APPENDIX G HYDROGEOLOGY TECHNICAL NOTE

URS

Memorandum

Our Ref: 47037827

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To: Gabriel Gallagher

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cc: Ali Bastekin

Subject: **York Street Interchange – Hydrogeological Assessment**

1. INTRODUCTION

URS has undertaken a desk based assessment to identify potential implications on the groundwater regime in the vicinity of the proposed York Street Interchange, Belfast. The work is required to support the Environmental Statement for the scheme. The assessment is based primarily on intrusive site investigation works undertaken by Causeway Geotech Ltd ('Causeway') between 21 January and 06 March 2013. The 2013 site investigation works were undertaken under the direction of URS. The findings of the Causeway investigation including all borehole records and test results are included in the Contractor's Factual Report[1]. A plan showing exploratory positions is also included.

A series of historical site investigation reports for the general vicinity of the scheme have also been made available to URS. The majority of the historical information relates to the vicinity of the existing Westlink to the west of the proposed interchange.

1.1 Scheme Description

The proposed scheme will provide full grade separation of vehicle movements between the Westlink, M2 and M3. Grade separation will be provided via underpasses below the Lagan Road Bridge and Dargan Rail Bridge. York Street will be partially raised to accommodate the underlying links. The scheme will therefore include construction of underpasses, embankments and over-bridges, which will cause disturbance of the ground and groundwater. It is proposed to form the underpass using diaphragm walls, which will have negligible permeability and will be advanced through water bearing superficial strata including estuarine alluvium ('Belfast sleech') and underlying fluvial deposits into Glacial Till or bedrock. Embankments will be supported by retaining walls which will be piled to till. It is anticipated that the diameter of the majority of piles will be 300mm and will be located at approximately 1.5m centres. No loadings will be transferred to the shallow superficial deposits. A drawing illustrating the locations of underpasses and retaining walls is provided as URS Drawing YSI-URS-XX-XX-DR-SE-ST001.

The objective of this memorandum is to provide an initial assessment of the potential impact of the proposed scheme on the current hydrogeological regime using the available site investigation data and to provide recommendations for any further work that may be required.

[1] Causeway Geotech Ltd, York Street Interchange, Belfast. Report prepared for URS Infrastructure & Environment UK Ltd. Report Number 13-014, dated December 2013.

2. BASELINE SITE CONDITIONS

2.1 Geology

The general sequence of strata recorded along the route of the proposed scheme during the Causeway site investigation is summarised in Table A.

TABLE A: SUMMARY OF GROUND CONDITIONS

Strata	Description	Depth to Top (m)	Thickness (m)
Made Ground	Highly variable materials from historical filling. Also includes quarry fill and concrete	From Ground Level	0.4 – 2.9
Estuarine Alluvium (Belfast Sleech)	Very soft to soft sandy silts and/or very soft to soft organic silty clay with occasional shells and plant remains. Lenses of silty sand present.	0.4 – 2.9	0 – 10.4 (Thickens to east)
Peat	Friable sub-amorphous with decayed roots.	7.3 – 11.6	0.0 – 1.0 (Absent to west)
Fluvial Deposits	Mainly sandy gravels and gravelly sand. Gravelly silt with medium cobble content to south. Silty sand to north.	9.3 – 11.6	0.0 – 5.3 (Absent to west)
Glacial Deposits	Firm – stiff laminated clay.	4.5 - 18	0.0 – 21.8 (Absent to west)
	Glacial sand and gravel bands	Variable within glacial deposits clay	0.8 – 7.5
	Stiff to very stiff sandy gravelly clay with low cobble content. Typically overlying bedrock and present below laminated clays. Occasional lenses of stiff to very stiff sandy gravelly clay within overlying laminated clays. Locally absent.	4.4 – 36.3	0.0 – 11.65
Bedrock	Sandstones, mudstone and marl. Dolerite intrusion (0.70m thick) encountered in BH217	0.7 – 44.15m (becoming deeper to south east of site)	Not Proven

As indicated in the table above, the generalised sequence comprises a thin cover of made ground overlying estuarine alluvium, known locally as ‘sleech’. The estuarine alluvium thickens in an easterly – south-easterly direction towards the River Lagan and associated dock areas (refer to URS Drawing 47037827/1004 and discussed below). Geological Survey of Northern Ireland (GSNI) mapping[2] indicates that the estuarine alluvium attains a

[2] Geology of Belfast and District, Engineering Geology Special Sheet, Scale 1:50,000 (1984)

maximum thickness adjacent to the River Lagan of approximately 15m. These deposits were not encountered in boreholes to the west of York Street.

The sleech is typically underlain by a thin layer of peat (maximum thickness 1m). Again, this was found to be absent to the west of York Street. The peat layer overlies fluvial deposits comprising mainly of sand and gravel. The fluvial deposits appear to become increasingly sandy and silty towards the north (BH201) and south (BH205). The maximum reported thickness of the fluvial deposits was found to be 5.3m in BH201. They were found to be absent in BH227 to the south of the scheme area and in boreholes to the west of York Street.

The glacial deposits underlying the fluvial deposits and/or sleech comprise of laminated clays underlain by sandy gravelly clays with cobbles (‘boulder clay’). Lenses of varying thickness of sand and gravel were encountered within the glacial clays.

