Project:

ASR application for Domestic Fresh Water Supply in the Vietnamese Mekong Delta

Report No 6:

Drilling and installation of monitoring well for ASR pilot in Hau Giang province

WP1: ASR Site development

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The opinions expressed in this report are those of the authors and do not necessarily reflect the views of the institutions supporting the project.

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1- Purpose and requirements

In January, the DWRPIS team drilled and installed the monitoring well M1 for the ASR project. The main goal of the drilling was to investigate the position and the characteristics of the target aquifer qp_1.

- Assess borehole stratigraphy, depth, thickness and quality of aquifers,
- Describe structure of pipes for the purpose of groundwater monitoring.

2- Machines, equipment and implementation methods

- Machine and equipment: GK300 drilling machine, 350/50 mud pump and Airman PDS-390 S air compressor pump
- Implementation method: Rotary drilling method, supplemented with bentonite clay solution.
    - Destructive drilling: Using a choke, drilling to destroy the entire bottom
    - Drilling to take samples: Using a drill blade, double bore sample tube with diameter 91/110.

3- Implementation

- Exploration drilling depth: 210.0 m.
    - destructive drilling is from 0.0m to 150.0m,
    - sampling drilling is from 150.0m to 210.0m.
- Drilling diameter and structure of casing and filter pipes:
    - Bore hole diameter 150mm from 0.0m to 210m
    - PVC D90 pipe from +0.5m to 167.0m
    - PVC D90 filter pipe from 167.0m to 187.0m
    - PVC D90 settling pipe from 187.0m to 190.0m

See Table 1 for overview.

Table 1: Overview of drilling and installation of casing

Depth (mbgl)	final drilling diameter (mm)	initial drilling diameter (mm)	drilling method	pipe installed
0 - 150	150	130	destructive	PVC D90
150 - 167	150	110	sampling	PVC D90
167 - 187	150	110	sampling	PVC D90 filter pipe
187 - 190	150	110	sampling	PVC D90 settling pipe
190 - 210	110	110	sampling	collapsed material from overdrilling with 150 mm has filled the bottom

4- Borehole geophysical measurement (Carota measurement)

Carota measurement was carried out after the exploratory drilling from 0.0 - 210.0m.

Equipment and measuring methods:

- MOUNTSOPRIS MGX – II console made in the US.
- Borehole geophysical method (carota measurement) records a combination of parameters:
  - Natural gamma radiation intensity (G), CPS unit.
  - Resistivity of 04 standard pole systems (R8, R16, R32 and R64), measuring unit ohm.m.

    Natural polarization potential (SP), unit of measurement mV.

    Solution resistivity (Fres), measuring unit ohm.m.

    Temperature (Temp), measuring unit oC.

Results are shown in the Annex 1 and confirm the presence of a good aquifer at 167-187 m depth.

5- Borehole stratigraphy

Based on the results of exploratory drilling and the Carota measurements, the borehole stratigraphy is divided into the following main layers (Table 2).

Table 2: Stratigraphic description of monitoring well M1

Depth (m bgl)	Material	Water holding capacity	water quality	aquifer
0 - 13	clay	unable		
13 - 72	silty clay	unable		
72 - 79	fine-grained sand	medium	fresh	qp_3
79 - 85	silty sand	low		
85 - 136	fine to medium grained sand	good	fresh	qp_{2-3}
136 - 143	silty sand	low		
143 - 154	blue-grey silty sand	low		
154 - 156	blue-grey, brown-grey silty clay, hard	unable		
156 - 163	blue-grey fine to medium grained sand	good	fresh	qp_1
163 - 167	blue-grey silt mixed with gravel	unable		
167 - 187	Medium to very coarse grained sand mixed with gravel	good	fresh	qp_1
187 - 201.5	grey-brown silty sand	low		
201.5 - 210	grey-brown silt with gravel, hard	unable		

In summary: There are two (02) layers of fine to medium-grained sand, capable of containing water with fresh water quality that can be exploited industrially for daily life and production.

Layer 1: 85.0 - 136 m (Middle-upper Pleistocene aquifer - qp_{2-3})

Layer 2: 167.0 - 187.0m (Aquifer Lower Pleistocene -qp_1)

The full borehole log is shown in Annex 2.

6- Air flushing and capacity testing

The well was cleaned by air flushing for 3 shifts on January 15. On 16 January, a capacity test was executed by **airlifting** using a barrel for capacity measuring (Figure 1).

Results:

- Static groundwater level: 12.3 m bgl
- Dynamic groundwater level: 17.4 mbgl
- Flow rate 4.5 L/s = 16 m^3/hr

Figure 1: Capacity measurement with barrel

7. Detailed lithological analysis

Small portions of the collected sediment cores were air-dried and grain size was compared to a sand ruler by Ate Oosterhof. See Annex 3 for results.

8. Pump test

As the available Van Essen Diver are too large in diameter to fit into the levelling pipe of the production wells G1 and G2, a single well pumping test was conducted at G1 with the installed submersible pump for 4 hours (start at 13:00) at an average flow rate of 71.5 m^3/hr, resulting in a total volume of 286 m^3 pumped. The water level change during 4 hours of drawdown and two hours of recovery was monitored in the monitoring well M1 at a distance of 43 m from G1, and manually in the pumping well G2 at a distance of 94m from G1 (see Figure 2).

During the last half hour of the recovery, the rise in groundwater level was very fast. It is suspected that another well in the neighborhood was turned off during this time.

Figure 2 Map with the wells used for the pumping test

For the analysis of the pumping test data, an analytical elements model for transient multi-layer groundwater flow was used (TTIM).

The hydrogeological system was schematized as two aquitards and two aquifers, representing four layers between -150 and -187 m. Below 187m there is a layer of silty clay considered here as impermeable. The lithology of M1 was taken for this schematization. The description of the lithology as registered during the drilling was used to define thickness, initial hydraulic conductivity, and storage coefficient values for the layers. Later these values were modified to calibrate the model and fit the model results to the measured drawdown values at M1 and G2. To account for uncertainties, the model was run several times with different values for some parameters.

The results of the analysis showed that when the wells M1 and G2 are used separately for the calibration of the model (Figure 3), a good fit can be obtained with an hydraulic conductivity of 115 m/d and a storage coefficient of 1.2E-05 for qp_1 with the M1 data, and an hydraulic conductivity of 209 m/d and a storage coefficient of 5.6E-05 for qp_1 with G2 data.

