, there is a difference of 1 meters to 23 meters between shallow ground water levels in monitoring wells and the those measured in injection wells in deep aquifer. This head difference indicates that a separating or confining layer is present between the aquifers at these locations.

IV. FIELD INVESTIGATION

As mentioned in the previous section, one of the major issues related to the project involves the evaluation of the gypsum unit, or more generally the upper confining layer, which has to prevent vertical migration of the injected water.

In order to determinate the natural site conditions and evaluate eventual environmental concerns, a series of site investigations will be performed during the well construction activities and after the beginning of the injection operations. The following sections will discuss the method, the nature and the modality of the test usually are involved in development of deep well injection projects.

TABLE IV
WATER LEVELS FOR INJECTION AND SHALLOW MONITORING WELLS

Area	Site	Well ID	Water Table (m QNHD)
09 - Mebaireek	1	S1_IW_1A	3.63
		S1_IW_1B	3.59
		S1_SM_1A	26.26
		S1_SM_1B	26.77
		S2_IW_1A	3.679
	2	S2_IW_1B	3.976
		S2_SM_1A	18.90
		S3_IW_1A	2.916
		S3_IW_1B	2.376
		S3_SM_1A	20.70
10 - Muither	3	S4_IW_1A	3.83
		S4_IW_1B	3.74
		S4_SM_1A	21.99
		S4_SM_1B	22.12
		S5_IW_1A	4.57
	5	S5_SM_1A	14.37
		S6_IW_1A	3.71
11 - Nuaija	6	S6_IW_1B	3.69
		S6_SM_1B	4.77
		S8_IW_1A*	3.677
		S8_IW_1B	2.849
		S8_SM_1A	10.15
14 - Al Dayeen	9	S9_IW_1A	3.97
		S9_SM_1A	11.85
		S10_IW_1A	4.13
		S10_IW_1B	3.66
		S10_SM_1A	9.38
	10	S11_IW_1A	0.084
		S11_IW_1B	1.832
		S11_SM_1A	1.87
19 - Al Wakra	11	S12_IW_1A	4.21
		S12_IW_1B	11.02
		S14_IW_1A	3.11
14 - Al Dayeen	12	S14_IW_1B	3.48
		S14_SM_1A	2.40
16 - Doha	14		

A. Field Data (Drilling Activities)

A first evaluation of the subsurface lithology was carried out during the drilling and the well construction activities. Various invaluable information was gathered by the field crew at each location, including:

- Cuttings were analyzed for geological patterns assessment (Fig. 6)
- Drilling rates that provided information about the nature of each layer
- Water strike, salinity variations with depth,
- Other parameters such as water level variations in the well.

Fig. 7 presents core sample taken at 80.0 meter below ground surface. This sample indicated that there is a suitable formation which could provide isolation between the shallow and deep aquifers and act as an aquitard.

B. Geophysical Logging

The geophysical logging is always run before the casing installation in order to have a detailed site stratigraphy. During

the exploratory drilling activities, general contractor carried out a suite of geophysical logs to sufficiently characterize the suitability of the project site subsurface geology for the intended use. The interpretation of the data was carried out in the context of extensive detailed geophysical and hydrogeological investigations carried out by general contractor throughout the Greater Doha area.



Fig. 6 Gypsum cuttings collected from drilling activities

C. E-Log (Gamma ray and Resistivity)

The E-log measures both natural gamma and resistivity. The natural gamma log is a good indicator of the presence of shale or other lithologies that are enriched in minerals and that are natural gamma ray emitters.

The amount of gamma emission in shale formations is proportional to the high natural radioactivity content of radioisotopes such as potassium-40, thorium-232, and uranium-238, which become concentrated in clays and shales by adsorption, precipitation, and ion exchange but may also occur in other rocks, including dolomite.

Resistivity logs measure the degree to which a formation resists the flow of electric current. The ability of the subsurface to conduct electricity depends on three main factors:

- 1) Water content – water will be the main medium in the subsurface to conduct electricity, and rocks with a high-water content (and porosity) will have low resistivity.
- 2) Water salinity – saline water conducts electricity more readily than fresh water, which is more resistive.
- 3) Lithology – different rock types differ in their ability to conduct electricity. For example, clay and shale conduct electricity better than limestone.

An example of the results obtained from E-log acquisition in most sites, carried out at injection well S8-IW-1B, is shown in Fig. 9. The resistivity plot reveals the presence of layers with low water content. High peaks of resistivity observed between approximately 37 to 59 m below ground level, which correlates to the presence of low permeability rock layers inferred to be gypsum.

D. Caliper

The downhole caliper provides a single continuous log of borehole diameter as recorded by the three mechanically coupled arms in contact with the borehole wall.

The caliper is a useful first log to determine the borehole

conditions before running more costly probes or those containing radioactive sources. The caliper log is also useful for the identification of anomalies, breaks and discontinuities in the formation.



Fig. 7 Chert core sample from 77.95m bgl

E. CCTV Camera Logging

In addition to the above geophysical logging methods described previously, a downhole CCTV camera logging was also performed to provide visual inputs and confirm the data acquired with other surveys. Fig. 8 presents a snap shot of CCVT cameral logging.