Bedrock was encountered beneath the glacial deposits at depths of between 0.7m and 51m bgl. To the east of York Street, the bedrock comprised mainly of orange brown fine grained sandstone. Up to two discontinuity sets were observed. Discontinuity Set 1 comprised sub-horizontal bedding to approximately 20 to 30 degrees. These were reported to be mainly close to medium spaced often infilled with sand and clay/silt up to 80mm. Discontinuity Set 2 comprised a possible joint set at 35 – 70 degrees. These were reported to be close to wide spaced and sand infilled. These joints may be partly drilling induced. Based on GSNI mapping, the sandstones are assumed to belong to the Sherwood Sandstone Group. Where dip arrows are shown on GSNI mapping, the Sherwood Sandstone Group is shown to dip gently to the west.

The superficial deposits to the east of York Street appear to occupy an approximately north – south trending rock head valley.

The bedrock to the west of York Street was observed to comprise of mudstone and marl. The mudstone was typically light grey and thickly laminated to thinly-bedded. It was moderately fresh but locally highly weathered. Lenses of fine sandstone were also present. A discontinuity set associated with bedding at 20 – 30 degrees was observed. This was generally closely spaced. Where present, marl was encountered as stiff reddish brown mottled orange and grey sandy silty clay. Based on GSNI mapping, the mudstones to the west of York Street are assumed to belong to the Mercia Mudstone Group.

A geological boundary, possibly a fault, exists between the Sherwood Sandstone and the Mercia Mudstone to the west of York Street. This boundary appears to mark to westernmost margin of the inferred rockhead valley. A NW-SE trending fault with a down throw to the southwest is shown on GSNI geological mapping to traverse York Street in the vicinity of its junction with Brougham Street. A further fault trends approximately N- S immediately east of the existing M2, terminating against the NW-SE trending fault.

Indicative N-S and E-W geological cross-sections are provided as URS Drawing 47037827/1002.

2.2 Hydrogeology

2.2.1 Groundwater productivity

The GSNI Geoindex[3] and *Characterisation of Groundwater Bodies within Northern* Ireland published by the Northern Ireland Environment Agency (NIEA)[4] indicate that the site is underlain by two main bedrock aquifers:

[3] http://maps.bgs.ac.uk/gsni_geoindex. Accessed on 6th February 2014.
[4] Northern Ireland Environment Agency, *Characterisation of Groundwater Bodies within Northern Ireland*

- The Sherwood Sandstone Group underlying the area to the east of York Street is situated within the Belfast groundwater body. Overall the aquifer is considered to have high productivity potential. Inter-granular porosity exists within the sandstone units, and flow is both inter-granular and through fractures.

- The Mercia Mudstone Group underlying the western part of the scheme belongs to the Belfast Hills – Islandmagee groundwater body. This aquifer is of very poor productivity with flow restricted to limited fractures.

The Sherwood Sandstone forming the Belfast Groundwater Body dips beneath and becomes confined by the overlying Mercia Mudstone. The Sherwood Sandstone extends west beneath Belfast Lough (where groundwater becomes saline). The sandstone is reported to be mostly fully saturated with piezometric levels occurring in the overlying deposits. Regional groundwater flow occurs although compartmentalisation of flow occurs due to significant faulting. Within the Central Belfast area, the Sherwood sandstone is overlain by significant thicknesses of low permeability deposits. Significant thicknesses of glacial sand and gravel deposits also occur, particularly in the Lagan Valley. The sand and gravel deposits will have primary intergranular porosity and are reported to have high productivity potential. Groundwater within these deposits tends to exhibit greater hydraulic connectivity with nearby surface waters than groundwater in the Sherwood Sandstone. There is generally very little surface exposure of the Sherwood Sandstone although GSNI mapping shows limited surface outcrop to the north of Brogham Street. Sand and gravel deposits are not recorded at surface in the area of interest.

The superficial deposits of estuarine alluvium that underlie the site have very low permeability and are not regarded to have the potential to store and transmit significant amounts of groundwater. The till in the Belfast Groundwater Body area is considered to be moderately permeable due to its association with the underlying sandstone dominated bedrock resulting in a significant sand/silt sized fraction.

The NIEA considers that recharge to the Belfast Groundwater Body is mainly along its margin with the Mercia Mudstone as runoff from higher ground crosses the body. An average recharge rate of approximately 126mm/a is reported compared with an annual average rainfall of 891 mm.

The NIEA considers that recharge to the Belfast Hills – Islandmagee groundwater body is mainly direct where bedrock occurs at or close to surface. They estimate a recharge rate of 181mm/a. Mercia Mudstone occurs close to surface towards the west of the scheme area and was encountered at shallow depth in BH221 and BH222.

Currently there are no known abstractions within or adjacent to the scheme boundary.

Groundwater bodies are classified by the NIEA with quality ratings ranging from Good to Poor. A search of NIEA's River Basin Management Plan database was conducted with regard to groundwater quality beneath the site. The Belfast groundwater body has an overall status of 'Poor'. The Belfast Hills - Islandmagee groundwater body groundwater body has an overall status of 'Good'.

2.2.2 *Groundwater Vulnerability*

The GSNI Geoindex web site indicates the vulnerability of groundwater within the uppermost aquifers and is the standard classification currently used for assessing activities which may impact on groundwater resources. The vulnerability classification is determined primarily on the basis of the assumed permeability and thickness of geological deposits overlying the strata containing the upper, significant water table. Where these deposits are absent, the depth to water table can influence the vulnerability class.