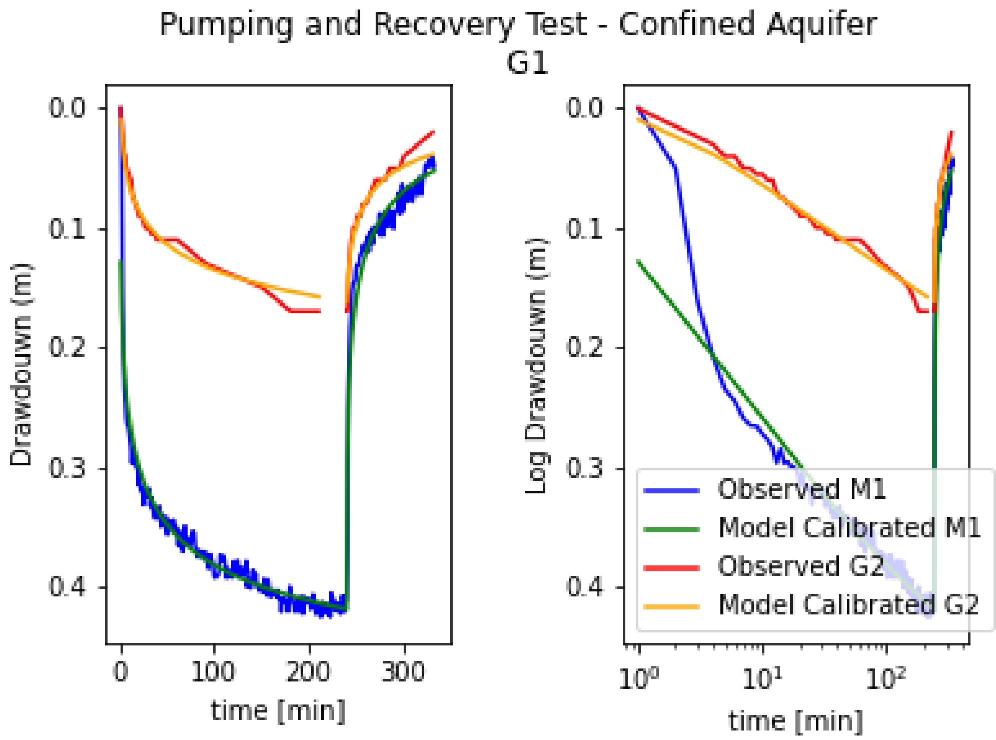


Figure 3: Measured drawdown and recovery and model fit for M1 and G2. The blue line shows the measured data by a sensor in the monitoring well M1. The red line shows the manual measurements conducted in the well G2, and the green and orange lines show the results of the model when calibrating it separately for M1 and G2.

The difference in values for hydraulic properties when using data from M1 and G2 separately, can be explained by the fact the G2 is further away from G1, and might have a different lithology than M1. The model made for M1 might thus not represent the lithology in the location of G2. Taking this into consideration, the results of M1 are taken as most reliable.

Given the uncertainties in the resistance of the aquitard above the aquifer monitored, and the hydraulic conductivity of the layer above that aquitard, it is not possible to conclude on one single value for the hydraulic conductivity for the aquifer, but the sensitivity analysis shows that it is most probably between 99 and 115m/d.

If other uncertainties such as the thickness of the aquifer and the aquitard are considered, the range of the hydraulic conductivity could be between 66 and 115m/d.

To obtain more conclusive results, the recommendations are to either:

- repeat the pumping test with an automatic sensor in M1 and G2
- conduct a pumping test using the well G2 to pump, and M1 and G1 as observation wells
- conduct a pumping test in the ASR well to be constructed and use M1, G1 and G2 as observation wells using slim automatic loggers in all four wells in addition to manual measurements in M1.

A full description of the pumping test analysis can be found in Annex 4.

9. Well Head

After all test the well head was finished as per this design (Figure 4)