Fig. 8 Recording acquired during CCTV camera logging – cavities in recharge zone

V. INJECTION WELL SYSTEM

A. Introduction

The potential environmental impact of a deep-well injection project depends upon the construction and operation of the project itself, and local environmental conditions. The local environmental conditions include: natural environments (ecosystems), physical environmental conditions, and human and cultural presence and activities. Identical projects may have greatly different environmental impacts depending upon where it is located.

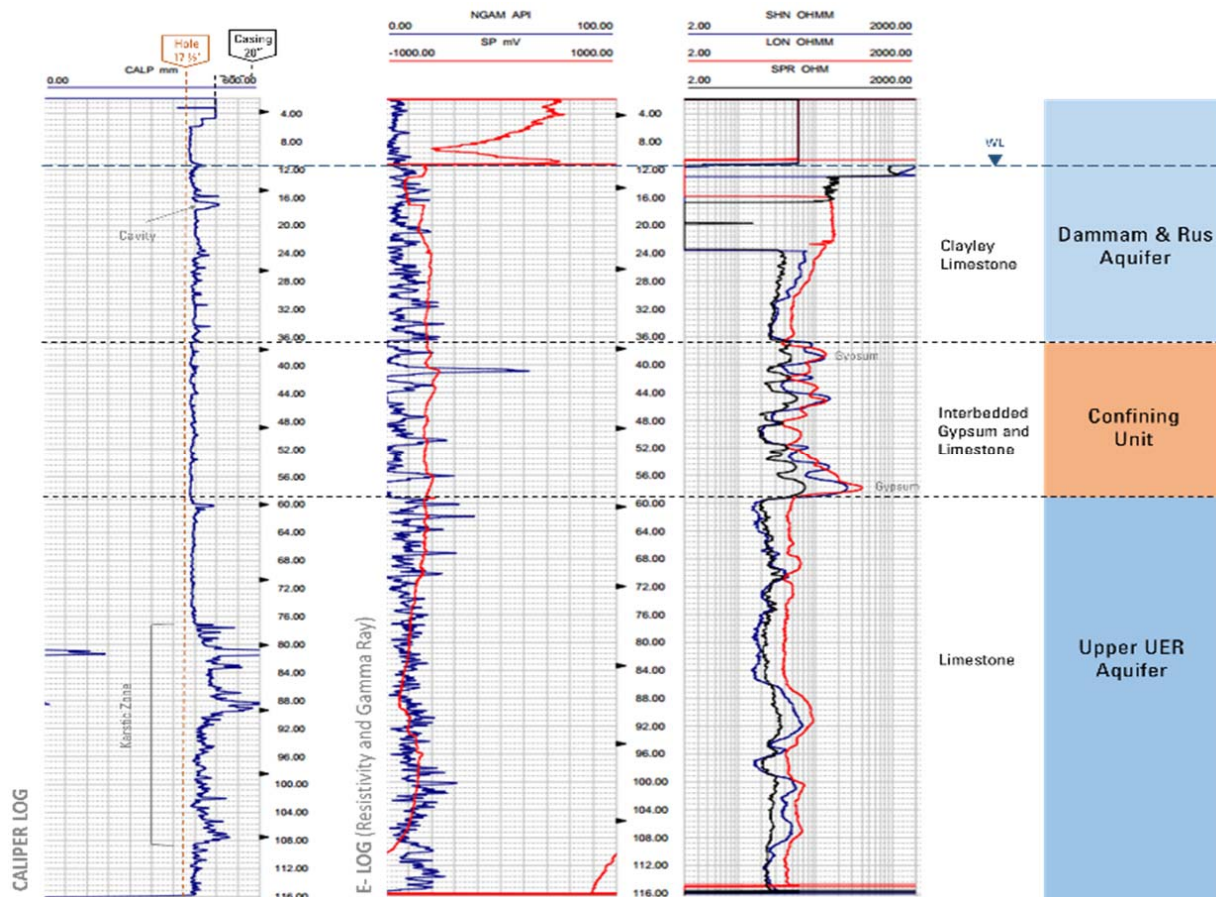


Fig. 9 Caliper and E-Log for well S8-IW-1B (0 to 116 m depth)

B. Injection Well Construction

An Environmental Permit was issued on 23/02/2017 by Ministry of Municipality and Environment (MME). Subsequently, Qatar General Electricity and Water Corporation (Kharamaa) issued permit on 01/03/2017. This permit included the requirement to extend casing of the deep injection and monitoring wells to not less than 120 m or 160 m (bgl), depending upon the site and presence of any foul network in the area. In the absence of proper foul network, the well casing was extended to 160 m bgl.

Recharge wells are generally completed with mild steel casing installed to the required depth, cemented in place and then extended to 400 m bgl to be left as open hole below casing. Factually, the open hole completion has been proven to maximize injection capacity while remaining a cost-efficient design.

For the sites were casing needed to extend to 160 m bgl, and due to the presence of major discontinuities and fractures below the gypsum layer which could have compromised grouting of the annulus under pressure, alternative completion methods were used. As such, three different designs were implemented for the injection wells:

- 1) Uniform 13 $\frac{3}{8}$ " casing cemented in a 17 $\frac{1}{2}$ " borehole to 160 m depth.
- 2) 13 $\frac{3}{8}$ " casing cemented in a 17 $\frac{1}{2}$ " borehole to 120 m depth, followed by installation of a liner hanger and then installation and cementing of a 9 $\frac{5}{8}$ " casing cemented in a

12 $\frac{1}{4}$ " borehole to 160 m depth.