The GSNI Geoindex website shows the groundwater in the bedrock aquifer is assigned to Vulnerability Class 1 (Sherwood Sandstone) and Class 2 (Mercia Mudstone), which indicate a generally low vulnerability potential.

2.2.3 *Groundwater Monitoring Records*

Data obtained during the Causeway 2013 investigation show that groundwater strikes were reported in the majority of borehole locations with the exception of BHs 206, 212, 213, 214, 217, 221, 222 and 227. Groundwater strikes within boreholes were recorded between 1.5m and 32.5m bgl. Strike and rise data are summarised in Table B. These data have been used to assist with the development of a hydrogeological conceptual site model.

TABLE B: STRIKE & RISE DATA (2013 INVESTIGATION)

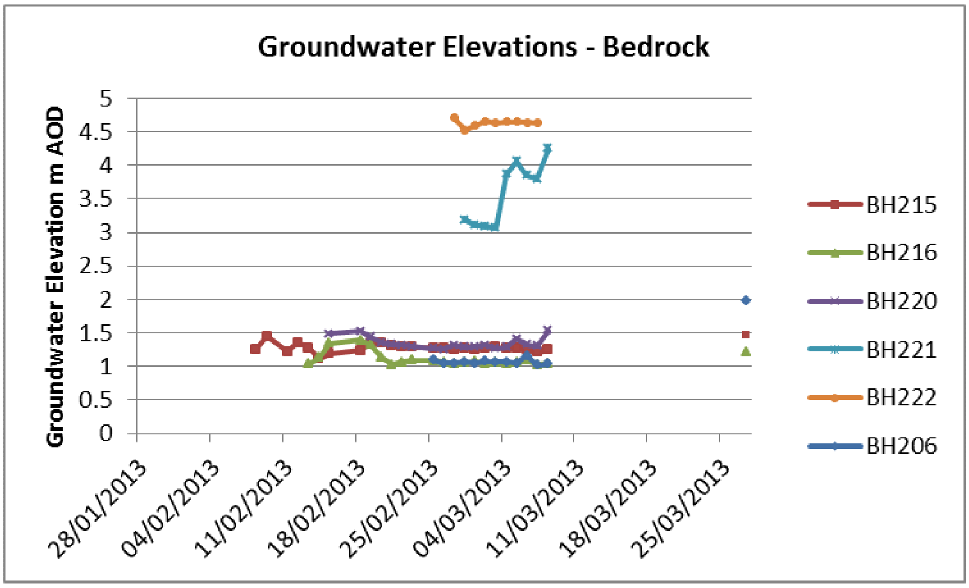
Borehole	Strike (m bgl)	Rose to (m bgl)	Lithology
BH201	10.50	6.10	Top of sand unit overlain by peat layer and silt (Alluvial)
BH201	25.60	21.60	Sand lens overlain by clay (Alluvial)
BH202	11.20	2.85	Top of sand unit overlain by peat layer and silt (Alluvial)
BH202	23.50	15.80	Top of fine sand overlain by gravelly clay (Till)
BH203	11.60	3.90	Top of gravel unit overlain by peat and clay
BH203	23.70	6.75	Top of sand overlain by clay (Alluvial)
BH204	9.30	4.50	Sand overlain by peat and clay (Alluvial)
BH205	9.60	2.10	Sand overlain by peat and clay (Alluvial). Blowing sand reported at 13.0 – 13.15m bgl
BH207	3.50	3.10	Top of silty sand overlain by very silty sand (Estuarine)
BH207	10.10	8.40	Sandy clayey silt overlain by peat and clay (Alluvial)
BH208	4.30	4.15	Sandy silt (Estuarine)
BH208	10.15	3.18	Sandy clayey silt overlain by peat and clay (Alluvial)
BH209	11.20	8.10	Sandy gravel overlain by pat and clay (Alluvial)
BH209	12.90	3.80	Gravel (Alluvial)
BH210	10.25	2.75	Sandy gravel overlain by peat and clay (Alluvial)

TABLE B: STRIKE & RISE DATA (2013 INVESTIGATION)			
Borehole	**Strike (m bgl)**	**Rose to (m bgl)**	**Lithology**
BH210	35.50	15.80	Silt overlain by still sandy gravelly clay (Till)
BH211	2.75	2.65	Organic silt (Estuarine)
BH211	11.00	2.90	Sandy gravel overlain by peat and clay (Alluvial)
BH214	1.50	-	Clay overlain by made ground (brick and rubble fill)
BH214	16.70	3.62	Contact between sandstone bedrock and overlying till
BH215	4.00	3.40	Organic clay (Estuarine)
BH216	10.30	8.80	Sandy gravelly clay (Till)
BH218	7.80	-	Sandy silt overlain by peat and clay (Alluvial)
BH219	12.70	8.80	Silty sand overlain by sandy gravelly clay (Till)
BH220	3.40	3.20	Sand (Estuarine)
BH225	9.50		Silty clay (Alluvial)
BH228	10.30	3.40	Gravel overlain by peat and clay (Alluvial)

In most cases, groundwater strikes were recorded within granular alluvial deposits at depths of between 9.30m and 26.50m bgl. Sub-artesian conditions were recorded in the fluvial deposits with rises 20 minutes following strike of up to 16.95m. Blowing sand was reported in BH205 between12.00m and 13.15m bgl. Strikes were also noted at depth within granular till deposits and at shallow depth within estuarine alluvium deposits.

