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Torridon: Borehole Drilling and Testing

Groundwater Systems and Water Quality Programme

Internal Report IR/04/183

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SYSTEMS AND WATER QUALITY PROGRAMME

INTERNAL REPORT IR/04/183

Torridon: Borehole Drilling and Testing

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1 Introduction

Two boreholes for potential public water supply were drilled at Annat, by Torridon, from August to September 2004. The boreholes were commissioned by Scottish Water. The project was managed by Galliford Morgan Joint Venture. Advice on borehole siting, construction and testing was provided by the British Geological Survey (BGS). The boreholes were drilled and pumping tests carried out by Drilcorp Ltd. of Seaham, Co. Durham.

This report presents geological and hydrogeological data collected during borehole drilling and testing and assesses the hydrogeological characteristics of the borehole and the surrounding aquifer with reference to the suitability of the borehole to provide a public water supply.

2 Borehole location

Torridon is a small settlement in the northern Highlands, located on the coast at the mouth of Glen Torridon, at NGR NG 89 56 (Figure 1). The boreholes are sited to the east of Annat, by Torridon, on the southern edge of the valley, which is almost 1.5 km wide at this point. Steep, rocky slopes rise up immediately to the south. The boreholes are located at NGR NG 90345 54683 (borehole 1) and NG 90316 54710 (borehole 2) (Figure 2), and are at an elevation of between approximately 17 and 20 m above Ordnance Datum (OD).