- 3) Uniform 13 $\frac{3}{8}$ " casing cemented in a 17 $\frac{1}{2}$ " borehole to 120 m depth.

Fig. 10 presents the various stages of well construction. Fig. 11 provides a schematic illustration of each injection well design. Figs. 12 and 13 present the drilling rig during drilling wells and the liner hanger used in developing deep injection well, respectively.

C. Monitoring Well Construction

Each deep injection system is designed in standardized units comprising an injection well or wells and at least two monitoring wells, one deep in the recharge zone and one shallow in the upper aquifer. The monitoring wells are positioned around the recharge well to monitor:

- 1) The interaction of the injected water with native water in the recharge zone,
- 2) The interaction of the injected water with formation minerals,
- 3) Any potential upward of injected water into the shallow formation.

Deep monitoring wells have similar construction to the Design A shown in Fig. 11 recharge well with a narrower casing extending to either 120 or 160 m bgl, and open hole section. Casing has an outside diameter of 7" while the open section was drilled using a 6 $\frac{1}{2}$ " diameter bit.

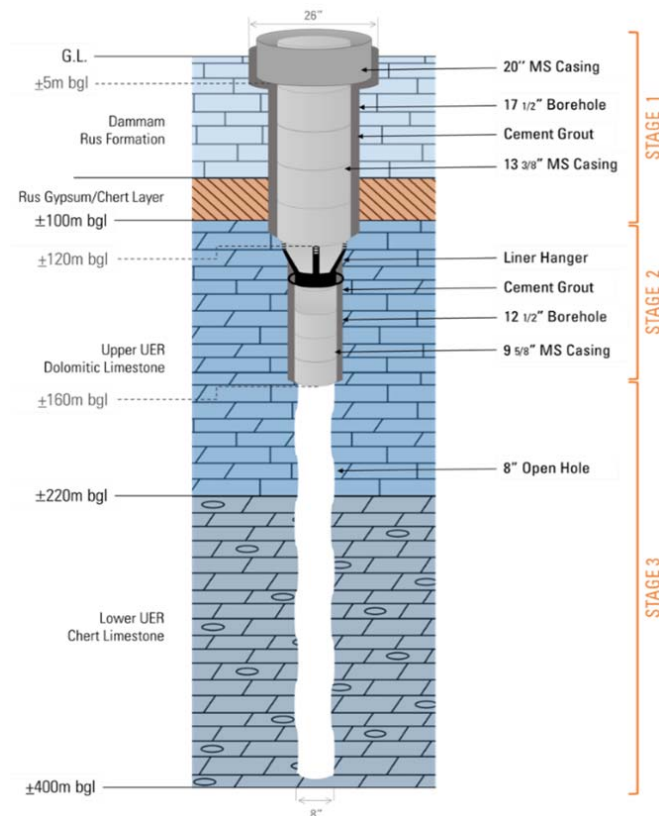


Fig. 10 Injection Well Completion – Stages 1 to 3

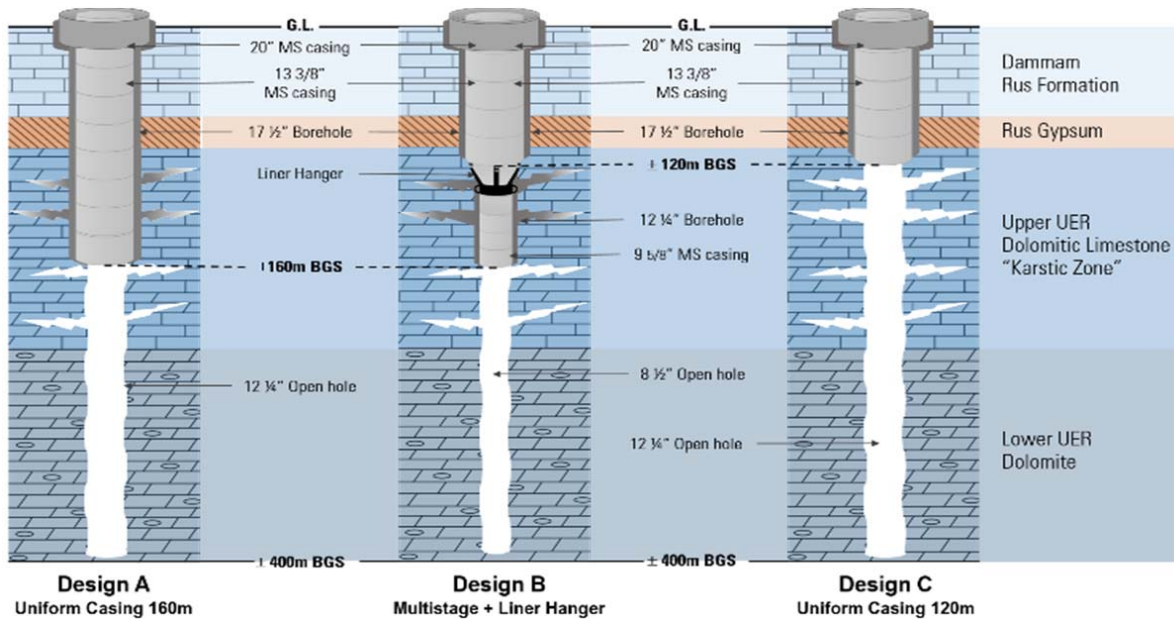


Fig. 11 Schematic of various injection well designs

Three deep monitoring wells were completed with casing extending to 120 m bgl (e.g. Design D in Fig. 14). For the remaining nine deep monitoring wells where casing was required to be extended to the depth of 160 m bgl, a cement basket was installed on the casing string above the presumed cementing lost zones to prevent cement loss during grouting operation (e.g. Design E in Fig. 14).

Shallow monitoring wells are drilled as open borehole up to 50 m depth with a 12 1/4" diameter bit and then completed with two piezometers. A 2" PVC piezometers for the surficial zone (i.e. 0-25m bgl) and a wider 4" PVC piezometer for the shallower zone (i.e. 25 to 50m bgl). The piezometers are vertically separated with the used of cement grout in order monitor Dammam and Rus formations separately.