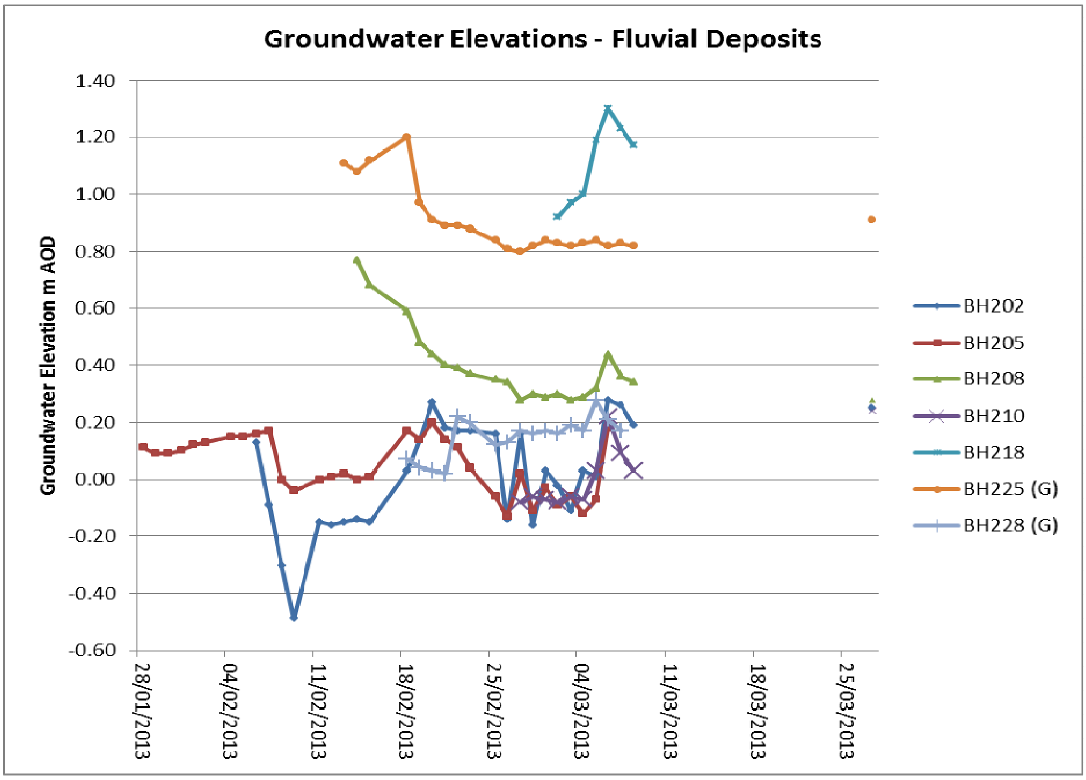
The majority of trial pits were recorded to be dry with the exception of TP210 and TP215 where water strikes were observed between 0.7m and 1.2m bgl.

Groundwater monitoring wells were installed at twenty three monitoring locations during the Causeway 2013 investigation. Groundwater level gauging was undertaken between 28 January and 27 March 2013. Groundwater monitoring installations were provided within both the alluvial deposits and the underlying fluvial deposits. In addition, six boreholes were screened within the bedrock. A hydrograph showing the results of groundwater level gauging in the bedrock is provided below.



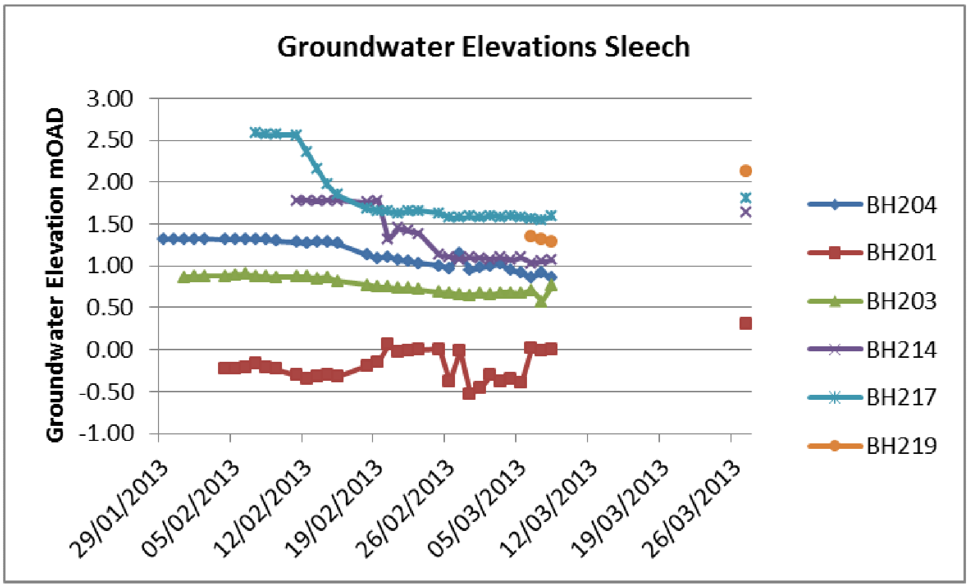
With the exception of BH221 and BH222, where bedrock reported as 'reconstituted marl' was encountered at a depths of 1.70m (3.46m AOD) and 1.65m (4.18m AOD), groundwater level gauging of boreholes installed in the bedrock (BH206 BH215, BH216 and BH220), recorded groundwater elevations well above the base of the superficial deposits. Groundwater elevations ranged between 4.55m AOD towards the west of the study area (BH221) and 1.02m AOD towards the northeast (BH206). BH206 BH215, BH216 and BH220 were installed into the Sherwood Sandstone.

