

Kildare County Council

Remediation of Legacy Landfill Site at Digby Bridge, Sallins,
Co. Kildare,
Stage 1: Environmental Risk Assessment
and Remediation Plan

Attachment D1- Tier 3: Refinement of CSM and Quantitative Risk Assessment

Volume 2: Groundwater

July 2020

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Abbreviations

BTEX	Benzene, Toluene, Ethylbenzene, Xylene
BOD	Biochemical Oxygen Demand
CoP	EPA Code of Practice in Environmental Risk Assessment for Unregulated Waste Disposal Sites, 2007
CoPC	Contaminants of Potential Concern
CSM	Conceptual Site Model
CWG	Criteria Working Group
DQRA	Detailed Quantitative Risk Assessment
DWS	Drinking Water Standard
EQS	Environmental Quality Standard
EPA	Environmental Protection Agency
GF	Gravel Formation
GI	Ground Investigation
GQRA	Generic Quantitative Risk Assessment
GSI	Geological Survey of Ireland
JAGDAG	Joint Agencies Groundwater Directive Advisory Group
Lk	Locally Important Karstified Aquifer
m OD	Metres above Ordnance Datum
MTBE	Methyl tert-butyl ether
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
RTC	Remedial Target Criteria'
RF	Rickardstown Formation
RTM	Remedial Targets Methodology
SI	Site Investigation
SPR	Source Pathway Receptor
SPZ	Source Protection Zone
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbons
UKTAG	UK Technical Advisory Group on the Water Framework Directive
VOCs	Volatile Organic Hydrocarbons
WFD	Water Framework Directive

Section 1 Introduction

1.1 Project Background

Digby Bridge legacy landfill site is located south east of Digby Bridge which crosses the Grand Canal, in the townland of Barrettstown, less than three kilometres from Sallins.

Landfilling first started at Digby Bridge in 20/06/1980 and finished approximately on 31/12/1982. A Tier 1 Risk Assessment of the site was completed in 2008 by Kildare County Council, in line with the Environmental Protection Agency (EPA) Code of Practice: Environmental Risk Assessment for Unregulated Waste Disposal Sites 2007 (CoP). A preliminary Conceptual Site Model (CSM) of the site was developed and the Source-Pathway-Receptor (SPR) linkages were evaluated. The Tier 1 categorized the site as being of 'High Risk (Class A)' due to the number of high risk SPR linkages. The site was entered on Kildare County Council's Waste Management Act Section 22 Register, a list of unregulated waste disposal sites.

Kildare County Council appointed CDM Smith Ireland Ltd (CDM Smith) in 2017 to prepare a Stage 1 Environmental Risk Assessment and Remediation Plan in accordance with the Environmental Protection Agency (EPA) Code of Practice and comprising of Tier 2 Site Investigation and Tier 3 Refinement of CSM and Quantitative Risk Assessment which was then used to inform the Remediation Plan. This will provide the basis for the Council's application for a Certificate of Authorisation to the EPA as required under S.I. No. 524 of 2008 Waste Management (Certification of Historic Unlicensed Waste Disposal and Recovery Activity), Regulations, 2008. It will also be required to inform Stage 2 of the Project: Remediation Works.

In accordance with the objectives of the project, as set out in the Project Brief, three reports will be prepared as part of the project deliverables.

- Tier 2: Site Investigations and Testing (Doc. Ref. 117838/40/DG/11);
- Tier 3: Refinement of Conceptual Site Model and Quantitative Risk Assessment
 - Volume 1 addressing Landfill Gas (Doc. Ref. 117838/40/DG/12); and
 - Volume 2 addressing Groundwater (this report).
- Remediation Plan (Doc. Ref. 117838/40/DG/14).

An additional report (Doc. Ref. 117838/40/DG/10) has been prepared which reviews background information relevant to the project, including the Tier 1 Risk Assessment of the site completed in 2008 by Kildare County Council. An Appropriate Assessment Screening Report (Doc. Ref. 117838/40/DG/16) was also prepared.

1.2 Objectives of the Current Report

A Tier 2 Report detailing Site Investigations and Testing was submitted to Kildare County Council in August 2019 (Doc. Ref. 117838/40/DG/11). Following the procedures outlined in the EPA CoP, the Tier 2 report provided a factual characterization of the site and an updated risk assessment with recommendations to conduct both a generic quantitative risk assessment (GQRA) and a detailed quantitative risk assessment (DQRA) for controlled waters.

This Tier 3 Report presents the GQRA and the DQRA in the context of a refined Conceptual Site Model (CSM). The findings will inform the subsequent decision-making about potential next steps, including remediation planning, if applicable.

Therefore, the objectives of this Tier 3 Risk Assessment are:

- To present the refined CSM - following the source-pathway-receptor (SPR) model of environmental risk assessment - and highlighting specific SPR risk factors;
- To conclude about risks associated with identified potential receptors; and
- To provide recommendations on next steps for remediation planning, as appropriate.

In the context of the site, controlled waters are groundwater and surface water bodies. As such, the GQRA uses relevant generic assessment criteria, notably existing standards and threshold values related to leachates, groundwater and surface water quality. The DQRA uses site-specific assessment criteria which are developed from recognized Risk Assessment tools and models, in line with regulatory guidance. Specifically, the DQRA relied on the application of the Remedial Targets Methodology (RTM) (EA 2006) published by the Environment Agency in the United Kingdom. The RTM is broadly accepted by the EPA for risk assessments related to contaminated land and groundwater at EPA Licensed Sites (EPA 2013).

1.3 Assumptions and Limitations

The key assumptions and limitations associated with the Tier 3 Risk Assessment are as follows:

- Geology is laterally and vertically variable. Site-specific geological information from onsite boreholes have been used to interpret the geology of the site. This involves interpretation between data points (boreholes). Actual conditions between data points may be dissimilar from that identified within the exploratory holes completed to date. Best technical judgement has been applied to the interpretations. Should any additional ground investigations be carried out in the future, the current interpretations may require updating/revision.
- Data from previous site investigations, undertaken by third parties, have been incorporated into this report where relevant. These datasets have been assumed to be correct for purposes of this assessment; and
- This assessment has been made on the basis of the current ground and water conditions, landfill cover and land use. Changes to existing conditions in the future could impact on current findings and would need to be revisited or updated should changes occur.

CDM Smith has not engaged with the EPA as the regulatory body in the production of this report. Consultation with the EPA and other stakeholder engagement may constitute a part of any future work.

Section 2 Summary of Site Conditions

This Tier 3 Risk Assessment uses information from the desk study and site investigation works documented in the draft Tier 2 Report. The key findings are summarized below.

2.1 Waste Materials and Cover

The landfill waste was observed to be composed of a mixture of materials, as follows (in decreasing order):

- Plastics;
- Decaying organic matter, timber, ash;
- Metal and wire;
- Glass and paper;
- Rope, cable rolls, concrete, insulation; and
- Fabrics, tyres, video film, cotton, brick.

The waste was deposited in historical gravel pits at the site. The waste mass was found to cover an estimated area of approximately 4.7 Ha and ranged in thickness between 1.8 and 7.9 m. Relevant cross-sections of the site and waste mass are reproduced in **Appendix A**. Based on the available data, the waste mass is above the groundwater table but the smallest estimated thickness of the unsaturated zone beneath the waste mass is approximately 1 m.

The waste mass is covered by silty to gravelly CLAY cover materials. These materials range in thickness between 0.3 and 2.4 m. Particle size distribution curves suggest these materials are of low permeability, but differential settlement was observed which could result in fissuring, implying the possible presence of preferential pathways (in relation to rainfall infiltration).