Fig. 12 Drilling rig for FPS 14, Site 8 (Al Dayeen) DM1A

Fig. 14 provides a schematic illustration of each monitoring well design. Fig. 15 presents the configuration of shallow monitoring well at ground surface with associated data logger.

VI. WATER QUALITY

The aim of the water quality analysis is to cover three main objectives:

- Provide baseline water quality analysis
- Establish any interaction between aquifers during injection operations
- Identify potential problems and perform corrective actions

In order to assess the groundwater quality, water samples will be collected from the shallow and deep wells and analyzed by an accredited laboratory prior and during the injection operations for baseline record.

Injected water quality (base and storm runoff flows) will be assessed during first 12 months of recharge operations.

The standard reference used for injected water quality analysis should be the Gulf Corporation Council (GCC) injection Treated Solid Effluent (TSE) guidelines and MME standards for crops and landscape irrigation.



Fig. 13 Liner hanger used for extending the casing to 160 meters bgl

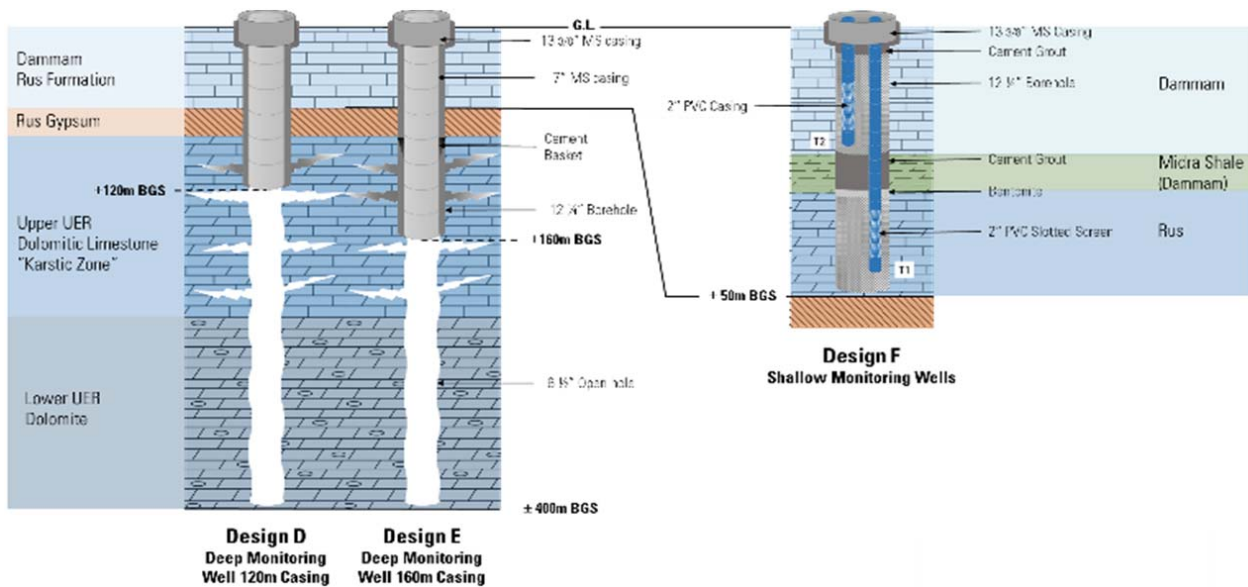


Fig. 14 Schematic of deep (left) and shallow (right) monitoring wells



Fig. 15 Top view of shallow monitoring well

Some early indications about surficial groundwater quality could be obtained comparing the water quality data acquired for projects with the similar scope of work, currently running in Doha area. Among these, Al Kharaitiyat Recharge Schemes project was implemented for injection of the rising shallow groundwater of the surrounding area into the deeper UER formation. Review of water quality of Al Kharaitiyat Recharge Schemes project indicated that out of the 54 parameters analyzed, only seven parameters, mainly cations and anions, were found exceeding the GCC guidelines during six months of monitoring Dec 2016-May 2017 for well KHAR_RW2.