Six boreholes (BH202, BH205, BH208, BH209, BH210 and BH218) were installed in fluvial deposits immediately below the peat horizon with a further two boreholes installed in deeper granular glacial deposits. (BH225 and BH228). All boreholes installed within the fluvial deposits are located to the east of York Street since these deposits are appear to be absent to the west. BH225 (screened across a sand lens beneath laminated glacial clay) is located on York Street. Groundwater depths of between 1.62m and 2.60m bgl were recorded. These depths correspond to elevations of between 1.20m AOD adjacent to York Street and -0.49 m AOD towards the east. A hydrograph showing the results of groundwater level gauging in the alluvial deposits is provided below. No monitoring records are available for BH209. Hydrographs for BH225 and BH228 installed in deeper glacial deposits are provided for reference.



From the information available, the extent of hydraulic connectivity between the bedrock and the fluvial deposits is uncertain. Overall, however, a vertically upwards hydraulic gradient is implied. Close correspondence between groundwater elevations in adjacent boreholes installed within the bedrock (BH215) and granular horizons in the till (BH228) may suggest that groundwater within the bedrock and the overlying till deposits may locally be at or close to hydrostatic equilibrium. Groundwater heads between the various units arefurther discussed below and in Section 2.2.4. The strike and rise data suggest that groundwater within the fluvial deposits is semi-confined by the overlying estuarine ('sleech') deposits.

Eight boreholes (BH201, BH203, BH204, BH211, BH214, BH217, BH219 and BH227) were installed within the estuarine alluvium deposits. Again, these are mainly located to the east of York Street although BH217 is located immediately to the west of York Street. Groundwater depths recorded within boreholes installed within the estuarine alluvium deposits ranged between 1.62m and 2.60m bgl. These are equivalent to groundwater elevations of between -0.53m in BH201 to the northeast of the area of interest and 2.58m AOD in BH217 immediately to the west of York Street. A hydrograph showing the results of groundwater level gauging in the estuarine deposits is provided below.



Combined hydrographs illustrating the relationship between the piezometric surface in the bedrock (green), fluvial deposits (orange) and sleech (blue) are provided in the figure below. Hydrographs for boreholes installed in granular horizons within glacial deposits underlying the fluvial deposits have also been included (red). The figure shows that during the period monitored groundwater elevations in the bedrock were consistently above those in the overlying fluvial deposits and glacial deposits implying an upwards vertical hydraulic gradient from the bedrock to the fluvial deposits. In general, groundwater elevations in the sleech are above those in the underlying fluvial deposits implying a vertically downwards hydraulic gradient from the low permeability sleech to the underlying fluvial deposits.

A low level combined sewer, which is understood to be brick lined, gravitates in a northerly direction along Corporation Street at a gradient of 1 in 20. It is understood that at Trafalgar Street, (north of BH201), the crown level of the sewer is at approximately -0.46m AOD while the invert level is at -2.59m AOD. Sub sub-sea level groundwater elevations recorded in the sleech (BH201) may reflect the influence of this low level sewer. The sewer may also affect groundwater elevations in the fluvial deposits (>25% of water levels at BH202 are <0m AOD).

TABLE C: ESTIMATED HYDRAULIC CONDUCTIVITY (FLUVIAL DEPOSITS)					
Borehole	**Depth (m)**	**Lithology (Log Description)**	**Porosity**	**Hydraulic Conductivity (m/d)**	**Transmissivity (m^2/d)**
BH210	12.0 – 12.5	Very silty very gravelly fine to coarse sand	0.26	0.08	0.10
BH211	12.0 – 12.5	Slightly silty fine to coarse gravel	0.26	540 – 990	2,300 – 4,400
	14.0 – 14.5				
BH214	10.0 – 10.45	Slightly sand clay	0.26	N/A	N/A
BH218	8.3 – 8.75	Sandy silt and very fine sand	0.26	0.03	0.06
BH228	10.3 – 10.7	Silty very sandy fine to coarse gravel	0.26	0.93	0.37
BH228	11.3 – 11.75	Slightly gravelly very silty fine to medium sand	0.30	0.49	0.93

It is apparent from Table C that the estimated hydraulic conductivities/transmissivities of the samples tested vary considerably. The highest hydraulic conductivity values relate to boreholes BH203 and BH207 located to the north of the scheme in the vicinity of the Dock Street Bridge that will carry the M2 over Dock Street. The estimated transmissivity of the fluvial deposits in this area of the scheme appears to be extremely high.