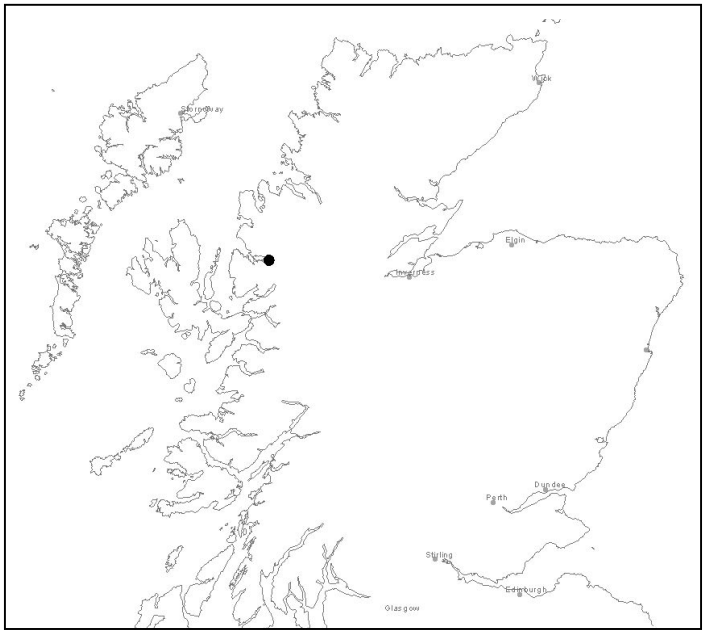

Figure 1 Location of Torridon in the northern Highlands

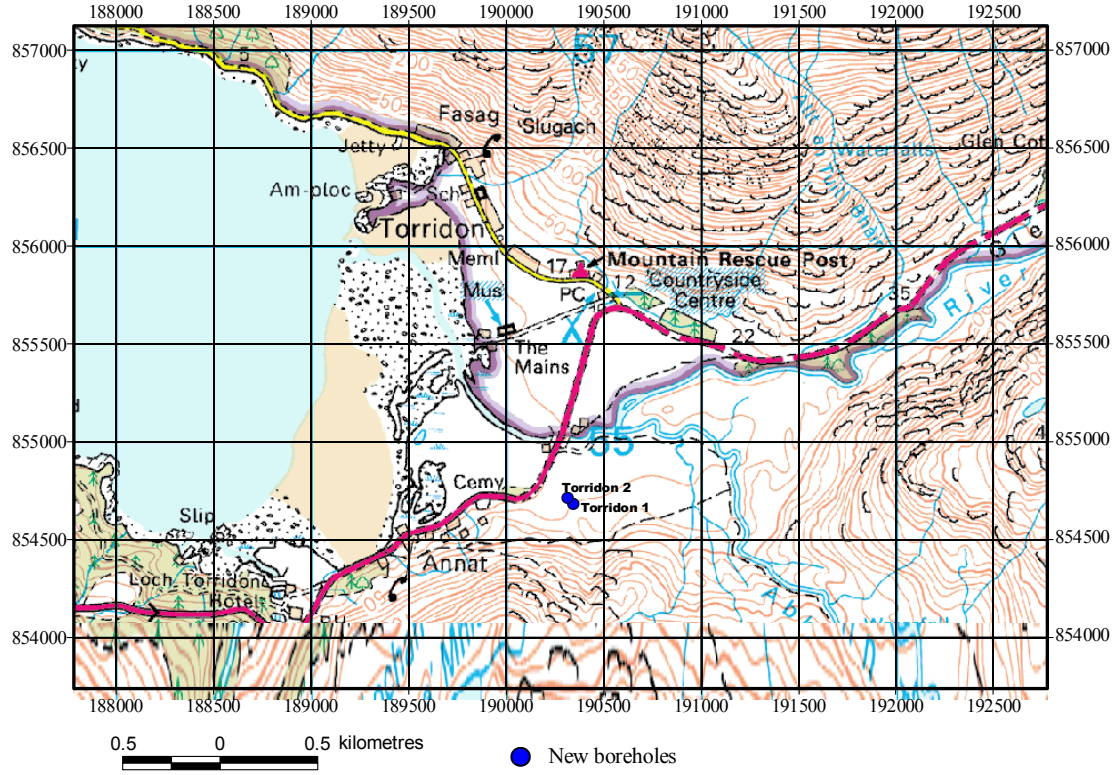

Figure 2 Location of new boreholes at Torridon

3 Geology

A complex sequence of superficial deposits underlies the valley between Annat and Torridon (Figure 3). Glacial deposits occur along the southern part of the valley and in a small tributary valley to the east of Annat. Alluvial fan deposits occur on the northern side of the valley. In the central part of the valley are river terrace deposits, which give way to raised beach and marine beach deposits closer to the coast.

The new boreholes are sited approximately 120 m from the southern edge of the mapped superficial deposits in the valley, on undifferentiated glacial deposits. Information from drilling indicates that the superficial sequence is at least 20 m thick here, and is dominated by poorly sorted sand and gravel with numerous boulders.

Bedrock in this area comprises Precambrian pebbly sandstones of the Applecross Formation, of the Torridonian sandstone. The depth to bedrock varied from 21.6 m in borehole 2 to over 25.4 m in borehole 1, which lies at a slightly higher elevation.

Summary geological logs of the boreholes have been drawn up, based on information collected during drilling (Figure 4).

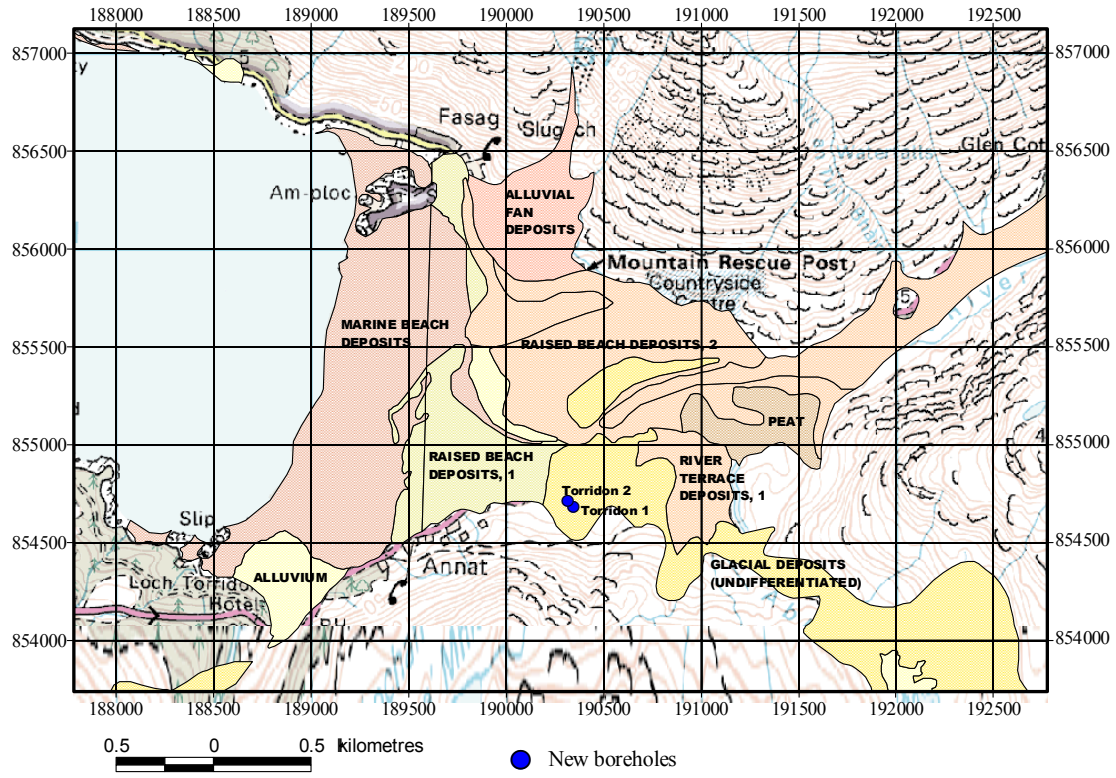

Figure 3 Superficial deposits in the Torridon area

(i) Borehole 1 (NG 90345 54683)

Depth (m)	Geology
0 – 1	Peat
1 – 6.10	Sand and gravel, with many rounded cobbles up to 100 mm
6.10 – 11.40	Red-brown sandstone boulders
11.40 – 25.40 +	Sand and gravel, coarse, with broken sandstone

(ii) Borehole 2 (NG 90316 54710)

Depth (m)	Geology
0 – 0.80	Peat
0.80 – 10.20	Cobbles, boulders, some gravels derived from sandstone
10.20 – 21.60	Red-brown gravels and cobbles/boulders derived from sandstone; many quartz fragments
21.60 – 22.00 +	Red-brown coarse sandstone (dry)

Figure 4 Geological logs for new boreholes at Torridon: (i) borehole 1; (ii) borehole 2

4 Borehole drilling

Borehole 1 was drilled between 17 and 18 August 2004, to a depth of 25.40 m. No water strike details were recorded by the driller. A geological log was drawn up based on observation of drilling returns (Figure 4 (i)).