Engineered liner materials were not encountered or observed during the site investigation. As such, the waste materials are in direct contact with the underlying geological strata.

2.1 Leachates

Eight monitoring wells were installed in the waste mass as part of the Tier 2 site investigation to allow for measurement and sampling of leachates. Well locations are presented in **Appendix B**.

During two sampling rounds, leachates were observed in some of the monitoring wells. The sampling was timed to coincide with rainfall events. The sampled wells were observed to go dry quickly after the rainfall events. This suggests that leachates are generated in pulses following wet weather events. Not all leachate wells dried up. Two wells-maintained leachate levels which were well above the groundwater table. As such, they represent perched levels within the waste mass. Leachate chemical results are presented in Section 3.3.

2.2 Site Geology

Eight boreholes were drilled and converted to monitoring wells across the site. Seven were installed in the GF and one was installed in the RF. The borehole logs show that the site is

underlain by sand and gravel deposits. These are Quaternary sediments and are mapped by the Geological Survey Ireland (GSI) as “gravels derived from limestones”. For ease of reference, the sand and gravel deposits are referred to in the current report as the Gravel Formation (GF). The GF ranges in thickness between 0.2 and 16.5 m across the site. Clay lenses are present but significant clay layers were not encountered which could be correlated or traced between boreholes.

The GF overlies limestones of the Rickardstown Formation (RF) as mapped by the GSI. The eastern boundary of the site is 100 m from the mapped boundary between the RF and Waulsortian Limestones.

Intervening clays or glacial till deposits were not encountered during drilling, which implies that the GF and the RF are in direct contact across the site. Geological cross-sections are presented in **Appendix A**. The base of the waste mass is not in direct contact with the RF.

2.3 Site Drainage

Natural streams are not present onsite. A shallow drainage ditch is present at the north-western margin of the site alongside a single farmyard and dug to divert surface runoff from the landfill away from the farmyard. During the Tier 2 site investigation, an overflow from the ditch onto the adjacent road was witnessed, where it pooled. The road in turn is located immediately adjacent to the Grand Canal.

2.4 Site Hydrogeology

Groundwater in the GF flows to the northeast across the site, turning east near the downgradient site boundary (**Appendix B**). The groundwater elevation at the northern boundary of the site is below the base elevation of the Grand Canal. Thus, groundwater is not in direct hydraulic communication with the canal. The 6-inch Cassini maps that can be accessed via the Ordnance Survey Ireland (OSI) web-viewer shows the presence of several “rises” to the north of the canal. “Rises” are indicative of springs and seeps, and imply shallow groundwater conditions to the north of the canal. This is further described in Section 2.5.3.

Groundwater flow in the RF is towards the northeast (**Appendix B**). The RF is categorized by the GSI as an ‘Lk’ aquifer, *i.e.* a locally important karstified aquifer. Although the GF has not been assigned an aquifer classification, both the GF and the RF represent potential receptors and pathways of site-related contaminants. Groundwater vulnerability is mapped by the GSI as ‘High’ across the site.

Groundwater levels in onsite monitoring wells were measured in November 2018 and May 2019, and fluctuated between 0.09 and 0.72 m in the GF across the site. The waste mass was above the groundwater table on both measurement dates. The minimum thickness of the unsaturated zone beneath the waste mass was approximately 1 m.

Because the GF directly overlies the RF, groundwater in the two units are hydraulically connected. The interpolated hydraulic gradients are approximately 0.028 in the GF and 0.018 in the RF.

Samples from the monitoring wells onsite indicate impact to groundwater in both groundwater flow units. This includes wells at the downgradient boundary of the site. Groundwater chemical results are presented in Section 3.4.

2.5 Updated Conceptual Site Model

Based on the Tier 2 site investigation, an updated CSM is presented below, with reference to Figure 1, a plan view of the CSM, and Figure 2, a SW-NE cross-section across the site, in the direction of groundwater flow.

2.5.1 Potential Sources

Potential sources of Contaminants of Potential Concern (CoPC) which have been identified within the site boundaries are:

- Leachate generated from the landfill waste materials;
- Land spreading of slurry (farmyard manure) and/or inorganic fertilisers; and
- Pesticide applications (although interviews with farmers suggest they are not used on the field within the site boundaries).

Potential sources of CoPC which have been identified upgradient of the site are:

- Land spreading of slurry (farmyard manure) and/or inorganic fertilisers;
- Septic tanks / percolation areas associated with farms and one-off housing;
- Fuel tanks (kerosene / green diesel) and
- Pesticide applications.

Cattle graze in fields around the site and there are also slatted sheds for keeping animals and farmyard slurry pit/tanks. A silage pit and fuel tanks are visible on aerial images upgradient of the site.

2.5.2 Pathways

The waste mass rests on the GF and is not in direct contact with the RF. Leachates that are episodically generated in the waste mass during wet weather events migrate vertically to the groundwater table. Clay lenses, but no distinct clay layers, were identified in the GF. As such, there are no confining layers or significant aquitards that would impede vertical transport of leachates.

The available groundwater level data indicate that the base level of the waste mass was above the groundwater table on both days of monitoring in November 2018 and May 2019. Nonetheless, the documented thin unsaturated zone in parts of the site means that groundwater levels may rise into the waste mass periodically or seasonally.

The leachates that reach the groundwater environment will mix and dilute with groundwater. The scale and extent of mixing/dilution is a function of the chemical and hydraulic loading of contaminants and the background concentrations and flux of groundwater across the site.

In groundwater, the contaminants migrate laterally and vertically under prevailing hydraulic gradients. Along the way, the contaminants undergo further attenuation mechanisms which reduce the concentrations of CoPC along the groundwater pathways.

Groundwater in the GF and the RF are inferred to be hydraulically connected, but their respective flow mechanisms are very different. In the GF, groundwater flows through interconnected pore spaces between sand/gravel particles. In the RF, groundwater flows through interconnected fractures and fissures, and possibly also karst conduits if these are present. Karst features were not encountered in boreholes that were drilled at the site, but this does not necessarily mean they are absent since intersecting karst conduits during drilling can be a hit-and-miss endeavour.

In the groundwater environment, the CoPC undergo attenuation mechanisms. In the GF, possible attenuation mechanisms are filtration, dispersion, adsorption, retardation and, depending on the contaminant in question, natural biodegradation. Additional mixing and dilution from recharge may also occur, including possible leakage of water from the Grand Canal.

In the RF, there is less opportunity for attenuation (beyond mixing/dilution) since groundwater flow takes place via open fractures, fissures or karst conduits, which allow for less interaction between groundwater and the geological media.

Groundwater flow and contaminant migration in the GF are slow, on the scale of a few metres per day (maximum). In contrast, groundwater flow and contaminant transport velocities can be higher. Where contaminants enter a karst conduit system, contaminants can migrate over long distances (hundreds of metres) in relatively short periods of time (hours/days). However, because karst conduits act as underground “pipe flow” systems, mixing/dilution can also be more significant than in porous (sand/gravel) aquifer media.

The available data show that the main groundwater flow vector onsite in the GF is to the northeast. The flow direction then turns eastward near the site boundary. In the downgradient direction, groundwater flow in the GF is expected to be influenced by the geometry of the sand and gravel deposits. According to GSI maps, these extend towards the southeast which, therefore, becomes the inferred flow vector further downgradient from the site. Ultimately, groundwater flows towards and discharges into the River Liffey.

Data from wells in the RF onsite and upgradient of the site indicates that groundwater flow in the RF is towards the northeast. Groundwater in the RF is also expected to ultimately discharge into the River Liffey.