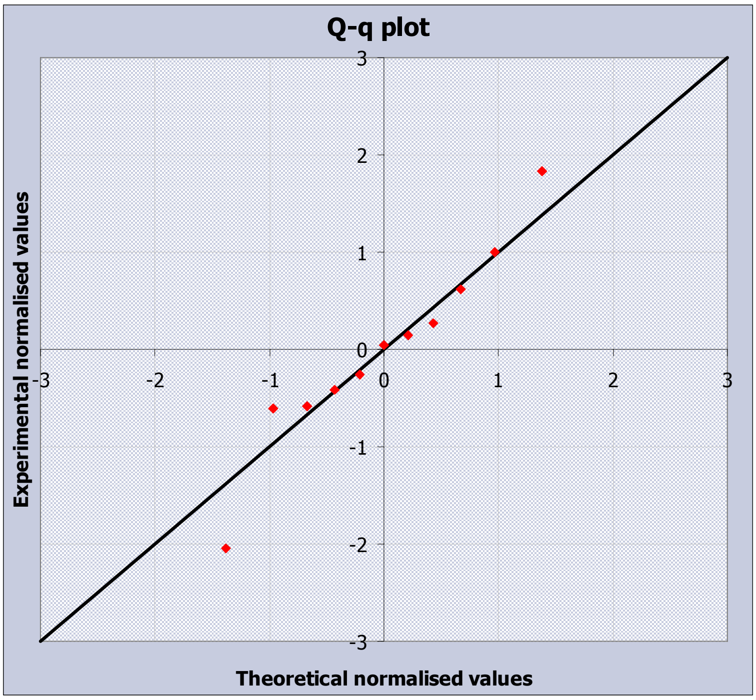
Slightly lower hydraulic conductivities were estimated in boreholes in the vicinity of the start of the M2 – Westlink underpass (BH205, BH209 and BH210), although here too the estimated transmissivity of the fluvial deposits is of the order of 450 – 9,000m^2/d.

Based on the log descriptions, it is possible that some of the higher estimated hydraulic conductivity values are high for the soils encountered. This may be due to loss of fines during sampling below the water table. Literature values for clean sand and sand and gravels are typically in the range 10 – 100 m/d. Values in excess of 100 m/d are typical of clean gravels[8]. Much lower values would be expected for sand, sand and gravel or gravel with high fines content. It is noted, for example, that the estimated hydraulic conductivity for the sample from BH208 described as very silty fine to coarse sand and fine to coarse gravel is only 0.06 m/d. The PSD for this sample indicates that it contains 37% fines (silt + clay).

While it appears that the fluvial deposits may become increasingly fine grained to the north and south, as illustrated on the geological cross-sections provided as URS Drawing 47037827/1002, it is not clear that the lower transmissivity values estimated for gravels to the south of the section are statistically significant. The data set of transmissivity values for soils in which the main constituent is gravel appears to be approximately log-normally distributed as shown by the quantile (Q-q) plot for the log-transformed data reproduced

[8] E.g. Brassington R (2007) Field Hydrogeology (3rd Edition). John Wiley & Sons Limited.

below suggesting that they may belong to the same population and reflect sampling variability within a highly heterogeneous unit The data set is also found to be log-normally distributed at 5% significance by application of the Shapiro-Wilks test to the log-transformed data. The geometric mean for the data set is approximately 1,400m^2/d. In the absence of in situ transmissivity data, this value has been used in subsequent calculations.



2.2.6 *Groundwater Discharge*

The total groundwater discharge passing beneath the section of the scheme perpendicular to the direction of groundwater can be estimated from Darcy's law as follows:

$$Q = TIw$$

Where

Q = Groundwater discharge (m^3/d)

T = Formation transmissivity (m^2/d)

I = Hydraulic gradient (dimensionless)

w = Aquifer width perpendicular to the direction of groundwater flow (m)

Based on interpolated groundwater contours for the estuarine alluvium presented as URS Drawing 47037827/1002, the majority of the proposed new road layout is parallel to the inferred direction of groundwater flow. For this reason, it is not anticipated that the diaphragm walls used to construct the underpasses or piles supporting retaining walls for the embankments will significantly hinder groundwater flow in these deposits. In addition, a calculation of expected vertical flow versus horizontal flow using the observed vertical and horizontal hydraulic gradients and derived vertical hydraulic conductivities (assuming that the horizontal conductivity is an order of magnitude higher), indicates that vertical flow may dominate over horizontal in this unit.

Assuming that the fluvial deposits represent the principal water bearing unit perpendicular to the direction of groundwater flow that could potentially be intercepted, the width perpendicular to the direction of groundwater flow is taken from interpolated groundwater contours for the fluvial deposits (URS Drawing 47037827/1001 as approximately 400m. This is effectively the length of the section of the M2 to the north of the Dock Street Bridge (in the vicinity of BH201/BH202 where the fluvial deposits appear to pass into sand and silt) and the underpass directly below the M3. Given an estimated hydraulic gradient of 0.004 and transmissivity *T* of 1,400m^2/d, the estimated total groundwater discharge in the fluvial deposits beneath this section of the scheme is 2,250m^3/d. Since the fluvial deposits appear to become increasingly fine grained to the south of this section and to be absent in BH227, it is not anticipated that groundwater flow in fluvial deposits will be significantly hindered by the southern part of the scheme comprising the M3 underpass.

While the inferred direction of groundwater flow in the bedrock is broadly the same as that in the fluvial deposits, it is not anticipated that groundwater flow in the bedrock will be intercepted since no structures will be formed below rockhead.

2.2.7 *Water Balance Calculation*

The purpose of the water balance calculation in this section is to estimate direct recharge from precipitation to the fluvial deposits beneath the scheme area through the overlying estuarine deposits. This can be used to provide an order of magnitude check of estimated hydraulic parameters and/or to assess whether additional sources of recharge may be present.