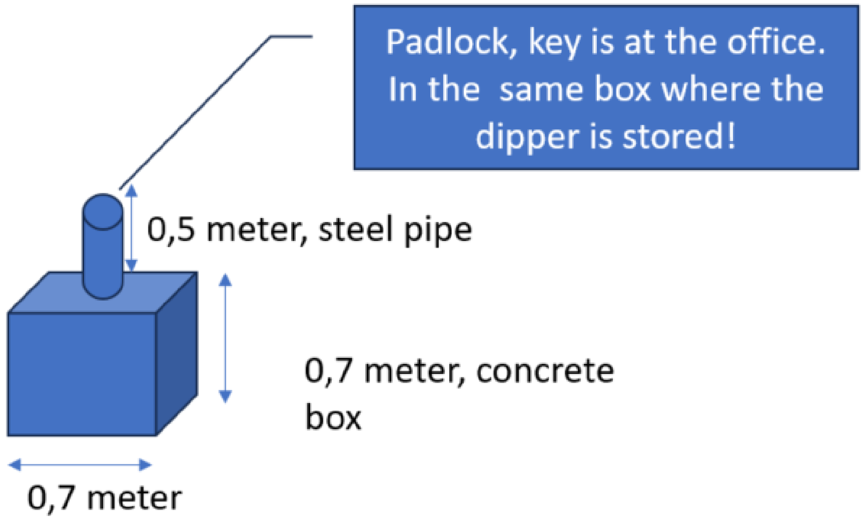


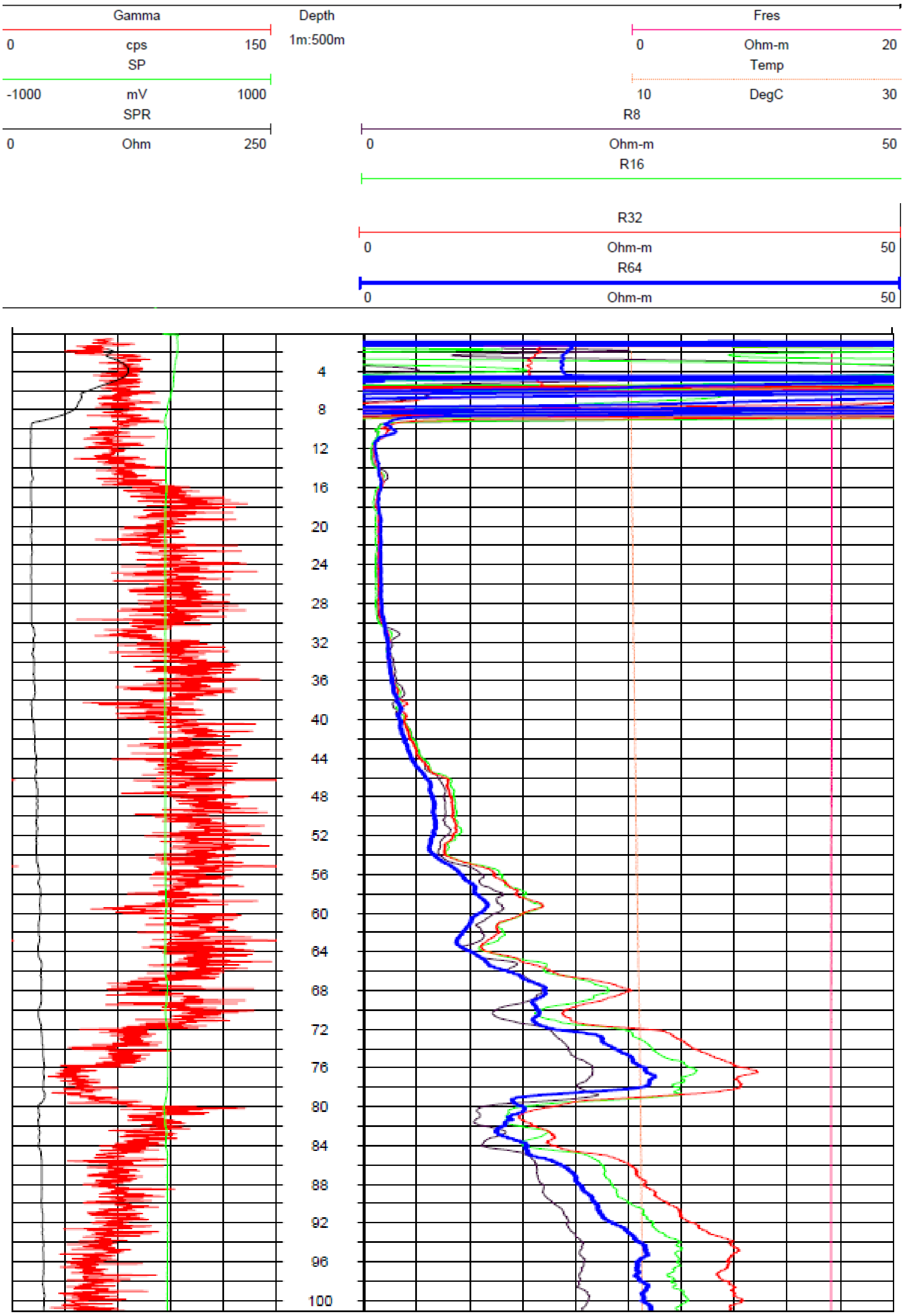
Figure 4: Well head design

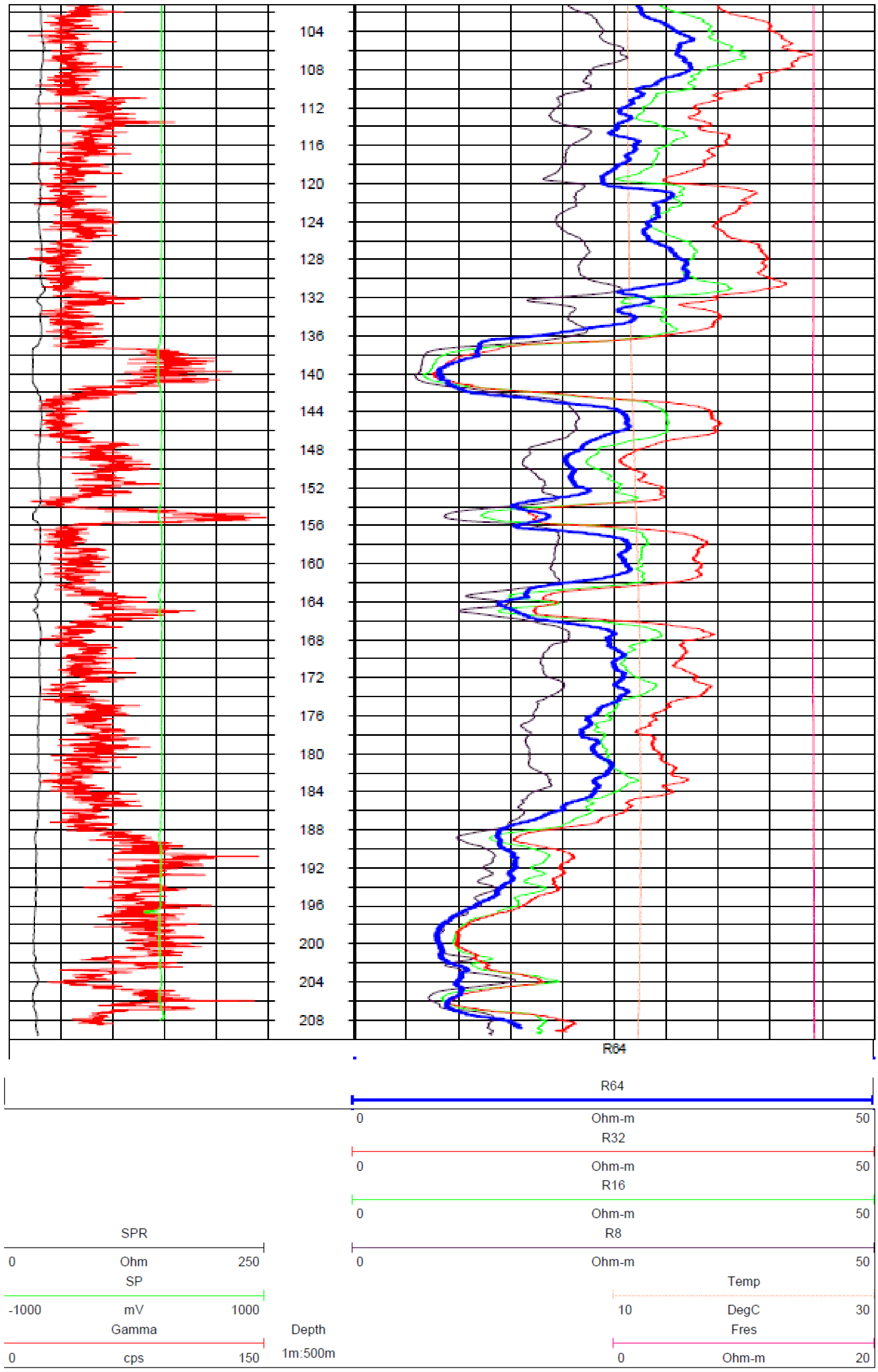
Annex 1: Carota Measurement results

Date: 14.01.2024

Gamma: 2PGA, Sign: SN, rate: 1R/h = 3.5 cps; Curve: Gamma, SP, Current, SPR

Resistivity: 2PEA, Sign: SN, Curve: Fres, Temp, R8, R16., R32, R64

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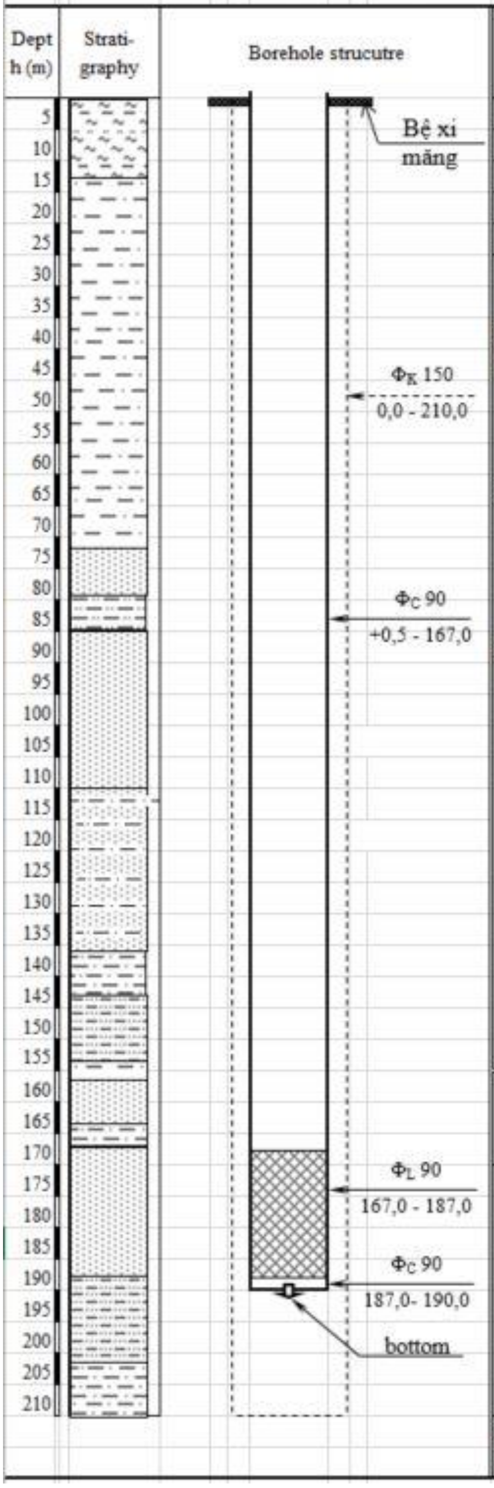
168
172
176
180
184
188
192
196
200
204
208
R64
R64
0 Ohm-m 50
R32
0 Ohm-m 50
R16
0 Ohm-m 50
R8
0 Ohm-m 50
SPR
0 Ohm 250
SP
-1000 mV 1000
Gamma
0 cps 150
Depth
1m:500m
Temp
10 DegC 30
Fres
0 Ohm-m 20

Annex 2: Borehole log

FINISHED DRAWINGS

PROJECT: MONITORING DRILL HOLE M1

LOCATION: NGA BAY WATER PLANT, NGA BAY CITY, HAU GIANG PROVINCE



No	MATERIALS AND SPECIFICATIONS	Unit	QUANTITY
1	PVC-resistant pipeΦ 90 is 6.7 mm thick	tube (4m)	42,0
2	PVC filter tubeΦ90 perforated, wrapped in mesh	tube (4m)	5,0
3	PVC settling tubeΦ 90 is 6.7 mm thick	tube (3m)	1,0
4	Bottom valvesΦ90	female	1,0
5	Cement base (1.0 x 1.0 x 0.5)m	female	1,0

PRESENT

I - Well structure

1- Drilling structure:

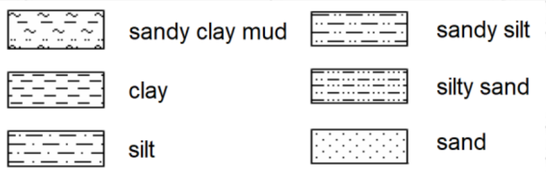