Along the lateral pathways in the GF and RF, some of the groundwater may also discharge locally at springs and seeps in offsite areas. This is described further below.

There are no streams, springs, visible seeps within the footprint of the landfill. A small artificial ditch in the north-western portion of the site intercepts and directs runoff waters (overland flow) to the roadway that runs parallel to and between the northern site boundary and Grand Canal.

2.5.3 Potential Receptors

Potential receptors which have been identified are:

- Groundwater – both in the GF and RF;
- Springs/seeps which are located just north of the Grand Canal; and
- River Liffey (as the ultimate downgradient receptor, via groundwater discharges, as baseflow to the river).

Private wells that are located downgradient of the site and in the path of contaminant transport are also potential receptors, although all dwellings and farms between the site and the River Liffey are connected to water mains via a public water supply.

Groundwater in both the GF and the RF are usable resources, even if the GSI have only assigned an aquifer category to the RF (designated as an 'Lk' aquifer, *i.e.* locally important karstified bedrock aquifer). A survey of private wells in vicinity of the landfill was conducted as part of the Tier 2 site investigation. The survey identified only one (unused) well in the downgradient direction. It should be noted that property owners in the vicinity of the landfill had previously complained to Kildare County Council about poor water quality from their wells, which prompted the extension of public water supply to properties.

The Grand Canal is not inferred to be a groundwater receptor since the base elevation of the canal is above the groundwater table at the northern site boundary location. As such, the canal may leak water into the GF where this hydraulic relationship exists or extends.

The groundwater flow gradient in the GF turns to the east near the northern site boundary. Immediately to the north of the Grand Canal, topography is low- and flat-lying. Several straight SW-NE trending artificial drains have been dug which collect and transport water to River Liffey. The drains have been dug for land improvement purposes, but some of the drains are also connected to an overflow channel which runs parallel to the Grand Canal (along the northern side of the canal).

As noted previously, the six-inch Cassini maps which are publicly available on the website of the Ordnance Survey Ireland (OSI), and which present the natural drainage systems which existed in Ireland in the mid-1800s, show the presence of several 'rises' in the area just north of Grand Canal. 'Rises' on the six-inch maps often and typically mark the positions of small springs or groundwater seeps. Some of the rises appear at the starting points of the SW-NE trending drains. Thus, it is considered feasible that the drains may receive some quantity of groundwater from the site if and where the base elevations of the drains intersect the groundwater table and if the drains are within the groundwater migration pathway from the site. In such a scenario, the drains would become potential receptors of site-related contaminants. A preliminary assessment of topography suggests that the drain elevations may be above the interpolated groundwater table at these locations, but this is not yet confirmed as the Tier 2 site investigation did not extend offsite. This is discussed further in Section 6 .

There is also an open pond in the fields approximately 500 m to the north of the Grand Canal. The pond is not connected to drains and the water level in the pond is likely a reflection of the local groundwater table. The pond's location is considered outside the migration pathway of the GF. It is also likely outside the groundwater pathway associated with the RF.

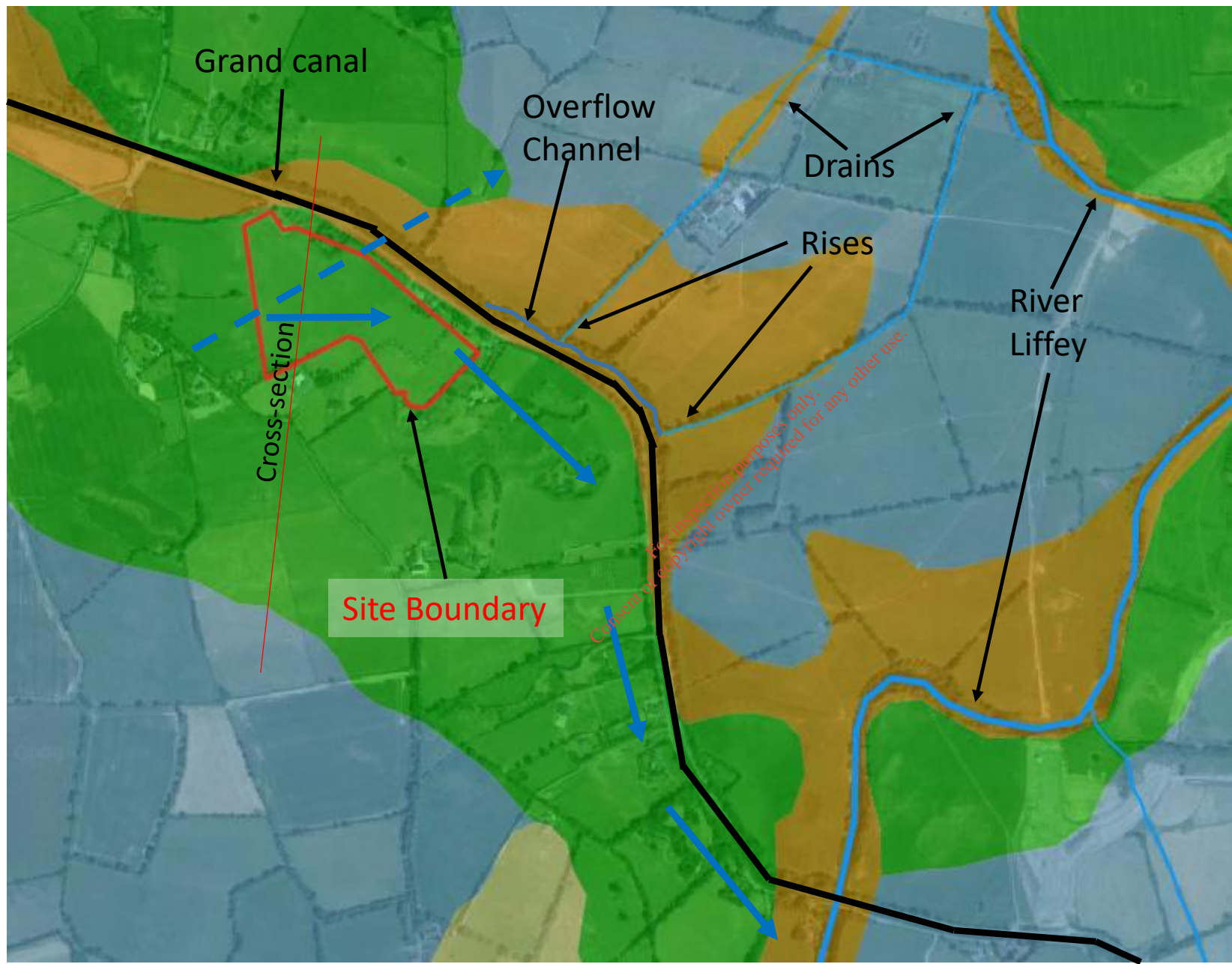
Furthest downgradient from the site, the River Liffey receives groundwater baseflow from both the GF and RF. As such, it is inferred to be the final potential receptor of site-related CoPC.

However, the River Liffey is located more than 1 km away (in a southeast to northeast arch from the site) and is considered unlikely to be at risk of impact from the site. This is described further in Section 4

There are no groundwater dependent terrestrial ecosystems (GWDTEs) such as fens or mapped wetlands at or downgradient of the site.

Finally, an existing ditch in the north-western portion of the site and which runs past a farmyard is known to direct runoff waters to the roadway that is adjacent to the Grand Canal. Although the canal is not considered a groundwater receptor of site-related contamination, the canal may receive pollutants associated with overflow from surface runoff at the site.