The area over which direct recharge to the fluvial deposits might be expected can be estimated from the groundwater contour plot (URS Drawing 47037827/1002) by constructing the groundwater capture zone enclosed by the southern part of the scheme running parallel to the direction of groundwater flow and the groundwater flow line perpendicular to the northernmost part of the scheme perpendicular to the direction of flow. Since the fluvial deposits appear to be largely absent to the west of York Street, this line can be taken as the western-most limit of the groundwater capture zone. The area enclosed by the groundwater capture zone is estimated to be approximately 60,000m^2.

The NIEA report the annual rainfall in Belfast is 891mm. In urban areas, the percentage of rainfall discharging to ground is typically similar to open vegetated areasdue to the absence of evapo-transpiration losses and considerable leakage from sewers [9] Based on the assumption that recharge represents 30% of rainfall, the minimum annual recharge to the fluvial deposits is therefore estimated as 16,000m^3. This is equivalent to approximately 40m^3/d. Making the highly conservative assumption that 100% of annual rainfall reaches the fluvial aquifer (e.g. no evapo-transpiration loss from impervious surfaces and 100% loss from drains), the estimated maximum recharge could potentially be as high as 150m^3/d.

The estimated maximum direct groundwater recharge of 150m^3/d compares with an estimated groundwater discharge in excess of 2,000m^3/d. The discrepancy may imply that additional recharge is present, i.e. from bedrock where a hydraulic connection exists, and/or overestimation of hydraulic parameters based on PSDs. This can be further evaluated only by carrying out in situ transmissivity testing (e.g. rising head tests or pump tests) in boreholes screened in the fluvial aquifer.

[9] Knipe, CV, Lloyd JW, Lerner DN and Gresswell, RB (1993) Rising Groundwater Levels in Birmingham and Engineering Implications. CIRIA Special Publication SP92

3. POTENTIAL IMPLICATIONS FOR SCHEME

Based on the discussion in Section 2.2.6, it is considered that potential impacts on the hydrogeology in the vicinity of the proposed scheme will be limited mainly to groundwater flow in the fluvial sands and gravels. Changes in hydraulic head are considered likely in the vicinity of those parts of the scheme that run perpendicular to the inferred direction of groundwater flow. Based on URS Drawing 470378271/1001 showing interpolated groundwater contours for the fluvial deposits, the following scheme sections are considered relevant:

- M2 – Westlink Underpass. Section to west and north of M3 on-slip. Identified as UP-001A on URS Drawing 470378271/1001. The approximate length of this section perpendicular to the direction of groundwater flow is 150m. The underpass will be constructed with diaphragm walls advanced to competent strata below the fluvial sands and gravels.

- M2 immediately south and north of Dock Street Bridge (BR-004). Embankment supported by retaining walls identified as RW017 and RW018 the south of Dock Street Bridge and RW022 to the north of Dock Street Bridge (URS Drawing 470378271/1001). The approximate length of the section perpendicular to the direction of groundwater flow to the south of Dock Street Bridge is 150m while that to the north is approximately 200m. Based on the information from BH202, it has been assumed that the fluvial sands and gravels are absent to the north RW022. The retaining walls will be supported by piled foundations advanced to competent strata below the fluvial sands and gravels.

The potential implications of the scheme on the local hydrogeology will depend on the extent to which diaphragm walls and piled structures intercept groundwater flow and the ability of the surrounding aquifer to accommodate any associated change in hydraulic head. A key consideration is the width of the section of fluvial aquifer perpendicular to the direction of groundwater flow intercepted relative to the width of the aquifer as a whole.

The length of the M2 – Westlink underpass perpendicular to the direction of groundwater flow is approximately 150m. Assuming an aquifer transmissivity of 1,400 m^2/d, and hydraulic gradient of 0.004, the groundwater flow through this section of the scheme is estimated to be approximately 850m^3/d. The diaphragm walls will cut off this flow completely.

In addition to groundwater intercepted by the diaphragm walls, groundwater may also be intercepted by piles supporting retaining walls. The estimated length of road perpendicular to the direction of groundwater flow in the fluvial sands and gravels supported by retaining walls is approximately 150m to the south and 200m to the north of Dock Street Bridge respectively. At present, it is understood that driven piles with a diameter of 300mm will be installed at approximately 1.5m centres. The number of piles required to support the retaining walls to the north and south of Dock Street Bridge is therefore approximately 230. Assuming a diameter of 300mm, their combined width is approximately 70m.

It was noted in Section 2.2.6 that the estimated total width of the fluvial aquifer perpendicular to the direction of groundwater flow is 400m. Given the length of the underpass of 150m, approximately 3/8ths of the aquifer may be cut off completely. In addition, the 230 piles supporting the retaining walls may partially cut off a further 70m of the aquifer. In total, therefore, approximately 220m representing more than half of the width of the fluvial sand and gravel aquifer may be cut off by the combined length of the M2-Westlink underpass and retaining walls perpendicular to the direction of groundwater flow. While in principle, any groundwater intercepted could migrate to the north and south of the sections intercepted, the available aquifer width over which this could take place is only approximately 180m (since sand and gravel deposits appear to be absent in the extreme north and extreme south of the scheme).