- Sample drilling from 0.0m to 150.0m, diameter 130mm
- Sample drilling from 150.0m to 210.0m, diameter 110mm
- Boring extension from 0.0m to 210.0m, diameter D150mm.

2- Structure of casing pipe

- From +0.5 to 167.0m PVC pipes Φ90
- From 167.0m to 187.0m PVC filter pipe Φ90, perforated, wrapped in mesh
- From 187.0m to 190.0m PVC settling pipe Φ90

II- Experimental water pump

- Washing pump: 03 shifts



SOUTHERN WATER RESOURCE PLANNING AND INVESTIGATION ASSOCIATION

UNION CHIEF	THE ESTABLISHMENT	CHECK

Coordinates: X = 1085488
(VN-2000) Y = 590272

January 17, 2024

Annex 3: Grain size analysis pictures

Grain size results from detailed analysis by Ate Oosterhof

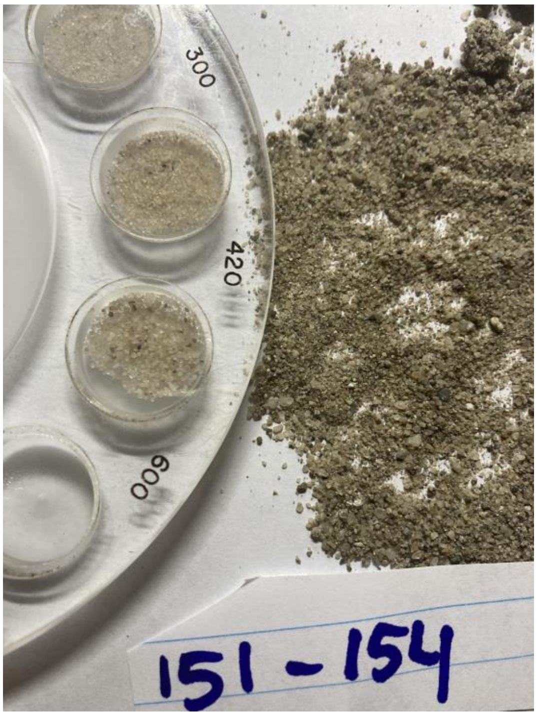
depth (mbgl)	grain size	color code
150	Clay	
151	Clay	
152	Clay	
153	Clay	
154	Clay	
155	Clay	
156	Clay	
157	silt	
158	MCS	
159	MCS	
160	MCS	
161	MCS	
162	MCS	
163	Clay	
164	Clay	
165	MCS	
166	Silt	
167	MCS	
168	MCS	
169	MCS	
170	MCS	
171	MCS	
172	MCS	
173	MCS	
174	MCS	
175	MCS	
176	MCS	
177	Silt	
178	MCS	
179	MCS	
180	MCS	
181	MCS	
182	MCS	
183	MCS	
184	MCS	
185	MCS	
186	MCS	
187	MCS	
188	MCS	
189	MCS	
190	silt/clay	