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Legend

Quaternary Deposits

Gravel (GLs)
Till (TLs)
Alluvium (A)
Lacustrine sediments (L)

Groundwater Flow Direction
Gravel Formation:



Limestone Formation



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Figure 1

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Figure 2	A

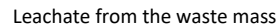
Figure 2

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Potential off-site sources

Pathways



Receptors

Onsite receptors comprise the following:

Offsite

Private well - Groundwater (Drinking water source)
Rises and connected drains
River Liffey

Section 3 Generic Quantitative Risk Assessment

3.1 Introduction

The GQRA examines the potential risks of impact to the identified receptors from the migration of CoPC.

3.2 Methodology

The GQRA compares water quality data to generic water quality screening criteria. The criteria are receptor-based. Based on the CSM, screening criteria for drinking water (private wells), groundwater (as a resource) and surface water (Liffey River) quality were considered. Specifically, laboratory analytical results from leachate, groundwater and surface water samples were compared to (as appropriate):

- Drinking Water Standards (DWSs).
- Groundwater quality standards (for those parameters that standards exist).
- Environmental quality standards for surface water (for those parameters that standards exist).
- Guideline Threshold Values (GTVs) or Interim Guideline Values (IGVs) for constituents that do not have published standards.

The relevant reference documents that contain the screening criteria are listed below.

3.2.1 Leachate Screening

- European Union Environmental Objectives (Groundwater) Regulations, 2016 (S.I. No. 366 of 2016);
- Joint Agencies Groundwater Directive Advisory Group (JAGDAG) list of hazardous substances; and
- Environmental Protection Agency (2000) Landfill Site Design Manual.

3.2.2 Groundwater Screening

- European Communities (Drinking Water) Regulations, 2014 (S.I. 122 of 2014);
- European Communities (Drinking Water) Regulations, 2007 (S.I. No. 106 of 2007);
- European Union Environmental Objectives (Groundwater) Regulations, 2016 (S.I. No. 366 of 2016);
- European Communities Environmental Objectives (Groundwater) Regulations, 2010 (S.I. No. 9 of 2010); and

- Environmental Protection Agency (2003), Towards Setting Guideline Values for the Protection of Groundwater in Ireland – Interim Report. Environmental Protection Agency, Wexford.

3.2.3 Surface Water Screening

- European Union Environmental Objectives (Surface Waters) Regulations 2015 (S.I. No. 386 of 2015); and
- European Communities Environmental Objectives (Surface Waters) Regulations 2009.

3.2.4 Application of Screening Values

The completed screening sheets for leachates, groundwater and surface water are included in **Appendix C**. Results and associated observations are summarized in Sections 3.3 through 3.5.

The screening values were applied as follows:

- Where statutory groundwater quality standards exist, these were given priority over GTVs or IGVs;
- Where two different applicable screening values exist for a given constituent, the most recently published standard was given precedence, e.g. where 2014 regulations provide a value that is updated from 2007 regulations, the value from the 2014 regulations was applied; and
- GTVs were given precedence over IGVs, and an IGV was only used where a GTV was absent.

Many GTVs are sourced from Schedule 5 of the Groundwater Regulation of 2016. These are used by the EPA to assess the status of groundwater bodies as part of their reporting requirements for Water Framework Directive (WFD) implementation. Only the EPA can assign WFD status. Exceedances of a GTV in groundwater at a landfill site does not mean that a groundwater body is at Poor status, only that there is a potential water quality impact.

Finally, the GQRA considered the ‘prevent or limit’ objective of the Groundwater Regulations, whereby:

- The ‘prevent’ objective relates to **hazardous substances**, whereby all necessary and reasonable measures should be taken to avoid the entry of such substances into groundwater and to avoid any significant increase in concentration in groundwater, even at a local scale; and
- The ‘limit’ objective relates to **non-hazardous substances**, whereby all necessary measures should be taken to limit inputs into groundwater to ensure that such inputs do not cause deterioration in status of groundwater bodies, nor significant and sustained upward trends in groundwater concentrations.”

The EPA (EPA 2010) published a list of hazardous and non-hazardous substances in 2010. The list has been further updated by the Joint Agencies Groundwater Directive Advisory Group (JAGDAG) (EPA active member) in January 2019 (UKTAG 2019). Based on this, the leachate and groundwater sample results were screened for the presence of JAGDAG hazardous substances

list, as well as criteria provided by UKTAG that incorporate “concentrations of hazardous substance in groundwater below which the danger of deterioration in the quality of the receiving groundwater is avoided”.

Minimum reporting values (MRVs) were used for hazardous substances where standards do not yet exist. An MRV is the lowest concentration of a substance that can be determined with a known degree of confidence using commonly available laboratory analytical methods, but is not necessarily equivalent to a limit of detection.

3.3 Leachate Screening and Assessment

3.3.1 GTVs/IGVs

Leachate analytical results were compared to groundwater GTVs or ITVs as there are no standards applicable to leachates. Locations where leachate samples exceeded GTVs/IGVs are plotted in **Appendix D** and results are presented in Table 1. The screening simply compares relative concentrations. It does not account for leachate volumes, chemical loads to groundwater or dilution with groundwater. Hydrocarbons were only analyzed in the second round of sampling in May 2019 after being detected in the soil samples during the early stages of site investigation.

Table 1: Leachate Screening Against Groundwater GTVs/IGVs

Determinand	Units	GTV/IGV	Minimum (result above detection limit)	Average (result above detection limit)	Maximum	No. of Samples	No. of GTV / IGV Exceedances
Electrical Conductivity	µS/cm	1875	780	1560	2300	5	2
Faecal Coliforms	cfu/100ml	0	5	8	11	2	2
Total Coliforms	cfu/100ml	0	2420	2420	2420	2	2
Potassium	mg/l	5	5.1	23.3	76.0	5	5
Magnesium	mg/l	50	7.7	30.7	62.0	5	1
Sodium	mg/l	150	8.9	124.8	260	5	2
Orthophosphate as PO ₄	mg/l	0.035	0.058	0.058	0.058	5	1
Ammoniacal Nitrogen	mg/l	0.175	6.50	16.84	40.00	5	5
Arsenic	µg/l	7.5	3.0	8.5	25.0	5	1
Boron	µg/l	750	99.0	917.8	3800.0	5	1
Iron	µg/l	200	680	9594	28000	5	5
Lead	µg/l	0.75	1.20	7.10	13.00	5	2
Manganese	µg/l	50	450	3912	8300	5	5
Nickel	µg/l	15	19.0	625.8	2900.0	5	5
Naphthalene	µg/l	1	1.45	1.45	1.45	6	1
Vinyl Chloride	µg/l	0.375	0.698	0.698	0.698	6	1
Benzene	µg/l	0.75	1.50	1.60	1.80	6	3
Ethylbenzene	µg/l	10	4.7	43.5	150.0	6	5
m & p-Xylene	µg/l	10	10.8	105.2	460.0	6	6

Determinand	Units	GTV/IGV	Minimum (result above detection limit)	Average (result above detection limit)	Maximum	No. of Samples	No. of GTV / IGV Exceedances
o-Xylene	µg/l	10	4.6	18.8	35.0	6	3
Aliphatic VPH >C5 - C10	µg/l	10	10.7	78.9	147.0	2	2
Aliphatic VPH >C6 - C8	µg/l	10	100.0	100.0	100.0	2	1
Aliphatic VPH >C8 - 10	µg/l	10	10.7	28.9	47.0	2	2
Aromatic VPH >C5 - C10	µg/l	10	25.6	82.3	139.0	2	2
Aromatic VPH >C8 - C10	µg/l	10	25.6	82.3	139.0	2	2

Key results are summarized as follows:

- Ammoniacal nitrogen exceeded its GTV/ITV frequently, and at high concentrations;
- Several metals exceeded their GTVs/ITVs (notably iron, manganese, arsenic, boron, nickel, magnesium and lead);
- Benzene, ethylbenzene, m & p-Xylene and o-Xylene (BTEX compounds) exceeded their respective GTVs/IGVs;
- Aliphatic and aromatic hydrocarbon compounds exceeded their GTVs/IGVs;
- Naphthalene, a polyaromatic hydrocarbon constituent, exceeded its GTV/ITV in one sample; and
- Vinyl chloride, a solvent, exceeded its GTV/ITV in one sample (the same sample as the naphthalene exceedance).