From Darcy's Law, a reduction in the aquifer width by one half requires that the hydraulic gradient be doubled to allow the same quantity of groundwater to pass through it. On this basis, it is considered that groundwater may back up behind the diaphragm walls potentially reversing the hydraulic gradient. If groundwater were to by-pass the diaphragm walls to the north and south, a hydraulic gradient across the remaining section of the aquifer of at least twice that at present would be required to drive groundwater flow. Given the length of the fluvial aquifer to the west of the M2 of 150 – 200m, an average increase in hydraulic head in excess of 1m might be expected. A larger might be expected if, for example, the transmissivity of the fluvial deposits to the north and south of the affected road sections is lower, e.g. due to greater fines content, than the central part of the fluvial aquifer.

It should be noted that while estimates of the total flow through the fluvial aquifer of up to 2,250m^3/d have been made using empirical formulae based on gradings, the potential effects described in this section do not depend on the aquifer transmissivity. The same effect would be observed both in a highly productive aquifer and an aquifer of lower productivity.

Given the potential change in groundwater head and hydraulic gradient in the fluvial deposits, changes may be transmitted to the other units including the estuarine deposits. This could result in an increase in the average groundwater elevation and resulting decrease in average groundwater depth (which is already shallow) although how and when this might manifest itself cannot be predicted at this stage. A groundwater flow model calibrated to in situ transmisssivity testing and long–term groundwater elevations is likely to be of assistance.

Potential mitigations of the effects of changes in groundwater level in the estuarine deposits as a result of possible changes in head in the fluvial deposits may involve provision of additional drainage at shallow depth. Also, such drainage in combination with impervious surfaces will intercept rainfall recharge and reduce this component in of the aquifer water balance and further aid in limiting any groundwater level changes. It should be noted, however, that the significance of any reduction in recharge through the estuarine deposits will depend on its contribution relative to possible recharge from the bedrock aquifer.

4. CONCLUSIONS

Following the desk based assessment of the available information, the following conclusions were made:

- The hydrogeology in the vicinity of the scheme is relatively complex. Three main hydrogeological units were identified as follows:
    - Groundwater in bedrock comprising sandstones belonging to the Sherwood Sandstone Group to the east and mudstones belonging to the Mercia Mudstone Group to the west;
    - Groundwater in fluvial deposits largely of sand and gravel. These are absent towards the west but thicken towards the east. They appear to become more silty/sandy to the north and south;
    - Groundwater in estuarine alluvium deposits ('Belfast sleech')
- Generally there appears to be an upwards vertical hydraulic gradient into fluvial deposits from the deeper bedrock. There is therefore a potential for recharge of the fluvial sands and gravels from the bedrock.
- There is a downwards vertical hydraulic gradient in the estuarine alluvium (sleech) to the fluvial deposits.
- The direction of groundwater flow in the bedrock and fluvial deposits is broadly south-east. The direction of groundwater flow in the estuarine alluvium is broadly northeast. It is possible that the low level sewer running along Corporation Street influences groundwater flow in the superficial deposits (and potentially in the underlying fluvial deposits).
- No in situ hydraulic conductivity testing has been undertaken. Hydraulic conductivities of the superficial groundwater units have therefore been estimated from empirical relationships, which are prone to error. The hydraulic conductivity of the estuarine alluvium is likely to be very low. Estimates of the hydraulic conductivity of the fluvial deposits based on gradings were highly variable. Loss of fines during drilling may affect the estimates, some of which appear high for the soils described.
- The estimated geometric mean for the transmissivity of the fluvial sand and gravel deposits was 1,400m^2/d. Based on Darcy's Law, the groundwater flow in the sand and gravel unit perpendicular to the north-south section of the M2-West link underpass and retaining walls was 2,250m^3/d.
- Based on the available information and proposed road layout, it is considered there is a potential for interception of groundwater flow within the fluvial deposits. It is estimated that more than one half of the available aquifer width will be intercepted. This may lead to back up of groundwater behind diaphragm walls and reversal of the vertical hydraulic gradient(s). The increased hydraulic head may be transmitted to the overlying estuarine deposits. Groundwater flow in the bedrock aquifer may also be affected where hydraulic connectivity is present.
- The potential hydrogeological effect described depends primarily on the width of the section of the aquifer intercepted in relation to the total aquifer width rather than on their hydraulic conductivity/transmissivity.

- Based on the available information, it is not known how or when any change in head in the fluvial deposits may manifest itself in the overlying estuarine alluvium. It is noted that groundwater levels in this unit are already shallow.

- At this stage, it is considered that potential mitigation measures may include provision of additional drainage at shallow depth

5. RECOMMENDATIONS

The information presented above suggests that the proposed road scheme may lead to a change in the local hydrogeological regime, potentially affecting groundwater flow in the fluvial deposits leading to changes in the hydraulic gradient and increased hydraulic heads that may be transmitted to the overlying deposits. At present, however, it is not possible to quantify this further. The following additional information is required:

- Further routine groundwater level gauging of boreholes installed during the Causeway investigation. It is recommended that weekly monitoring be undertaken over several weeks.

- In situ hydraulic testing of wells installed in the three hydrogeological units, i.e. the bedrock, the fluvial deposits and the estuarine alluvium.

- Numerical groundwater modelling to test the effects of deep foundation structures on the groundwater flow regime and to quantify the potential implications of head changes in the fluvial deposits on groundwater levels in the estuarine alluvium. A simple groundwater model can be developed to represent the generally understood geological units and with simple boundaries evaluate current and affected groundwater flow regimes. Such modelling will be reliant on the accuracy of understood aquifer permeabilities and is best undertaken only after such data is available. The modelling will assist with the design of appropriate mitigation measures such as additional drainage at shallow depth.