depth (mbgl)	grain size	color code
192	sand/clay	
193	MCS	
194	MCS	
195	Clay	
196	Clay	
197	Clay	
198	Clay	
199	Clay	
200	silt	
201	Clay	
202	Clay	
203	MCS	
204	Clay	
205	MCS	
206	MCS	
207	MCS	
208	MCS	
209	MCS	
210	MCS	

Legend

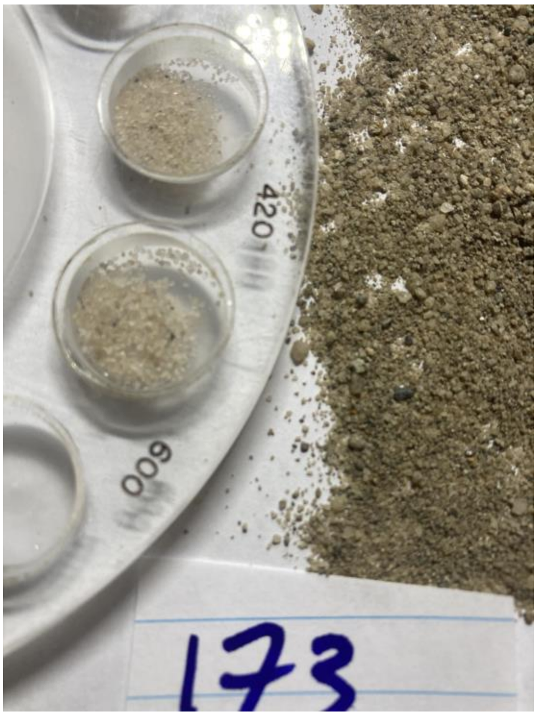
	Clay
	Silt
	MCS (medium coarse sand)

Pictures of air-dried sediment compared to sand ruler by Ate Oosterhof:




300
420
600
171


300
420
600
172


420
600
173


300
420
600
174


300
420
600
175


105
150
210
176


300
420
600
177-178


300
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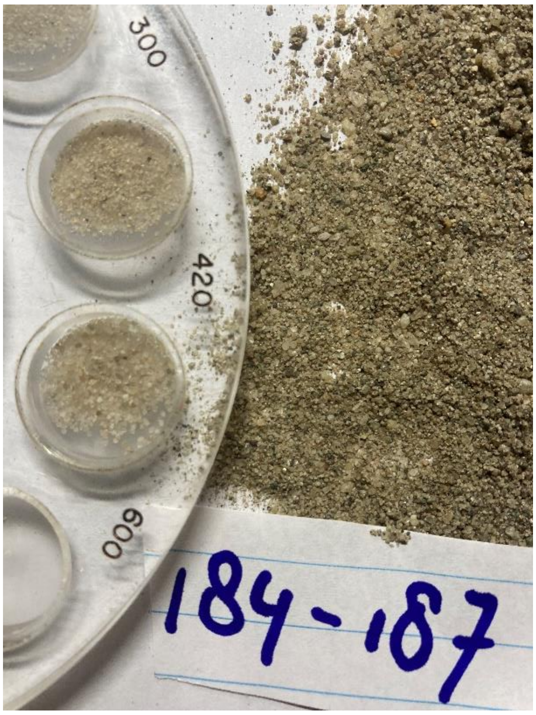
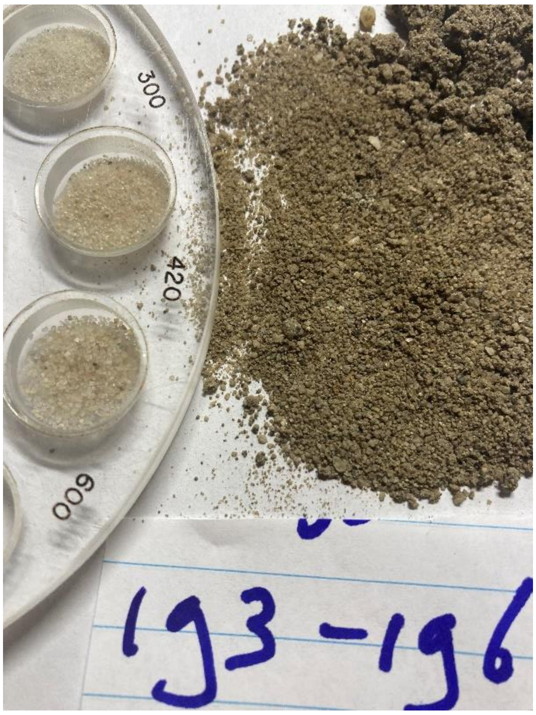
600
1000