The exceedances reflect the mixed nature of the waste. The elevated levels of ammoniacal nitrogen are associated with landfills in methanogenic stages of landfill life. It will potentially have a significant impact on groundwater quality (see Section 3.4).

Detections of BTEX, naphthalene and vinyl chloride indicate that petrol/diesel products and/or solvents may be present in the waste. Naphthalene is also a constituent in coal tar. BTEX, TPH and PAH compounds were also observed in soil samples during the Tier 2 site investigation.

The range and spatial variability of ammonia and metal concentrations in the leachate may reflect different conditions in the landfill where the leachate is generated, *i.e.* acetogenic vs methanogenic conditions. This is also indicated by landfill gas monitoring results during the Tier 2 site investigation, whereby some monitoring wells in the waste mass (e.g. MW14) had high methane concentrations (e.g. 66.5% v/v in MW14) whilst other wells had relatively low methane concentrations (e.g. 1.2 % v/v in MW11). High methane concentrations can reflect methanogenic conditions. Low methane concentrations can reflect acetogenic conditions (EPA, 2000).

3.3.2 Hazardous Substances

The leachate results were screened against the JAGDAG hazardous substances list, and results are presented in Table 2.

Table 2: Hazardous Substances in Leachate Samples

Determinand	Units	GTV/IGV	UKTAG Value ¹	Minimum (result above detection limit)	Maximum ²	No. of Samples	No. of samples with conc. above detection limits
Arsenic	µg/l	7.5	5	3.0	25.0	5	5
Chromium	µg/l	37.5	5	2.2	37.5	5	4
Lead	µg/l	0.75	5	1.20	13.00	5	2
Naphthalene	µg/l	1	none	1.45	1.45	6	1
Vinyl Chloride	µg/l	0.375	0.25	0.698	0.698	6	1
Benzene	µg/l	0.75	0.5	1.50	1.80	6	3
Toluene	µg/l	525	350	1.10	29.00	6	6
Ethylbenzene	µg/l	10	none	4.7	150.0	6	6
m & p-Xylene	µg/l	10	none	10.8	460.0	6	6
o-Xylene	µg/l	10	none	4.6	35.0	6	4
1,2,4-Trimethylbenzene	µg/l	No GTV/IGV	none	17.5	50.0	6	4

Note:

¹ – Per UKTAG, “Concentrations of hazardous substance in groundwater below which the danger of deterioration in the quality of the receiving groundwater is avoided”

² - Values in **blue bold** exceed the UKTAG concentration thresholds.

The landfill leachate samples had detectable concentrations of 11 constituents classed as hazardous substances. Five of the hazardous substances do not have UKTAG screening values - ethylbenzene, o-Xylene and m & p-Xylene, 1,2,4-trimethylbenzene and naphthalene.

Concentrations of toluene and benzene are below respective UKTAG screening values. As such, they would have a lower potential of impacting on groundwater quality. Arsenic, lead, vinyl chloride, benzene and chromium exceeded respective UKTAG values.

3.3.3 Composition of Leachates

The site-specific leachate concentrations were compared to typical leachate concentrations presented in the EPA Landfill Manual (2000). The methanogenic stage landfill values were selected because of the predominantly high methane concentrations detected in the gas monitoring wells during the Tier 2 site investigation. Results of the comparison are presented in Table 3.

Table 3: Site Leachate Concentrations Compared to Typical Methanogenic Leachate Concentrations

Digby Bridge Samples						Landfill Manual (EPA 2000)		
Determinand	Units	Minimum (result above detection limit)	Average (result above detection limit)	Maximum	No. of Samples	Minimum	Mean	Maximum
pH		6.9	7.2	7.6	5	6.8	7.52	8.2
Electrical Conductivity	µS/cm	780	1560	2300	5	5990	11502	19300
Biochemical Oxygen Demand	mg/l	10.0	271.2	1050.0	5	97	374	1770
Chemical Oxygen Demand	mg/l	57.0	283.8	558.0	5	622	2307	8000
Calcium	mg/l	130	359	847	5	23	151	501
Potassium	mg/l	5.1	23.3	76.0	5	100	854	1580
Magnesium	mg/l	7.7	30.7	62.0	5	40	250	1580
Sodium	mg/l	8.9	124.8	260.0	5	474	1480	3650
Chloride	mg/l	15.0	80.2	130.0	5	570	2074	4710
Orthophosphate as PO ₄	mg/l	0.058	0.058	0.058	5	0.3	4.3	18.4
Sulphate	mg/l	21.0	49.0	75.0	5	<5	67	322
Ammoniacal Nitrogen	mg/l	6.50	16.84	40.00	5	283	889	2040
Arsenic	µg/l	3.0	8.5	25.0	5	<1	34	485
Cadmium	µg/l	0.09	1.15	2.20	5	<10	15	80
Chromium	µg/l	2.2	14.7	37.5	5	<30	90	560
Copper	µg/l	3.3	11.2	19.0	5	<20	130	620
Iron	µg/l	680	9594	28000	5	1600	27400	160000
Lead	µg/l	1.20	7.10	13.00	5	<40	200	1900
Manganese	µg/l	450	3912	8300	5	40	460	3590
Nickel	µg/l	19.0	625.8	2900.0	5	<30	170	600
Zinc	µg/l	1.60	19.95	51.00	5	<30	1140	6700

3.3.4 Leachates - Discussion

The pH and concentrations of BOD, COD, calcium, and sulphate are broadly similar to the concentrations that are presented in the EPA Landfill Manual (2000) for a landfill leachate in the methanogenic stage (Stage IV) of its life cycle.

Concentrations of several metals, including arsenic, cadmium, chromium, copper, iron, lead, magnesium and zinc, are lower than those presented in the EPA Landfill manual. There are also lower concentrations of nutrient compounds, notably ammoniacal nitrogen and orthophosphate, when compared against the EPA Landfill Manual 2000. In contrast, calcium, manganese and nickel showed higher concentrations than those listed in EPA Landfill Manual 2000.

As described by the EPA (2000), metal concentrations in leachate during the acetogenic phase (Stage III) of a landfill may contain high concentrations of iron, manganese, calcium and magnesium, due to the leachate being chemically aggressive, resulting in enhanced leaching and dissolution of metals from both the waste material and the native rocks/sediments. Conversely, during the methanogenic stage, concentrations of heavy metals (especially) tend to be lower. Thus, the leachate sample results to date suggest that both acetogenic and methanogenic conditions are present within the footprint/volume of the waste mass.

The notion that different conditions exist within the landfill (depending on location) is supported by the Tier 2 gas monitoring results from wells with response zones in the waste mass, whereby:

- Higher concentrations of methane (>36% v/v) and carbon dioxide (26.1 % v/v), combined with an absence of oxygen, were recorded in wells MW12, MW13 and MW14, indicating that anaerobic/ methanogenic conditions prevail (in the area of these wells); and
- Higher concentrations (20%) of oxygen, combined with lower concentrations of carbon dioxide (> 0.2 % v/v) and an absence of methane, were recorded in wells MW15 and MW16, indicating that more aerobic / acetogenic conditions likely prevail (in the area of those wells).