Borehole 2 was drilled between 22 and 28 August 2004, to a depth of 22.00 m. Water was struck at 10.2 mbgl. A geological log was drawn up based on observation of drilling returns (Figure 4 (ii)).

5 Borehole construction and development

5.1 BOREHOLE 1

Location:	NG 90345 54683
Total depth:	25.4 mbgl
Surface casing:	200 mm diameter mild steel (GL to approx. 50 mbgl)
Screen/casing:	113 mm diameter plain uPVC casing (GL to 19.5 mbgl)
	113 mm diameter uPVC well screen; slot size 1 mm (19.5 to 25.4 mbgl)
	End cap installed
Gravel pack:	Clean 'Scotsand' type; size in the range 1.9 to 2.6 mm diameter, from approximately 15 m to 25.4 mbgl.
Wellhead:	300 mm heavy duty flange and blank plate
Development:	Air lift over 1 day; exact time unknown.

5.2 BOREHOLE 2

Location:	NG 90316 54710
Total depth:	21.6 mbgl
Surface casing:	200 mm mild steel (GL to approx. 13 mbgl)
Screen/casing:	113 mm diameter plain uPVC casing (GL to 14 mbgl)
	113 mm diameter uPVC well screen; slot size 1 mm (14 to 21.6 mbgl)
	End cap installed
Gravel pack:	Clean 'Scotsand' type; size in the range 1.9 to 2.6 mm diameter, from 13 m to 21.6 mbgl). Bentonite pellet seal above the pack to 0.7 m bgl.
Wellhead:	300 mm heavy duty flange and blank plate
Development:	Air lift over 2 days; exact time unknown.

6 Test pumping

6.1 BOREHOLE 1

A 14-day pumping test was carried out on borehole 1 from 3 to 17 September 2004 using an electrical submersible pump. The pump intake was at 23.60 m below datum (mbd). The datum level was the top of the dip tube at 0.25 m above ground level. The borehole was pumped at an average rate of 1.3 litres/second (l/s) during the test (based on flowmeter readings). Pumping was stopped temporarily once during the test, due to malfunctioning equipment. Changes in pumping rate were made during the test to prevent water levels from drawing down below sea level.

The rest water level in the borehole is approximately 13.9 mbd. An automatic water recorder (a Diver compensated pressure transducer) was used to collect borehole water level data during the test. The recorder was set at 22.40 mbd. Water level measurements were taken at 10 minute intervals between 2 and 23 September 2004. A chart showing the data collected by the automatic recorder during the pumping test is shown in Figure 5.

Detailed manual water level measurements were made during the first 2 hours of the pumping test and then at twice daily intervals throughout the test. These can be seen in Appendix 1. Measurements were made using an electronic dipper. A dip tube was installed in the borehole for the duration of the test pumping. A log-normal chart of manually measured water levels during the pumping test is shown in Figure 6, which also plots the pumping rate during the test, showing how pumping rate varied and affected water level drawdown, particularly near the end of the test.

The pumping water level in the borehole fluctuated during the test as a result of pump switch off (due to temporary generator failure) and of changes in pumping rate. The water level did not stabilise during the 2 week pumping test, but continued to fall slightly, even at a relatively constant pumping rate of approximately 1.6 l/s. The maximum water level drawdown in the borehole during the test was 2.94 m, on the seventh day of the test. The water level recovered when the pumping rate was decreased to approximately 0.75 l/s, but fell noticeably below the previous level when the pumping rate was increased to approximately 1.4 l/s.

Automatically measured data from the recovery period of the test are shown in Figure 7.

The data from the pumping period of the test are difficult to analyse because of the variations in pumping rate. The transmissivity of the aquifer in the area of borehole 1 has been estimated from recovery data using Jacob's method, at 13 m^2/day.

The specific capacity of the borehole was estimated at 38 m^3/day/m, based on the average pumping rate of 1.3 l/s during the test and a drawdown of 2.94 m.