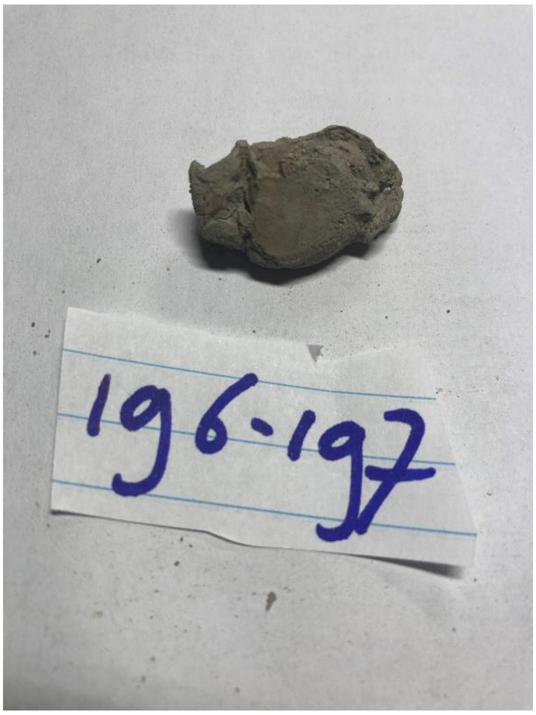

420
600
181-184

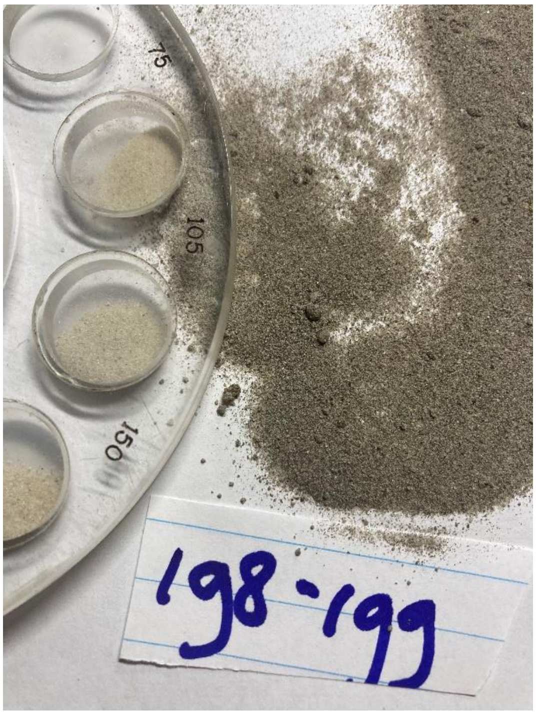

300
420
600
184-187


210
300
420
600
187-190


210
300
420
190-193


300
420
600
193-196


196-197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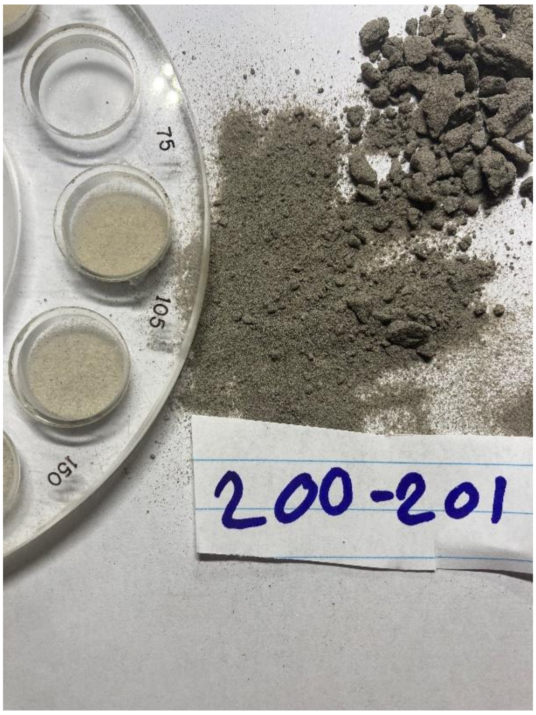
105
150
198-199


75
105
150
200-201

Annex 4: Pumping test

Pumping test set-up

The wells used for the pumping test (Figure A) were:

- G1 – this well was used to pump the water. A constant discharge of 71.5 m^3/h for 4 hours was pumped. Then the pump was turned off and the recovery was monitored for 1.5 hours. The levels were monitored and registered manually. There are pictures of these values but according to the professionals present during the pumping test, these values are probably not accurate, therefore they have not been used.
- G2 – this well was used to measure groundwater levels manually. The frequency of the measurements changed during the test.
- M1 – this well was used to measure groundwater levels with a sensor. To have a back-up, two sensors were installed. The frequency of the measurements was fixed to 1 minute.

The coordinates of the 3 wells in EPSG:3405 - VN-2000 / UTM zone 48N are:

Well	x	Y	Distance to pumping well	Screen depth (m bgl)
M1	590272	1085488	42	167 - 187
G1	590229	1085487	0	171 – 192
G2	590323	1085479	94	171 – 192

Figure A Map with the wells used for the pumping test

The three wells are screened in the same aquifer layer (qp_1) according to their design and lithological description. Figure B shows a cross-section with the location of the 3 wells, showing the detail of their lithological description and design. As can be observed, well G1 and G2 have the exact same lithology, while M1, located between them, seems to have more differentiated layers. This could be due to the drilling and sampling methods used for the wells. While the drilling method used for G1 and G2 is unknown, it is often the case that production wells are drilled with methods that do not allow the collection of undisturbed samples. M1 was meant as a monitoring well and care was taken to take samples between 150 and 200m.

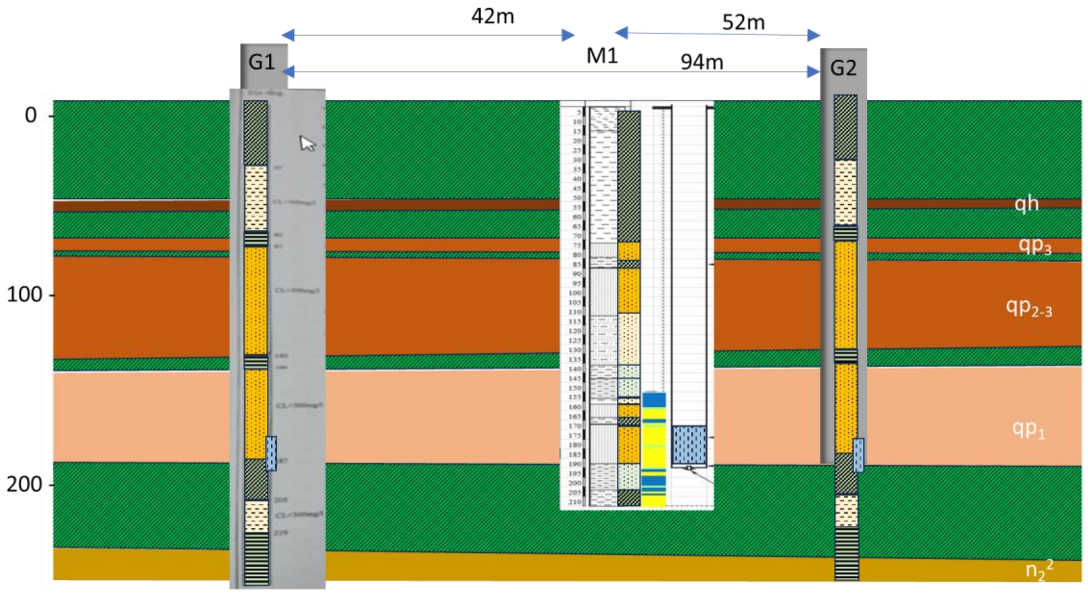


Figure B Cross-section showing the location, lithology and design of G1, G2 and M1 in the Nga Bay site. The layers in the cross-section representing the aquifers and aquitards are the result of the interpolation of available wells in the region.