3.4 Groundwater Screening and Assessment

3.4.1 Drinking Water Standards (DWS)

Screening results for DWSs are presented in Table 4 for groundwater samples. Locations of monitoring wells that show exceedances of DWSs are presented in **Appendix D**. Analysis for hydrocarbons was conducted on leachate samples only.

Table 4: Groundwater Screening Against Drinking Water Standards

Determinand	Units	DWS	Minimum (result above detection limit)	Mean	Maximum	No. of Samples	No. of DWS Exceedances
Gravel Formation (GF)							
Cyanide	mg/l	0.05	0.066	0.066	0.066	14	1
Faecal Coliforms	cfu/100ml	0	0	882	10000	8	8
Total Coliforms	cfu/100ml	0	1	1005	10000	14	14
Ammoniacal Nitrogen	mg/l	0.3	0.68	14.25	66.70	14	9
Boron	µg/l	1000	74.0	343.9	1120.0	14	1
Chromium	µg/l	50	3.3	23.3	107.0	14	1
Iron	µg/l	200	240	342	440	14	6
Manganese	µg/l	50	8.0	500.4	1900.0	14	12
Nickel	µg/l	20	2.7	15.0	79.1	14	2
Terbutryn	µg/l	0.1	0.071	0.126	0.181	13	1
Rickardstown Formation (RF)							
Cyanide	mg/l	0.05	0.155	0.155	0.155	2	1
Total Coliforms	cfu/100ml	0	0	290	579	1	1
Ammoniacal Nitrogen	mg/l	0.3	0.87	3.54	6.20	2	2

Determinand	Units	DWS	Minimum (result above detection limit)	Mean	Maximum	No. of Samples	No. of DWS Exceedances
Iron	µg/l	200	250	250	250	2	1
Manganese	µg/l	50	1700	1765	1830	2	2
Nickel	µg/l	20	12.0	17.1	22.0	2	1

Groundwater in the GF shows exceedances of DWSs for ammoniacal nitrogen, total coliforms, faecal coliforms, several metals and terbutryn (a pesticide).

- The ammoniacal nitrogen was exceeded in Round 1 in wells MW01, MW02, MW04, MW05, MW06 and MW07, and in Round 2 in wells MW03, MW05 and MW07. The sample with the highest concentration (66.7 mg/l) was taken from the downgradient well MW05.
- Ammoniacal Nitrogen was also detected in wells at the upgradient boundary of the site, implying an offsite source (septic tanks/effluent percolation areas). However, the highest concentrations occurred in the downgradient well MW05.
- Total coliforms and faecal coliforms were detected in several wells, including wells at the upgradient boundary of the site.
- Exceedances for boron, chromium, cyanide and terbutryn are localised. Terbutryn, a pesticide constituent, was detected in the upgradient monitoring well MW01. Atrazine and simazine were also detected upgradient, in well MW03, but concentrations were below their respective standards and were not confirmed in both rounds of sampling. Malathion was tested in May 2019 (only), and was detected in wells MW07 and MW08 (downgradient). However, concentrations were below the groundwater quality standard for pesticides.
- Elevated concentrations of iron and manganese in groundwater are consistent with landfills and can be attributed to the anoxic conditions which often typify landfill settings.

In the RF, exceedances of DWSs were noted in the single well MW08 for ammoniacal nitrogen, iron, manganese, nickel and cyanide. Total coliforms counts were also recorded in Round 2 in well MW08.

3.4.2 GTVs/IGVs

Screening results for GTVs/ITVs are presented in Table 5 for groundwater in the GF and RF. Locations of monitoring wells that show exceedances of GTVs/ITVs are presented in **Appendix D**.

Table 5: Groundwater Screening Against GTVs/ITVs

Determinand	Units	GTV/IG V	Minimum (result above detection limit)	Mean	Maximum	No. of Samples	No. of EWS Exceedances
Gravel Formation							
Electrical Conductivity	µS/cm	1875	575	1008	1990	14	1
Cyanide	mg/l	0.0375	0.0660	0.0660	0.0660	14	1
Faecal Coliforms	cfu/100 ml	0	0	882	10000	8	8
Total Coliforms	cfu/100 ml	0	1	1005	10000	14	14
Potassium	mg/l	5	1.6	13.1	62.9	14	9
Magnesium	mg/l	50	5.9	43.1	151.0	14	3
Orthophosphate as PO ₄	mg/l	0.035	0.066	0.109	0.260	14	6
Ammoniacal Nitrogen	mg/l	0.175	0.680	14.253	66.70	14	9
Boron	µg/l	750	74.0	343.9	1120.0	14	1
Chromium	µg/l	37.5	3.3	23.3	107.0	14	2
Iron	µg/l	200	240	342	440	14	6
Manganese	µg/l	50	8.0	500.4	1900.0	14	12
Nickel	µg/l	15	2.7	15.0	79.1	14	4
Rickardstown Formation (RF)							
Cyanide	mg/l	0.0375	0.155	0.155	0.155	2	1
Total Coliforms	cfu/100 ml	0	0	290	579	1	1
Potassium	mg/l	5	5.1	5.1	5.1	2	1
Magnesium	mg/l	50	21	69	117	2	1
Orthophosphate as PO ₄	mg/l	0.035	0.071	0.071	0.071	2	1
Ammoniacal Nitrogen	mg/l	0.175	0.870	3.535	6.200	2	2
Iron	µg/l	200	250	250	250	2	1
Manganese	µg/l	50	1700	1765	1830	2	2
Nickel	µg/l	15	12.0	17.1	22.1	2	1

Exceedances of GTVs/ITVs in both the GF and RF were observed for broadly the same parameters that exceeded DWs.

3.4.3 Hazardous Substances

The groundwater results were screened against the JAGDAG hazardous substances list, and results are presented in Table 6.

Table 6: Hazardous Substances in Groundwater Samples

Determinand	Units	GTV/IGV	UKTAG Value	Minimum (result above detection limit)	Maximum ²	No. of Samples	No. of sample with conc. above detection limits	Aquifer/ Formation
Arsenic	µg/l	7.5	5	1.0	2.2	16	5	GF / LF
Chromium	µg/l	37.5	5	3.3	107.0	16	12	GF
Mercury	µg/l	0.75	0.5	0.203	0.246	16	2	GF
Simazine	µg/l	0.1	0.05	0.023	0.040	15	3	GF / LF
Atrazine	µg/l	0.075	0.05	0.024	0.042	15	4	GF / LF
Triallate	µg/l	No GTV/IGV	none	0.063	0.063	8	1	GF
Malathion	µg/l	0.01	0.05	0.005	0.006	8	2	GF / LF
Gamma-HCH	µg/l	0.075	0.05	0.0043	0.0057	15	2	GF / LF
2-Chlorophenol	µg/l	200	150	1.16	1.16	16	1	GF

Note:

¹ – Per UKTAG, “Concentrations of hazardous substance in groundwater below which the danger of deterioration in the quality of the receiving groundwater is avoided”

² - Values in **blue bold** exceed the UKTAG concentration thresholds.

Groundwater samples had detectable concentrations of 9 substances classed as hazardous, notably arsenic, chromium, mercury, atrazine, simazine, malathion, gamma-HCH, 2-Chlorophenol and triallate. These are metals and pesticides.

However, it is noted that the detected concentrations of arsenic, atrazine, simazine, malathion, gamma-HCH, and 2-Chlorophenol were below respective UKTAG values, *i.e.* the “Concentrations of hazardous substance in groundwater below which the danger of deterioration in the quality of the receiving groundwater is avoided”.