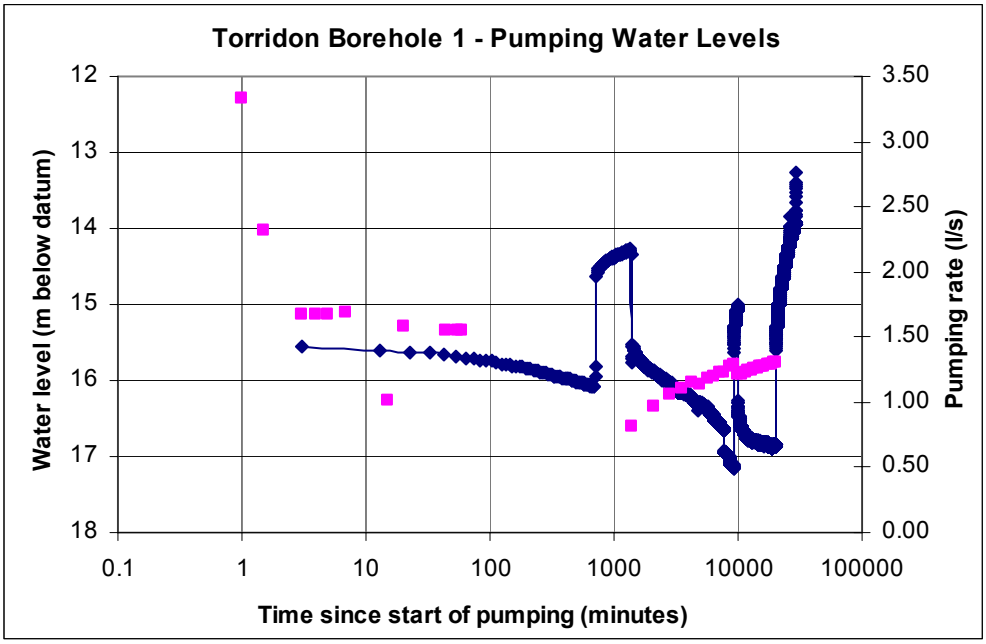

Figure 5 Water levels in borehole 1 during pumping test on borehole 1. From the automatic data recorder

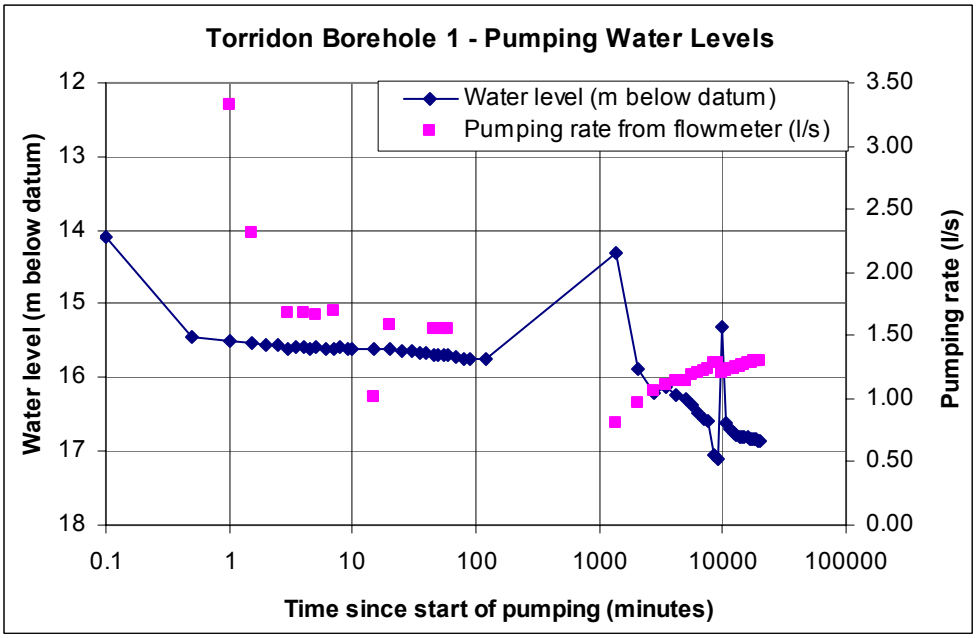

Figure 6 Water levels and pumping rates in borehole 1 during the pumping test on borehole 1. From manually measured data

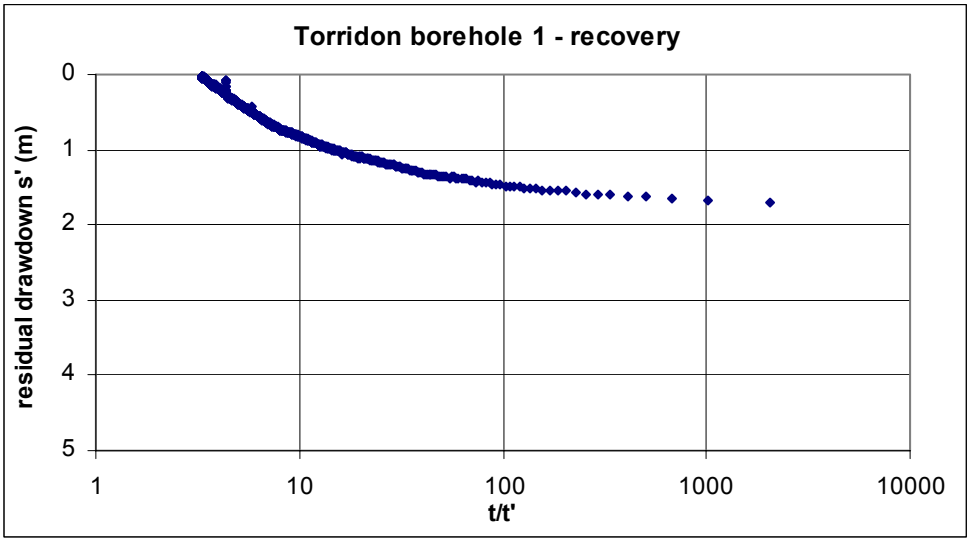

Figure 7 Recovery data from test pumping on borehole 1

6.2 BOREHOLE 2

A 14-day pumping test was carried out on borehole 2 from 1 to 15 October 2004. The pump intake depth was not recorded. The datum during the test was the top of the dip tube. The elevation of the top of the dipper tube was not recorded, but it was close to the top of the steel surface casing. The borehole was pumped at an average rate of 1.56 l/s during the test (based on flowmeter readings). Water level data were also recorded in borehole 1 during the test on borehole 2.