Methodology

For the analysis of the pumping test data, an analytical elements model for transient multi-layer groundwater flow was used (TTIM).

The hydrogeological system was schematized as two aquitards and two aquifers, representing four layers between -150 and -187 m (*Table A4-1*). Below 187m there is a layer of silty clay considered here as impermeable. The lithology of M1 was taken for this schematization.

The description of the lithology as registered during the drilling (Table A4-1) was used to define thickness, initial hydraulic conductivity, and storage coefficient values for the layers. Later these values were modified to calibrate the model and fit the model results to the measured drawdown values at M1 and G2.

The leaky aquitard represented by layer 1 was considered to be confining and not have storage, meaning that the head was kept constant above the leaky layer. This was chosen given the clear description of a clay layer with no water holding capacity.

Table A4-1 Depth (mbgl) and description of hydrogeological layers used for the TTIM model.

Depth (m bgl)	Grain size	Aquifer code	Model layer
150-156	Clay		1
156-162	blue-grey fine to medium grained sand	qp_1	2
162-167	Clay and silt		3
167-187	Medium to very coarse grained sand mixed with gravel	qp_1 (filter)	4

As mentioned, the lithological description of G1 and G2 was compared to the lithological description of M1 to understand if there might be some discontinuous layers between these wells. Notably, the lithological description of G1 and G2 showed thicker layers in general, which might indeed be because the layers are ticker or because the description of the lithology was less detailed due to the drilling technique used.

Taking this into account, it was decided to use the description of M1 to build the model and calibrate it. To account for uncertainties, the model was run several times with different values for the thickness of layers 3 and 4, for the resistance of layer 3, and for the hydraulic conductivity of layer 2. The thickness values were taken from the differences between field notes and the reported description of the well M1. For the resistance of layer 3, the values of 100 and 1000 days were used. These values could represent a very leaky layer (100d) and a rather impermeable layer (1000d). For layer two a range of hydraulic conductivity values that could fit the lithological description was used (20, 50 and 100m/d).

Runs executed:

Model 1

Depth (m bgl)	Grain size	Aquifer code	Model layer	Initial hydraulic conductivity	Initial resistance
150-156	Clay		1		
156-162	Medium coarse sand	qp_1	2	50	
162-167	Clay and silt		3		1000
167-187	Medium coarse sand	qp_1 (filter)	4	85	

Model 2 (lower resistance layer 3)

Depth (m bgl)	**Grain size**	**Aquifer code**	**Model layer**	**Initial hydraulic conductivity**	**Initial resistance**
150-156	Clay		1		
156-162	Medium coarse sand	qp_1	2	50	
162-167	Clay and silt		3		100
167-187	Medium coarse sand	qp_1 (filter)	4	85	

Model 3 (thinner layer 3 and thicker layer 4)

Depth (m bgl)	**Grain size**	**Aquifer code**	**Model layer**	**Initial hydraulic conductivity**	**Initial resistance**
150-156	Clay		1		
156-162	Medium coarse sand	qp_1	2	50	
162-164	Clay and silt		3		1000
164-194	Medium coarse sand	qp_1 (filter)	4	85	

Model 4 (thinner layer 3, thicker layer 4 and lower resistance layer 3)

Depth (m bgl)	**Grain size**	**Aquifer code**	**Model layer**	**Initial hydraulic conductivity**	**Initial resistance**
150-156	Clay		1		
156-162	Medium coarse sand	qp_1	2	50	
162-164	Clay and silt		3		100
164-194	Medium coarse sand	qp_1 (filter)	4	85	

Models 5 and 6 (same as Model 1, only k layer different values)

Depth (m bgl)	Grain size	Aquifer code	Model layer	Initial hydraulic conductivity	Initial resistance
150-156	Clay		1		
156-162	Medium coarse sand	qp_1	2	20 (Model 6),100(Model 5)	
162-167	Clay and silt		3		1000
167-187	Medium coarse sand	qp_1 (filter)	4	85	

The models were first calibrated using the measured drawdown and recovery in M1 and G2 separately. After that, the models were calibrated using the data collected in both M1 and G2 combined.

Results

The results that were analyzed are the fit between water levels computed and measured, and the values of hydraulic conductivity, transmissivity and storage coefficient that provided the best fit for each model.

Model 1

When the wells M1 and G2 are used separately for the calibration of the model (Figure C), a good fit can be obtained with an hydraulic conductivity of 115 m/d and a storage coefficient of 1.2E-05 for qp_1 with the M1 data, and an hydraulic conductivity of 209 m/d and a storage coefficient of 5.6E-05 for qp_1 with G2 data.

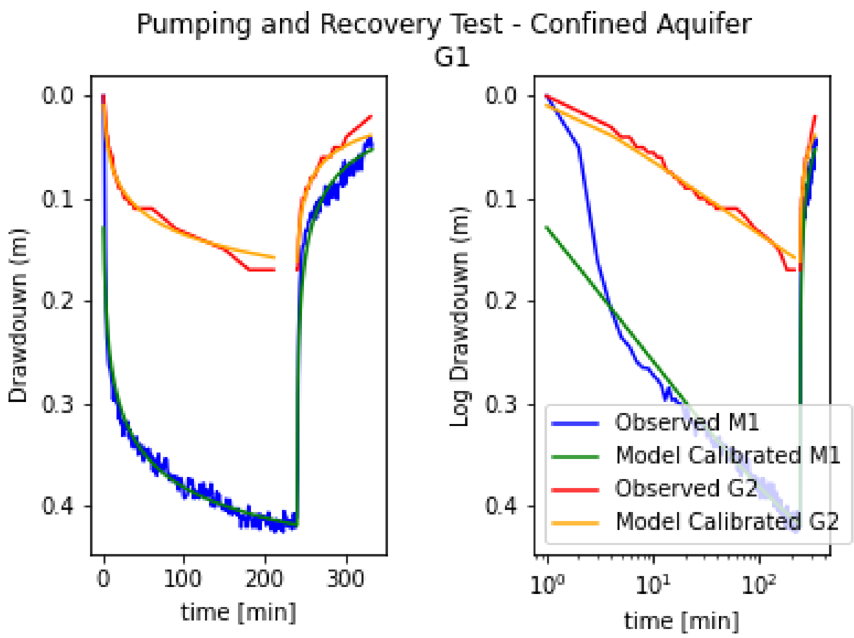


Figure C Measured drawdown and recovery and model fit for M1 and G2. The blue line shows the measured data by a sensor in the monitoring well M1. The red line shows the manual measurements conducted in the well G2, and the green and orange lines show the results of the model when calibrating it separately for M1 and G2.