3.5 Surface Water Screening and Assessment

3.5.1 Environmental Quality Standards

Surface water samples collected from the Grand Canal were screened against the EQSs for surface water. Results are presented in Table 7.

Table 7: Surface Water EQS Screening Summary

Determinand	Units	EQS	Minimum (result above detection limit)	Mean	Maximum	No. of Samples	No. of EQS Exceedances
Biochemical Oxygen Demand	mg O ₂ /l	1.5	3.0	3.5	4.0	3	2
Orthophosphate as PO ₄	mg/l	0.035	0.071	0.071	0.071	4	2
Ammoniacal Nitrogen	mg/l	0.065	2.900	2.950	3.000	4	2
Chromium	µg/l	3.4	7.7	8.0	8.3	4	2

Two samples from the canal taken upgradient and downgradient of the site showed exceedances of Biochemical Oxygen Demand (BOD) in May 2019. Nutrient constituents exceeded respective EQSs in samples collected in November 2018, but exceedances did not occur in samples collected in May 2019. Chromium exceeded the EQS in both samples in November 2018.

3.6 GQRA Conclusions

Leachate is produced in the landfill which contains both hazardous and non-hazardous substances. Thirteen classed hazardous substances were identified, represented by heavy metals, BTEX and aliphatic and aromatic volatile hydrocarbons. As presented in Table 8, the available data indicate that leachate concentrations are significantly higher than the available groundwater GTVs/ITVs.

Table 8: Ratios of Average Leachate Concentrations and GTVs/ITVs

Parameter	Ratio of Average Leachate Concentrations and GTV/IGV
Ammoniacal Nitrogen	96
Manganese	78
Iron	48
Nickel	42
m & p-Xylene	11
Aliphatic VPH >C ₆ - C ₈	10
Lead	9.5
Aromatic VPH >C ₅ - C ₁₀	8.2
Aromatic VPH >C ₈ - C ₁₀	8.2
Aliphatic VPH >C ₅ - C ₁₀	7.9
Potassium	4.7
Ethylbenzene	4.4
Aliphatic VPH >C ₈ - C ₁₀	2.9
Benzene	2.1
o-Xylene	1.9
Vinyl Chloride	1.9
Orthophosphate as PO ₄	1.7

Parameter	Ratio of Average Leachate Concentrations and GTV/IGV
Naphthalene	1.5
Boron	1.2
Arsenic	1.1
Electrical Conductivity	0.83
Sodium	0.83
Magnesium	0.61

Note: Coliform counts not included as they are measured in Colony Forming Units and not expressed as concentration

The concentrations of substances identified in the leachate are broadly similar to concentrations expected in a landfill leachate which is in the methanogenic stage of its life cycle, as defined by the EPA Landfill Manual (EPA 2000). Nonetheless, there were some differences, notably:

- Lower concentrations of major ions (chloride, potassium and sodium);
- Lower concentrations of nutrient compounds (ammoniacal nitrogen and orthophosphate);
- Higher concentrations of metals (arsenic, cadmium, chromium, copper, Iron, lead, magnesium and zinc); and
- There are also some differences, notably lower concentrations of chloride, potassium and sodium in the leachate samples, as well as a lower electrical conductivity.

The leachate migrates vertically to groundwater. Whilst the leachate mixes and dilutes with groundwater beneath the source locations, data from the existing monitoring wells document that impact to groundwater quality is occurring in relation to the applicable screening criteria that were used.

A list of identified CoPC in groundwater within the site is presented in Table 9. These include ammoniacal nitrogen, iron and manganese, which tend to be sitewide, and other metals (e.g. chromium, cadmium, mercury, boron), which tend to be localized. Pesticides were detected sporadically in groundwater, and concentrations were generally below relevant screening criteria. Microbial counts were noted in most wells across the site.

Table 9: Ratios of Average Concentrations and Standards or GTVs/ITVs in Groundwater in the GF

CoPC	Ratio of Average Groundwater Concentrations and:	
	DWS	GTV/IGV
Ammoniacal Nitrogen	48	81
Boron	0.34	0.46
Chromium	0.47	0.62
Cyanide	1.3	1.8
Electrical Conductivity	-	0.54
Iron	1.7	1.7
Magnesium	-	0.86
Manganese	10	10
Nickel	0.75	1

CoPC	Ratio of Average Groundwater Concentrations and:	
	DWS	GTV/IGV
Orthophosphate as PO ₄	-	3.1
Potassium	-	2.6
Terbutryn	1.3	-

Note: Coliform counts not included as they are measured in Colony Forming Units and not expressed as concentration

Concentrations of ammoniacal nitrogen, iron, manganese, chromium, nickel, and cyanide are generally higher in monitoring wells along the northern site boundary. Impacted groundwater is, therefore, migrating offsite.

Finally, surface water samples taken from the Grand Canal showed exceedances of EQSs for chromium, BOD, ammoniacal nitrogen and orthophosphate. However, the Grand Canal is hydraulically disconnected from groundwater in the GF, which infers pollution from other sources.

3.6.1 Inflowing Groundwater Quality

Whilst leachate is a confirmed source of groundwater contamination onsite, other potential contributing sources are agricultural land uses (e.g. slurry spreading, pesticide applications) and wastewater effluents (e.g. septic tanks, percolation areas). This conclusion is based on the observations that groundwater samples from wells along the southern, upgradient site boundary (notably, wells MW01 and MW02) had CoPC concentrations which exceeded GTVs/IGVs, as follows:

- Ammoniacal nitrogen, in wells MW01 and MW02 in November 2018;
- Faecal coliform counts, in wells MW01 and MW02 in November 2018, and in MW01 in May 2019;
- Orthophosphate, in well MW01 and MW02 in May 2019;
- Chromium, in wells MW01 and MW02 in May 2019;
- Iron, in wells MW01 and MW02 in November 2018; and
- Manganese, in well MW01 in both rounds of sampling, and in well MW02 in November 2018.

The ammoniacal nitrogen, orthophosphate, and coliforms may be related to agricultural land use but septic tanks and/or percolation areas associated with houses near the southern site boundary are probable sources as well. Elevated iron and manganese may be mobilized by redox conditions downgradient of the septic tanks/percolation areas.

3.6.2 Outflowing Groundwater Quality

Wells near and along the northern downgradient site boundary show evidence of groundwater quality impact. This implies that impacted groundwater is migrating offsite. Constituents which are migrating offsite at concentrations which have exceeded relevant standards or GTVs/IGVs in

at least one round of sampling are ammoniacal nitrogen, chromium, nickel, cyanide (total), and potassium.

For example, concentrations of ammoniacal nitrogen are highest in well MW05 (66.7 mg/L in May 2019). This compares to a maximum concentration in well MW02 at the southern upgradient boundary of 2.5 mg/L (in November 2018). Accordingly, the leachate in the waste mass is confirmed as the main source of ammoniacal nitrogen even though a contribution from upgradient is apparent.

Other substances, some hazardous, are present in leachate and groundwater at the site, but their detections have been sporadic and their concentrations at the northern site boundary wells indicate that they are not migrating offsite at concentrations which exceed relevant standards or GTVs/IGVs. That said, this conclusion should be tempered against the limited groundwater quality monitoring that has been carried out to date.

3.7 Refined CSM – Tier 3, Post-GQRA

3.7.1 Sources

Leachate wells drain quickly after rainfall events and chemical loading to groundwater onsite is, therefore, episodic. Landfill leachates and land uses both contribute to groundwater quality impact at the site. The GQRA has identified a total of 25 substances in leachate which are influencing groundwater quality, of which 11 are classed as hazardous substances. The majority of these were detected in wells in the GF. Groundwater in the RF also shows signs of impact, but the evidence-base is less extensive.