High concentrations of major ions such as fluoride (F), chloride (Cl), sulphate (SO_4) and sodium (Na), are representative of the shallow aquifer groundwater quality in Qatar and indicate a high degree of evolution due to arid climatic setting. This is correlated by a Total Dissolved Solids concentration of around 2,500 mg/l.

Microbiological contamination, such as Fecal Coliforms and *E. Coli*, was detected occasionally, indicating that shallow groundwater in the project area may be partially contaminated

by sewage or black waters.

Metals, nutrients and oil and grease were found to be below detection limits. However, the site-specific data for injected water will be required for the project FPS24 to carry out accurate assessment.

VII. WELLHEAD ASSEMBLY CONFIGURATION

Due to the unknown water quality and quantity to be discharged into the deep injection wells, it is not possible to design an effective yet cost conscious treatment solution. It is most likely that each injection site will be subjected to different conditions and the treatment will need to be tailored for particular drainage catchments. This is true especially in relation to suspended solids as depending on the complexity of the network, pipe diameters, velocities and gradients as some particle settlement will take place in the upstream network and in the overflow lagoon (EFA).

Each site will be left with allocated space to build a required treatment designed based upon collected water quality and flow data during first 12 months of operation. Fig. 16 presents the typical wellhead assembly and its major components. Fig. 17 presents the general configuration of injection system. On this configuration, the collected storm water and groundwater from the network will enter into a split flow manhole. In dry season when the flow rate is too low, the collected water will enter directly into the injection well via wellhead assembly. However, during rain and high flow rate into network, the collected storm and groundwater in the network will flow into the lagoon/EFA and then into the injection wells via the wellhead assembly. The wellhead assembly will be installed in three manholes.

Fig. 18 shows the construction of the three manholes which housed the wellhead assembly. Fig. 19 presents the wellhead assembly installed within the manholes. The EFA pond and the completed three manholes (see manhole covers)) are

shown in Fig. 20.

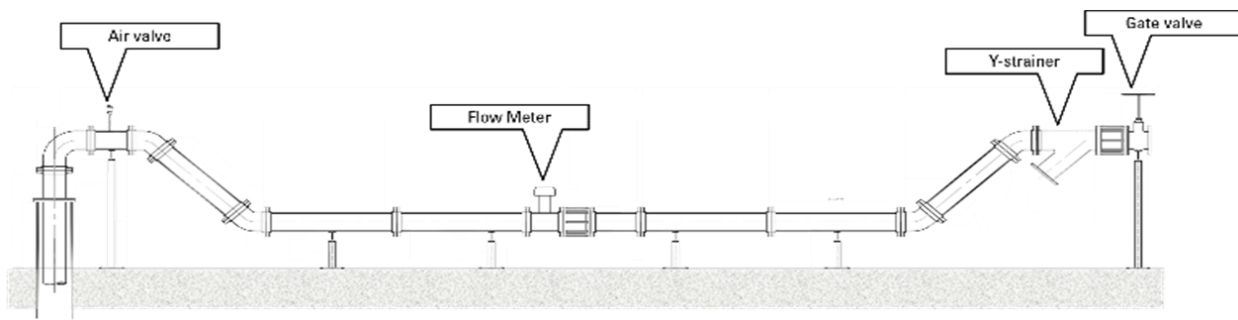
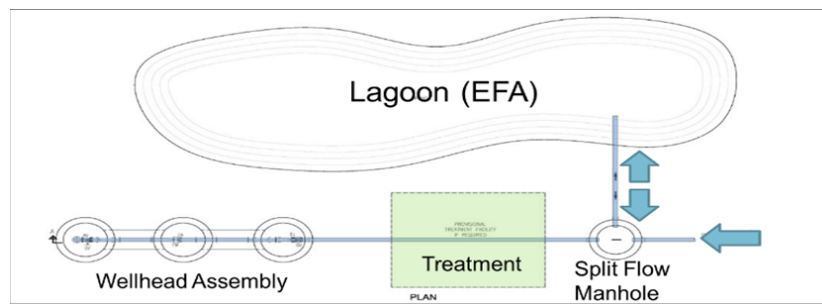
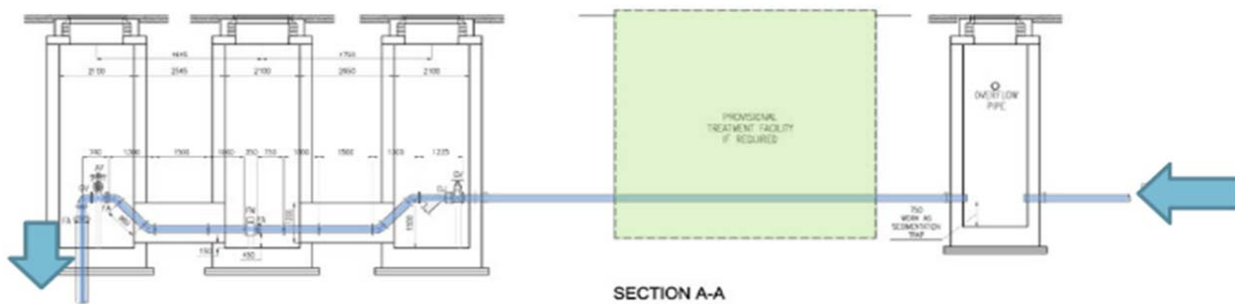