The rest water level in borehole 2 is approximately 9 mbd. An automatic recorder (a Diver compensated pressure transducer) was used to collect borehole water level data during the test. The depth the recorder was set at was not recorded. Water level measurements were taken at 15 minute intervals. A chart showing the data collected by the automatic recorder is shown in Figure 8. The time of the start of the test, and the rest water level at the start of the test, were not recorded manually. Manual water level measurements were made at twice daily intervals during the pumping period of the test. These can be seen in Appendix 1. A chart of manually measured water levels in borehole 2 during the pumping test is shown in Figure 9. This chart also shows water levels measured in borehole 1, used as an observation borehole during the test, and the pumping rate during the test. Note that this chart does not record time since the start of the pumping test and is not log-normal.

As in borehole 1, the water level in borehole 2 did not stabilise during the 2 week pumping test, but continued to fall, even at a relatively constant pumping rate of approximately 1.5 l/s. Assuming a rest water level of 9 mbd, the maximum drawdown during the test was 2.1 m.

Automatically measured data from the recovery period are shown in Figure 10.

Data from both the pumping and the recovery periods of the test were used to estimate the transmissivity of the aquifer surrounding borehole 2, using Jacob's method. Analysis of pumping data gives a transmissivity value of 38 m^2/day and analysis of recovery data gives a value of 35 m^2/day.

The specific capacity of the borehole was estimated at 62 m^3/day/m, based on an average pumping rate of 1.5 l/s during the test and a drawdown of 2.1 m.

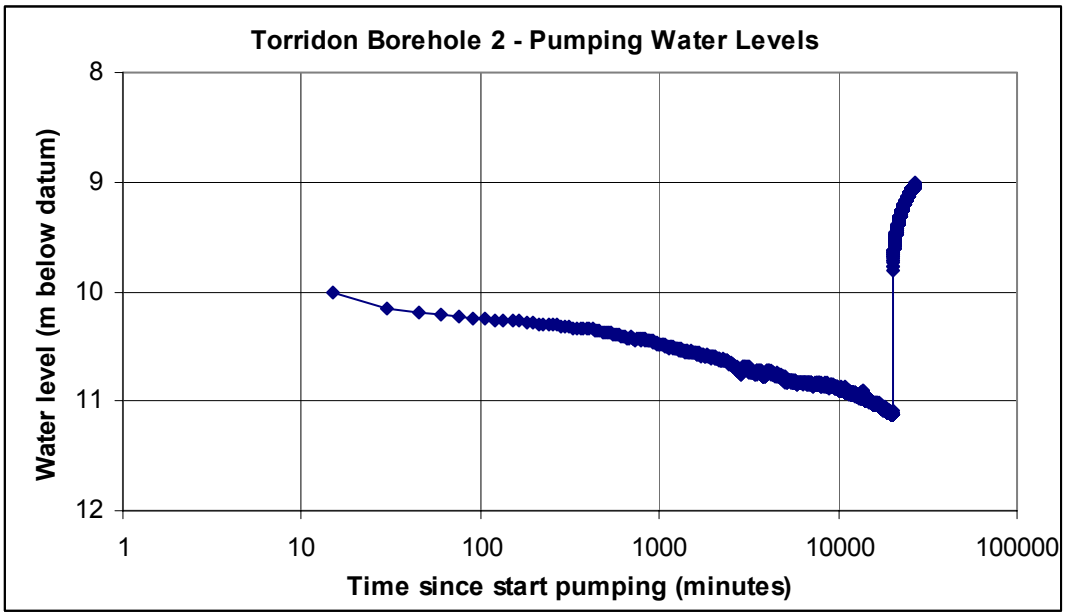

Figure 8 Water levels in borehole 2 during the pumping test on borehole 2. From automatically measured data