If M1 and G2 are used combined for the calibration (Figure D), there is no good fit for both observation wells. The fit is particularly poor for G2. The resulting hydraulic conductivity is 112 m/d.

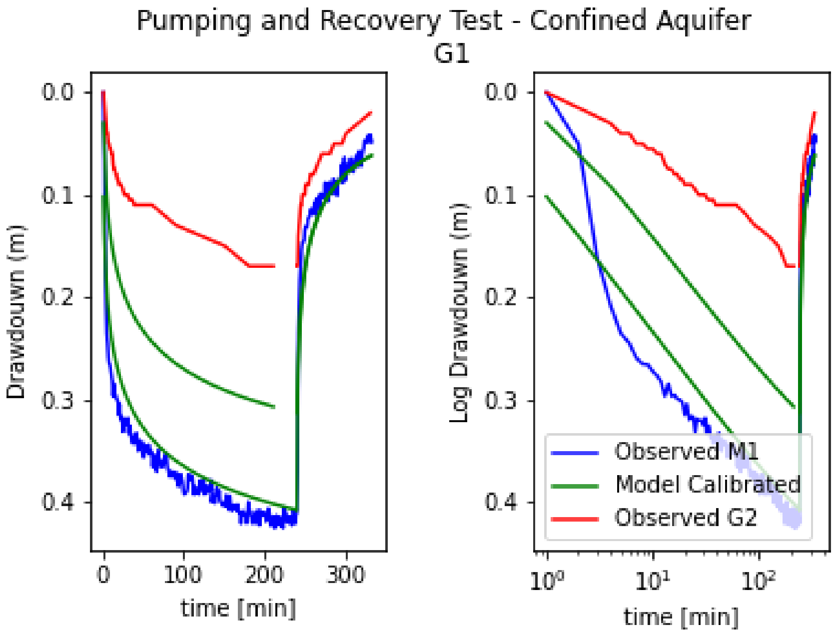


Figure D Measured drawdown and recovery and model fit for M1 and G2. The blue line shows the measured data by a sensor in the monitoring well M1. The red line shows the manual measurements conducted in the well G2, and the green lines show the results of the model when calibrating it for M1 and G2 combined.

Table B Modelled results for hydraulic conductivity (K) in m/d, transmissivity (T) in m²/d and storage coefficient (S) dimensionless using data of M1 and G2

Well	K (m/d)	T (m^2/d)	S
M1 pumping and recovery	115	2307	1.2E-05
G2 pumping and recovery	209	4185	5.6E-05
M1and G2 pumping and recovery	112	2246	2.0E-05

The values found for the different calibration options for layer 4 are shown in *Table* .

The difference in values for hydraulic properties when using data from M1 and G2 separately, can be explained by the fact the G2 is further away from G1, and might have a different lithology than M1. The model made for M1 might thus not represent the lithology in the location of G2. Taking this into consideration, the results of M1 are taken as most reliable. For that reason, only results for M1 are shown for the other models.

Model 2 (lower resistance layer 3)

A lower resistance between layers 2 and 4 results in lower hydraulic conductivity values for layer 4 as expected because water from layer 2 can flow with less resistance to the well.

Table C Modelled results for hydraulic conductivity (K) in m/d, transmissivity (T) in m²/d and storage coefficient (S) dimensionless using data of M1.

Well	K (m/d)	T (m^2/d)	S
M1 pumping and recovery	99	1977	1.3E-05

Model 3 (thinner layer 3 and thicker layer 4, resistance layer 3 = Model 1)

This model shows a good fit with an hydraulic conductivity of 77m/d and transmissibility of 1538 m²/d. These values are lower than for models 1 and 2 as expected, as the layer 3 offers less resistance to the flow being thinner, and layer 4, the aquifer, is thicker.

Table D Modelled results for hydraulic conductivity (K) in m/d, transmissivity (T) in m²/d and storage coefficient (S) dimensionless using data of M1.

Well	K (m/d)	T (m^2/d)	S
M1 pumping and recovery	77	1538	7.9E-06

Model 4 (thinner layer 3, thicker layer 4 and lower resistance layer 3)

In this case, the resistance of layer 3 is the lowest of all models. That combined with a thicker layer 4, results in a fit when the hydraulic conductivity of 66m/d.

Table E Modelled results for hydraulic conductivity (K) in m/d, transmissivity (T) in m²/d and storage coefficient (S) dimensionless using data of M1.

Well	K (m/d)	T (m^2/d)	S
M1 pumping and recovery	66	1318	8.9E-06

Model 5 (same as model 1, only k layer 2 different values)

If the hydraulic conductivity of layer 2 changes (in this case values of 20m/d and 100m/d were tested), the k for layer 4 remains the same.

Table F Modelled results for hydraulic conductivity (K) in m/d, transmissivity (T) in m²/d and storage coefficient (S) dimensionless using data of M1.

Well	K (m/d)	T (m^2/d)	S
M1 pumping and recovery	115	2302	1.19E-05

Conclusions and recommendations

Given the uncertainties in the resistance of the aquitard above the aquifer monitored, and the hydraulic conductivity of the layer above that aquitard, it is not possible to conclude on one single value for the hydraulic conductivity for the aquifer, but most probably it is between 99 and 115m/d.

If other uncertainties such as the thickness of the aquifer and the aquitard are considered, the range of the hydraulic conductivity could be between 66 and 115m/d.

As seen in the results for Model 1, the hydraulic properties that give a good fit for the model at M1 differ to those that give a good fit for G2. This is most probably due to heterogeneities in the geology between the wells, however, this could not be depicted from these pumping test results.

Therefore, the recommendations are to either:

- repeat the pumping test with an automatic sensor in M1 and G2
- conduct a pumping test using the well G2 to pump, and M1 and G1 as observation wells
- conduct a pumping test in the ASR well to be constructed and use M1, G1 and G2 as observation wells using slim automatic loggers in all four wells in addition to manual measurements in M1.