Fig. 16 Typical wellhead assembly and its components



(a)



(b)

Fig. 17 (a) Plan of Typical Injection Site and (b) Section of Typical Injection Site

VIII. PUMPING AND INJECTION TESTS

A. Introduction

As part of deep injection well construction and operation hydraulic testing including pumping and injection tests were performed. The main objectives of hydraulic testing are summarized as:

- 1) Determine hydraulic properties (transmissivity, storage coefficient) of deep UER formation;
- 2) Insure proper confinement of injection zone (i.e. no communication between shallow and deep aquifers);
- 3) Determine the specific injectability of the well.

B. Pumping Tests

Pumping tests were performed in accordance with British Standard BS ISO 14686 Hydrometric Determinations –

Pumping Tests for water Wells. The tests were performed for two conditions as follows:

1. Step Rate Pumping Test

- 3 steps of 100 minutes each
- Recovery

2. Constant Rate Pumping Test

- 48 hours or as per the site condition (volume of lagoon/EFAs will determine the amount of water to be pumped)
- Recovery

3. Recharge Test

- Maximum 20 l/s
- Three steps of 100 minutes for each step
- Recovery



Fig. 18 Construction of three manholes for wellhead assembly



Fig. 19 Constructed manholes and wellhead assembly



Fig. 20 General View of EFA Pond with Completed Manholes for Wellhead Assembly

Results of pumping tests indicated that most sites displayed medium to high level of lateral interconnectivity which is a testimony of the importance of secondary and tertiary permeability within the tested aquifers. Although the shape of time-drawdown curves for the tests does not show large effect of dual porosity, permeability values calculated categorize the tested system as fractures karstic limestone aquifer with hydraulic conductivity values ranging from 3.12×10^{-6} to 9.47×10^{-4} m/s. Average storativity values calculated from aquifer test data range between 1.25×10^{-1} and 5.00×10^{-1} , placing the tested aquifers in the unconfined aquifer type groups, while being effectively confined, because of

overestimating of specific storage values which is obtained from time-drawdown curve segment interpretation. This is supported by the shape of time-drawdown curves (dual porosity) and the absence of effect of pumping on the shallow and surficial aquifers.

C. Injection Tests

The main objective of the injection tests is to provide an assessment of the efficiency of the recharge at each test location and estimate the required pressure to reach maximum injection rate of 50 l/s (i.e. $182 \text{ m}^3/\text{h}$ or $4318 \text{ m}^3/\text{day}$).

Injection tests were performed at six sites: site 1, Site 2, Site 3, Site 8, Site 10, and Site 14. Water was pumped and injected from near EFA ponds as shown in Fig. 21.

Principally, injection test data acquisition involved collection of discharge time and water level measurement. Diesel surface pumps capable to provide an injection rate of $120\text{-}150 \text{ m}^3/\text{h}$ with a suction from depth of 9.0 meters were used for injections (Fig. 22). Whenever possible electromagnetic flow meters installed on horizontal conductor pipes were also used to monitor more accurately the injection rate and volume.

Dataloggers “CTD-Divers[®]” were installed in all injection wells and programmed to collect water levels, electrical conductivities and temperatures every 30 seconds throughout the testing period. CTD-Divers[®] data have been downloaded and used for analysis. Manual monitoring was sporadically undertaken as a precautionary measure and backup to automatic water level measurements.



Fig. 21 Pumping Test Set-up

The results of injection tests illustrate heterogeneity and complexity of a karstic aquifer such as the UER aquifer. With water level rising over 10 meters, FPS10 seems to be less prone to receive the anticipated volume of recharge water than the other sites such as FPS09 where under similar injection rate increased by 1.6 m. This observation is indeed controlled by the permeabilities, respectively in the range of 10^{-5} m/s versus 10^{-4} m/s, extracted from pumping tests. Fig. 23 presents the maximum expected injection rate under gravity at different site. As it is shown in Fig. 23, most of the wells can accept injection rate of 200 to $300 \text{ m}^3/\text{h}$ (56 to 83 l/s) under gravity with average value of $250 \text{ m}^3/\text{h}$ (70 l/s) which is higher than

the value of peak injection rate of 50 l/s in the network. This means that all the injection wells will accept the design flow rate under gravity without requiring a booster pump.

Fig. 21 presents the set up for pumping test.

IX. ENVIRONMENTAL IMPACT ASSESSMENT

The overall objectives of this Environmental Impact Assessment (EIA) are to assess the impacts of the construction and operation of the project on the environment, to determine potential adverse environmental effects, to determine appropriate means to control any potential negative effects, and to maximize the potential positive impacts of the project upon the environment in accordance with Article 1.18 of Qatar Law No. 30 of 2002 (Law of Environment Protection).

This EIA assesses the potential sources of environmental impacts that may occur due to the implementation of the FPS project. Each of 12 deep injection well sites for the project uses the same injection zone and have similar geological conditions. The potential environmental impacts of the deep injection at the sites are therefore expected to be similar.