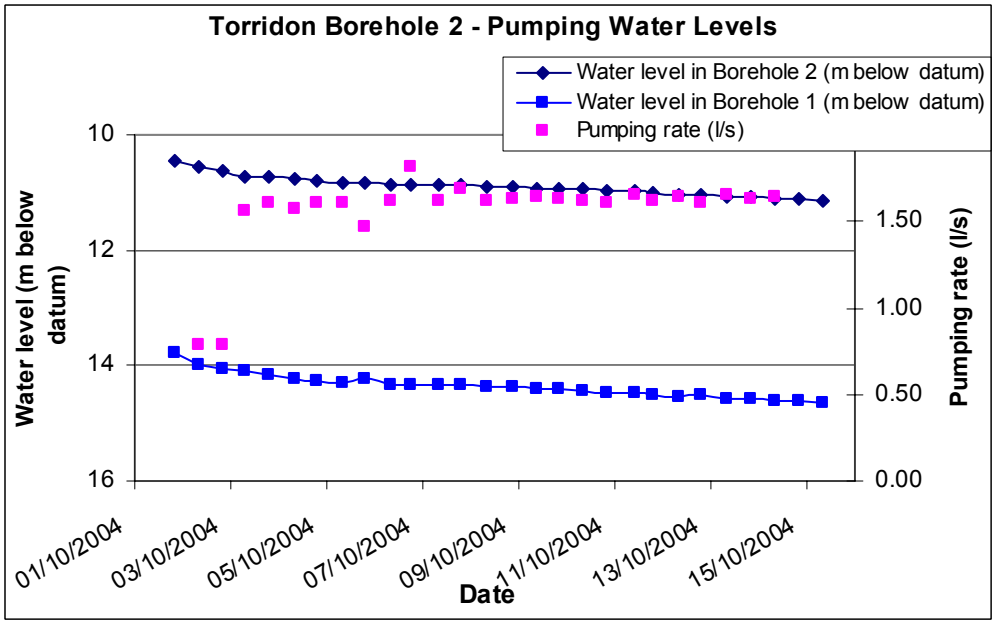

Figure 9 Water levels and pumping rates in borehole 2 and borehole 1 during the pumping test on borehole 2. From manually measured data

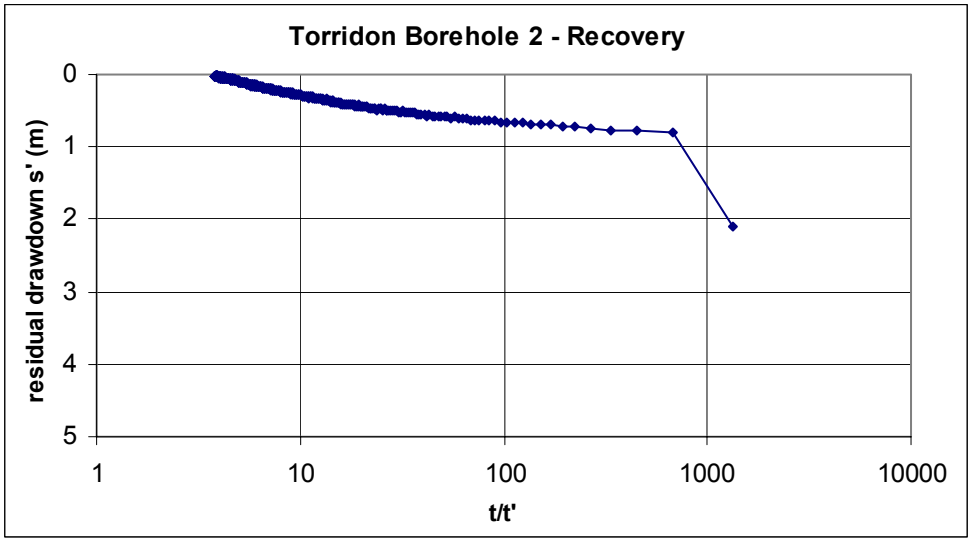

Figure 10 Recovery data from test pumping on borehole 2

7 Groundwater quality testing

7.1 BOREHOLE 1

Water samples were taken from borehole 1 at intervals specified by the client, before and during the pumping test. The first sample was taken on 27 August. The samples were taken as specified by Scottish Water. Before each of the samples was taken, the borehole had been pumped continuously for long enough to purge the borehole effectively. The samples were analysed at a Scottish Water laboratory for a limited range of constituents. No analysis results are, as yet, available.

7.2 BOREHOLE 2

Five water samples were taken from borehole 2 at intervals specified by the client during the pumping test, on 5, 8, 11, 13 and 15 October. The samples were taken as specified by Scottish Water. Before each of the samples was taken, the borehole had been pumped continuously for long enough to purge the borehole effectively. The samples were analysed at a Scottish Water laboratory for a limited range of constituents. No analysis results were available.

8 Assessment of the groundwater resource

8.1 BOREHOLE 1

Borehole 1 lies approximately 660 m distant from the high water mark at an elevation of approximately 20 m OD.

The borehole was tested at a pumping rate that ranged between approximately 1 and 1.7 litres/second (l/s) (86 – 147 m^3/day). A pumping rate of approximately 1.5 l/s was maintained for the first 2 hours of the test. On the second day the pumping rate fell to approximately 1 l/s and from then until the end of the test on the 14th day the pumping rate

increased slowly to 1.3 l/s. This increase in yield over the length of the test may have been related to increased borehole efficiency due to the development effects of pumping.

The rest water level in the borehole is approximately 13.9 mbd. The maximum water level drawdown in the borehole during the test was 2.94 m, on the seventh day of the test. The manually measured data show that the pumping water level did not stabilise but continued to fall slightly throughout the test. This suggests that the long-term sustainable pumping rate for this borehole is less than the actual test discharge rate of 1.3 l/s, but further testing is required to confirm this. Sustainable pumping rate refers to that abstraction rate that is expected to be sustainable throughout the design life of the borehole. In other words, recharge will replenish the aquifer at the same rate, allowing abstraction to take place for an infinite time. The sustainable pumping rate for borehole 1 is likely to be of the order of 80 – 90 m^3/day (approximately 0.93 to 1.04 l/s). At this rate, pumping water level is expected to stabilise at approximately 16 mbgl, or slightly above sea level.