Fig. 22 Water pumped into the injection well from EFA pond at Site 10, FPS14

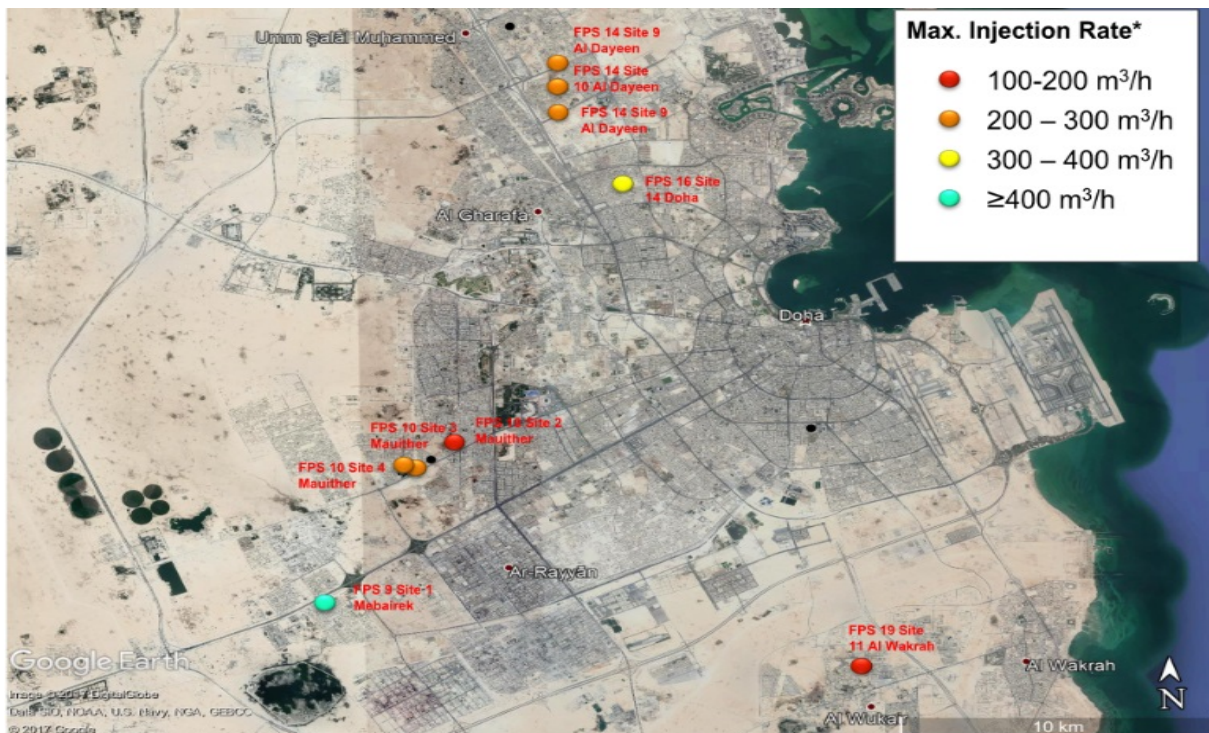


Fig. 23 Extrapolation of injection test results for maximum injection rate under gravity at various sites

Injection projects are generally not characterized by the environmental constraints that are normally associated with large-scale development projects. Deep-well injection systems have a minimal surface footprint, are visually and ecologically unobtrusive, and if operated correctly, do not cause significant noise or air pollution.

Many typical concerns associated with development projects are not applicable to the project and were not included

in the scope of the EIA investigations (i.e. they were “scoped out” of the EIA). This practical approach has been applied to other deep-well injection and recharge projects in Qatar. A discussion of the items scoped out of the EIA report is provided in EIA report.

The Law of Environment Protection aims to achieve the following:

- 1) Protection of the environment and maintenance of its

- quality and natural balance.
- 2) Counteract the various types of pollution and avoid short-term and long-term damages that result from plans or programs of construction, industrial, agricultural, or economic development.
 - 3) Development of natural resources and conservation of biological diversity for the maximum benefit of the current and future generations.
 - 4) Protection of society and the health of humans, and other living creatures from all environmental injurious actions and functions, or that retard the legal use of the environment.
 - 5) Protection of the environment from the harmful impact of activities outside the State.

The preparation of this project-specific EIA is to ensure that the purposes and goals of the Law of Environment Protection are achieved. The main requirements of EIAs are to:

- Identify and evaluate potential significant adverse impacts to the environment associated with development projects.
- Identify and incorporate into the project appropriate abatement and mitigation measures to eliminate or minimize significant adverse impacts.
- Identify and incorporate mitigation and monitoring plans.
- Maximize the incorporation of environmental enhancement opportunities.

The EIA also ensures that the project proponents are fully aware of their environmental obligations and incorporate sustainable development and environmental best management practices for development. The EIA report for this project presents a comprehensive mitigation opportunity and an Environmental Management Plan to achieve these goals.

The principal environmental advantage of deep-well disposal systems is that they provide the greatest degree of separation from human and environmental receptors. A deep-well disposal system can remove injected water from the environment provided that the systems operate as they were

intended and designed.

The potential environmental concerns of deep-well injection projects previously identified in the Environmental Scoping Report for the FPS injection projects are applicable to the proposed project sites. These concerns are summarized in Table V below along with an assessment of the potential impacts.

Four main barriers exist for the deep-well injection that minimize the potential for adverse impacts to humans and other sensitive receptors:

- Pre-treatment of the injected water, where required
- Natural attenuation processes within the recharge zone.
- Presence of low permeability layer above the recharge zone in the upper UER formation, and the absence of an upwards hydraulic gradient.
- Geographic separation of the recharge system from potential sensitive receptors, particularly potable water wells.

Both the UER Formation and surficial aquifer contain brackish water that is not suitable for use as a potable water supply without advanced water treatment. No potable water wells are present in the immediate vicinity of the FPS project sites. If upwards migration of the injected water were to occur, the water would still be geographically separated from potable water wells.

The interbedded gypsum of the Rus Formation or the chert of the upper UER Formation provides effective confinement between the recharge zone and the overlying surficial aquifer provided that the confining layer is horizontally continuous. The natural head differences between the recharge zone and surficial aquifer is evidence for the presence of effective vertical confinement, at least locally.

Previous investigations have shown that injection increases water levels within the recharge zone, but the heads will be contained below land surface during ongoing injection.

TABLE V
ASSESSMENT OF IDENTIFIED POTENTIAL ENVIRONMENTAL CONCERNS

Concern	Assessment
Hydrology and geology constraints	
Migration of recharged water out of the recharge zone could adversely impact groundwater quality and aquifer users and other sensitive receptors.	Multiple barriers exist, which results in a low potential for impacts to human health and sensitive environments. Long-term monitoring of barriers is recommended.
Injected water could reach land surface impacting land uses, buildings, and surface ecosystems.	None expected. Water levels (heads) reported in injection wells, and deep monitoring wells are below land surface. Monitoring of recharge rates and water levels is recommended.
There is low potential for the injected water to dissolve the formation materials (e.g. gypsum, dolomite, etc.), which could create flow conduits or cause land surface collapse.	Gypsum dissolution will occur, but the possibility of adverse impacts is low (but not negligible). Long-term monitoring is recommended.
Air Quality – odor and health impacts	
The recharge zone naturally contains high concentrations of H ₂ S gas, which can create an odor nuisance and have local health impacts	Potential exists for serious health impacts to personnel who work on the deep-well injection systems. This should be addressed in the project health and safety plan.

The proposed injection fluids are likely to be slightly undersaturated with respect to gypsum and capable of dissolving residual gypsum within the UER recharge zone. Gypsum dissolution would be expected to occur in a dispersed manner throughout the part of the injection zone as an extension of the naturally-occurring dissolution responsible for the formation

of the secondary porosity within the aquifer. The possibility exists that gypsum dissolution could be disproportionately concentrated near the injection wells. Monitoring of gypsum conditions adjacent to recharge wells is recommended.

Natural attenuation processes within the relatively warm groundwater environment of the UER Formation recharge

zone are effective in removing microbial pathogens, which are the primary health concern associated with recharge water. Most organic chemicals of concern also undergo biodegradation or are otherwise immobilized in groundwater environments.

The Environmental Impact Assessment has identified the potential risks and appropriate associated mitigation measures for the proposed FPS injection projects.

X. SUMMARY AND CONCLUSIONS

As part of FPS project to control surface and groundwater table, 21 one deep injection wells of 400 m deep were constructed in Doha, Qatar. These injection wells are in areas where the drainage networks could not be connected to existing positive (gravity) system due to the lack of such system or risk of overloading downstream networks and creating flooding elsewhere. The flow will be injected into a porous formation (deep aquifer) which is isolated by impermeable formation preventing the contamination of the shallow aquifer. Special drilling, casing and grouting techniques were utilized in construction of these wells. Filed tests including geophysical, pumping, and injection tests were performed to insure the wells will function properly during their service life. The real behavior of these wells shall be demonstrated in coming months and years during rainy seasons. This project indicated that deep injection wells can be utilized to remove storm water runoff permanently from the biosphere, when the technology is properly applied. Furthermore, successful deep injection well systems do not adversely impact the environment or human health.

REFERENCES

- [1] Van Voorhees, R. F., 2001, Removed from the environment. The Environmental Forum, March/April 2001, pp. 23-31. <http://www.gwpc.org/e-library/documents/general/Removed%20From%20the%20Environment,%20VanVoorhees%202001.pdf>.
- [2] Al-Saad, H., 2005, Lithostratigraphy of the Middle Eocene Dammam Formation in Qatar, Arabian Gulf: effects of sea-level fluctuations along a tidal environment: Journal of Asian Earth Sciences, v. 25, pp. 781-789.
- [3] Seltrust Engineering Ltd., 1980, Qatar Geological Map, Industrial Development Technical Centre, Doha.
- [4] Streetly, M. J., and Kotoub, S., 1998, Determination of Aquifer Properties in Northern Qatar for Application to Artificial Recharge: Quarterly Journal of Engineering Geology and Hydrogeology, v. 31, pp. 199-209.
- [5] Eccleston, B. L., and Harhash, I. E., 1982, The Hydro-Geology of Qatar: Ministry of Industry and Agriculture, Department of Agricultural and Water Resources.