An examination of the automatically measured water level data before and after the pumping test suggests there is no direct tidal impact on water levels in the borehole. There may be a relationship between borehole water levels and the level of water in the river to the north of the site, but in the absence of river level data this cannot be investigated.

In the absence of groundwater chemistry, no assessment of groundwater chemistry can be made.

8.2 BOREHOLE 2

Borehole 2 lies approximately 630 m distant from the high water mark at an elevation of approximately 17 m OD.

The borehole was tested at a pumping rate that ranged between approximately 0.8 and 1.7 l/s. During most of the test a rate of approximately 1.6 l/s was maintained.

The rest water level was not measured manually at the start of the pumping test, but from automatically measured data is estimated at 9 mbd. Assuming this rest water level, the maximum drawdown is 2.1 m. The pumping water level in borehole 2 did not stabilise but continued to fall throughout the test. This suggests that the long-term sustainable pumping rate (>20 years) for this borehole is less than 1.6 l/s and is likely to be of the order of 1.1 l/s (90 m^3/day). However, further testing is required in order to confirm this.

An examination of the automatically measured water level data before and after the pumping test suggests there is no direct tidal impact on water levels in the borehole. There may be a relationship between borehole water levels and the level of water in the river to the north of the site, but in the absence of river level data this cannot be investigated.

In the absence of groundwater chemistry, no assessment of groundwater chemistry can be made.

8.3 OVERALL ASSESSMENT

The aquifer comprises gravelly superficial deposits, which are between 21 and at least 25 m in the area of the boreholes. The aquifer is likely to have high intergranular permeability. There is likely to be a considerable thickness of gravelly superficial deposits between the borehole sites and the coast, which contain a considerable volume of groundwater that is slowly discharging to the sea and the river. At an abstraction rate of 80 m^3/day, the pumping water level in the abstraction boreholes is expected to be close to sea level. This will minimise any risk of saline intrusion.

During the pumping test on borehole 2, the drawdown in borehole 1, at a distance of 45 m, was approximately 2 m. If both boreholes were pumped together at the same time, interference between them is likely to cause some reduction in borehole efficiency and potential yield in both

boreholes. However, the effects of pumping on the water table across the valley are not expected to be significant.

A proportion of recharge to the gravel aquifer comes directly from rainfall, the rest being derived from surface water runoff flowing down from the mountains to the south. The volume and pathways of recharge to the aquifer are likely to be variable, as peaty layers near the surface will act as barriers to infiltrating rainfall. This was demonstrated during the early stages of the pumping test on borehole 1, when water discharging from the borehole was allowed to form a pond adjacent to the site. In spite of the presence of a thick gravelly layer at the surface, the water did not soak away readily.

The actual amount of recharge has not been quantified, but it is likely to be much greater than the planned abstraction rate for the Torridon site (less than 80 m^3/day). Long-term abstraction at this rate is not likely to cause an overall decline in the water table. Over the long term (more than 20 years) the aquifer is expected to be able to sustain an abstraction rate of 80 m^3/day.

9 Risks to groundwater abstraction

The following is a summary of the risks to groundwater abstraction from the Torridon boreholes. It does not constitute a comprehensive risk assessment.

- Saline intrusion: the boreholes lie approximately 650 m from the high water mark and at elevations of approximately 17 to 20 m OD. If the pumping water level in the boreholes is drawn down below sea level over the long-term (i.e. more than 17 to 20 m below ground level), there is a risk of drawing saline water into the local aquifer.
- Insufficient recharge: the main sources of recharge to the local aquifer are direct infiltration from rainfall and indirect recharge from surface water runoff. Recharge to the aquifer cannot be accurately estimated based on available data, but it is likely to be much greater than 80 m^3/day. Neither rainfall nor aquifer permeability are likely to limit recharge to the aquifer.
- Point source contamination: no known point sources of contamination directly pose a risk to the boreholes. The nearest house is downgradient of the boreholes. Potential point sources include septic and fuel tanks and landfill.
- Diffuse contamination: local land use is not such that there is likely to be a risk from diffuse contamination.
- Other groundwater abstractions: there are no known other groundwater abstractions in the area.

10 Conclusions

- Drilling at Torridon has proved the presence of a superficial sequence dominated by sand and gravel.
- Fourteen day pumping tests carried out on the two boreholes at Torridon have indicated that the sand and gravel forms a productive aquifer.
- Initial indications from test pumping are that the site (i.e. the combined potential of both boreholes) has a potential yield of at least 80 m^3/day. This rate is likely to be sustainable over the long term, i.e. at least 20 years, in that recharge to the aquifer is expected to be sufficient to replace the water abstracted.

- However, further long-term testing of the boreholes at Torridon is necessary to confirm the limits to long term abstraction at the site.

Appendix 1 Manual water level measurements during test pumping

BOREHOLE 1

Date	Time	Minutes since start pumping	Water level (m below datum)	Pumping rate (l/s) reported by driller	Flowmeter (m^3)	Average pumping rate (l/s) calculated from flowmeter	Comments
03/09/2004	09:07	0.1	14.1		7294.70		
		0.5	15.45				
		1	15.51		7294.90	3.33	
		1.5	15.53		7294.91	2.31	
		2	15.55				
		2.5	15.57				
		3	15.61		7295.00	1.68	
		3.5	15.59				
		4	15.58		7295.10	1.67	
		4.5	15.6				
		5	15.59		7295.20	1.67	
		6	15.61				
		7	15.6	1.55	7295.41	1.69	
		8	15.58				
		9	15.6				
	09:17	10	15.6	1.55			
		15	15.61		7295.61	1.01	
	09:27	20	15.62		7296.60	1.58	
		25	15.63	1.55			
	09:37	30	15.64				
		35	15.66				
	09:47	40	15.67				
		45	15.68	1.55	7298.90	1.56	
	09:57	50	15.69				
		55	15.69	1.55	7299.80	1.55	
	10:07	60	15.7		7300.30	1.56	
	10:17	70	15.72	1.53			
	10:27	80	15.74				
	10:37	90	15.76				
	11:07	120	15.76	1.55			
04/09/2004	08:00	1373	14.3		7361.50	0.81	pump stopped
	20:00	2093	15.88		7415.90	0.97	
05/09/2004	08:00	2813	16.2		7473.70	1.06	
	20:00	3533	16.12		7529.50	1.11	
06/09/2004	08:00	4253	16.23		7586.80	1.14	
	20:00	4973	16.28		7634.60	1.14	
07/09/2004	08:00	5693	16.36		7699.90	1.19	
	20:00	6413	16.48		7755.10	1.20	
08/09/2004	08:00	7133	16.55		7818.30	1.22	
	18:00	7733	16.6		7864.40	1.23	

Borehole 1, continued

Date	Time	Minutes since start pumping	Water level (m below datum)	Pumping rate (l/s) reported by driller	Flowmeter (m^3)	Average pumping rate (l/s) calculated from flowmeter	Comments
09/09/2004	08:00	8573	17.04		7953.90	1.28	
	19:00	9233	17.1		8007.00	1.29	
10/09/2004	08:00	10013	15.3		8021.30	1.21	pump stopped during night
	20:00	10733	16.61		8077.70	1.22	
11/09/2004	08:00	11453	16.7		8138.80	1.23	
	20:00	12173	16.76		8198.60	1.24	
12/09/2004	08:00	12893	16.78		8259.20	1.25	
	20:00	13613	16.8		8319.60	1.25	
13/09/2004	08:00	14333	16.81		8380.90	1.26	
	18:00	14933	16.8		8431.10	1.27	
14/09/2004	08:00	15773	16.81		8504.50	1.28	
	18:00	16373	16.82		8552.10	1.28	
15/09/2004	08:00	17213	16.82		8624.90	1.29	
	18:00	17813	16.84		8675.40	1.29	
16/09/2004	08:00	18653	16.84		8745.20	1.30	
	18:00	19253	16.85		8797.30	1.30	
17/09/2004	08:00	20093	16.85		8869.80	1.31	

BOREHOLE 2

Date	Time	Water level (m below datum)	Water level in borehole 1 (m below datum)	Flowmeter (m^3)	Pumping rate (l/s) calculated from flowmeter	Comments
01/10/2004	20:00	10.44	13.79	1136.5		
02/10/2004	08:00	10.55	14	1204.4	0.79	
	20:30	10.63	14.06	1273.5	0.78	
03/10/2004	07:00	10.73	14.1	1332.4	1.56	
	18:30	10.74	14.17	1399.1	1.61	
04/10/2004	07:30	10.76	14.22	1472.7	1.57	
	18:30	10.8	14.27	1536.2	1.60	
05/10/2004	08:00	10.84	14.3	1614.4	1.61	
	18:30	10.84	14.24	1670.1	1.47	Water level reading for Borehole 1 uncertain
06/10/2004	08:00	10.85	14.32	1748.8	1.62	
	18:00	10.85	14.32	1814.2	1.82	
07/10/2004	08:00	10.86	14.32	1895.5	1.61	
	18:00	10.87	14.33	1956.1	1.68	
08/10/2004	08:00	10.89	14.36	2037.4	1.61	
	20:45	10.91	14.38	2112.1	1.63	
09/10/2004	08:45	10.92	14.4	2182.9	1.64	
	20:00	10.93	14.42	2248.7	1.62	
10/10/2004	08:30	10.95	14.44	2321.5	1.62	
	20:30	10.96	14.46	2390.9	1.61	
11/10/2004	10:00	10.98	14.49	2471	1.65	
	18:30	11.01	14.51	2520.4	1.61	
12/10/2004	08:00	11.04	14.53	2600	1.64	
	18:30	11.05	14.51	2660.8	1.61	
13/10/2004	08:00	11.06	14.58	2741	1.65	
	20:00	11.09	14.59	2811.4	1.63	
14/10/2004	08:00	11.11	14.62	2882.4	1.64	
	20:00	11.12	14.63	2935.4		No time recorded - estimated as 20:00
15/10/2004	08:00	11.13	14.65	3025.4		