Groundwater flowing into the site from the south is also impacted, mainly by nutrient and microbial pollutants. Upgradient pollution sources are septic tanks/percolation areas associated with single houses as well as agricultural land use practices.

Elevated metals concentrations are present in both the leachates and groundwater. Metals can be significantly influenced by redox conditions in landfill settings. For example, arsenic can dissolve in groundwater under anoxic conditions, along with metals such as iron and manganese. Anoxic conditions are brought about by the burial of organic materials leading to reducing conditions (Smedley & Kinniburgh, 2001). As shallow groundwater is expected to become (re)oxygenated in the downgradient direction, the fate and transport of both metals as well as ammoniacal nitrogen is expected to change, with metals precipitating from solution and the nitrogen oxidizing to nitrates and nitrites.

Sporadic detections of pesticides may also be leachate-related. However, pesticides could equally reflect diffuse applications to agricultural lands. The detected herbicides atrazine and simazine are amongst the more commonly used herbicides in Ireland and are mobile in the subsurface environment (CDM, 2008).

3.7.2 Pathways

The principal pathway for horizontal transport of site-related contaminants is groundwater in the GF. Impacted groundwater is migrating offsite. The absence of extensive, competent clays and an inferred hydraulic communication between the GF and the underlying RF can explain the detection of site-related CoPC in the bedrock aquifer. Groundwater in the RF is conceptually at

increasing risk of contamination in a downgradient flow direction, but this will depend on the actual hydraulic gradients between the GF and the RF along the principal flow path.

Groundwater flow in the GF turns to the east near the northern site boundary, influenced by the River Liffey as a regional discharge boundary and influenced by the (mapped) extent (and physical geometry) of the sand and gravel deposits. Groundwater in the RF is inferred to follow a north-easterly flow path in the offsite area, discharging to the River Liffey northeast of the site.

A possibility exists that some of the site-impacted groundwater flowing beneath the Grand Canal may discharge at small springs and seeps just north of the canal, i.e. contributing flow to the open land drains which join the River Liffey more than 1 km to the northeast. In these drains, such site-related contaminants would mix and dilute with other baseflow components to the drains, as well as runoff waters within the drain system.

3.7.3 Receptors

Groundwater at the site is an impacted receptor. Site-related contamination is migrating offsite. Downgradient private wells are at risk of impact, although they may not be used since public water supply has been extended to all houses and farms in the vicinity of the landfill. As such, if well owners downgradient from the site are not using groundwater for supply purposes, there should be no risk to human health.

The ultimate downgradient receptor is the River Liffey. However, risks of impact are considered low to negligible due to the large distance that contaminants must travel, the attenuation that will occur over that distance, and the significant dilution that would occur in the river. Moreover, if any of the site contaminants discharge to the land drains referenced above, less of the contaminant mass would migrate towards the river.

To address current uncertainty about the extent of potential contaminant migration offsite, and whether contaminants may be 'intercepted' by the land drains referenced above, additional offsite investigation is needed and recommended, as outlined in Section 6.

The Grand Canal is not a groundwater receptor. The canal might receive pollutant load from other sources, such as stormwater from overflowing ditches, drains and roadways. Only one site-related surface pathway has been identified, which is the ditch along the farmyard near the north-western corner of the landfill site.

3.7.4 Summary of Risk to Receptors, Post-GQRA

Inferred risks to specific potential receptors based on the GQRA are summarized in Table 10. There is potential risk of impact to offsite receptors, which is considered further in the DQRA (Section 4).

Table 10: Assessment of Risks to Specific Receptors, post-GQRA

Confirmed Onsite Sources	Pathway	Onsite Receptor	Offsite Receptor
CoPC in leachate	Vertical migration through the waste mass and GF	Groundwater in the GF	--
CoPC in groundwater	Groundwater in the GF	Groundwater in the GF. Groundwater quality is already impacted	Groundwater: Potential Risk Private Wells: Low Risk Grand Canal: No Risk

Confirmed Onsite Sources	Pathway	Onsite Receptor	Offsite Receptor
			Drainage Channels: Potential Risk River Liffey: Low Risk
	Groundwater in the RF	Groundwater in the RF. Groundwater quality is showing signs of impact; thus, an inferred risk of impact exists	Groundwater: Potential Risk Private Wells: Low Risk Grand Canal: No Risk Drainage Channels: Low Risk River Liffey: Low Risk
CoPC in surface runoff (farm activity)	Surface runoff; Ditch	None	Groundwater: Potential Risk Grand Canal: Potential Risk
Confirmed or Potential Upgradient Sources (Offsite)	Pathway	Onsite Receptor	Upgradient Offsite Receptor
Septic tanks and/or percolation areas Infilled Pits Fuel tanks, heating oil Agricultural land uses (land spreading, pesticides) Other (e.g. spills)	Groundwater in the GF	Groundwater quality in the GF is impacted (nutrient and microbial parameters)	Groundwater: Potential Risk Private wells: Potential Risk
	Groundwater in the RF	Groundwater in the RF	Groundwater: Potential Risk Private wells: Potential Risk

Section 4 Detailed Quantitative Risk Assessment

The DQRA was carried using the remedial targets methodology (RTM) published by the Environment Agency (EA 2006). A brief overview of the RTM is provided below, followed by a description of input parameters, calculations, summary of results, discussion, and conclusions with recommendations.

4.1 Remedial Targets Methodology

The RTM is a means of conducting a phased risk assessment using an analytical model that produces remedial target criteria (RTC) in soils and groundwater. The RTC is a concentration for a contaminant in soil or groundwater below which the defined risk to the receptor is removed.

The RTM considers four levels of assessment which progressively describe the fate and transport of a CoPC from source to receptor. Along the SPR chain, the RTM progressively factors in more detailed fate and transport processes. When a contaminant concentration at a prescribed compliance point falls below the RTC, there is no need to proceed to the next level.

Level 1 – Soil Zone: The first level of assessment considers the soil zone. The RTM produces a porewater concentration of a CoPC in soil which is sufficient to impact on the receptor when attenuation mechanisms along the vertical pathway are ignored. Accordingly, the level 1 assessment is the most stringent/conservative level of assessment, and the compliance point is the soil zone.

Level 2 – Groundwater Concentration Beneath the Source: The second level of assessment considers attenuation through the unsaturated and mixing/dilution with groundwater beneath the source, beneath the waste mass in the case of the Digby Bridge landfill. The RTM produces a groundwater concentration which determines whether attenuation of contaminants in the unsaturated zone and dilution in groundwater at the source location are sufficient to reduce contaminant concentrations to acceptable levels (e.g. DWSs, GTVs). The compliance point is in groundwater immediately below the source.

Level 3 – Groundwater Concentration Downgradient of the Source: The third level of assessment considers further attenuation processes in groundwater as contaminants migrate away from the source. The RTM produces a groundwater concentration downgradient of the source which determines whether attenuation in the aquifer is sufficient to reduce contaminant concentrations to acceptable levels at user-defined compliance points. This compliance point is hydraulically downgradient of the source. It is often receptor-based (e.g. a private well) or an otherwise agreed distance between the source and receptor.

Level 4 – Final Receptor Concentration: The fourth level of assessment considers ‘final’ dilution in a receptor at the end of the SPR chain, and is typically represented by a surface water body. The RTM produces a concentration which determines if mixing/dilution is sufficient to reduce contaminant concentrations to acceptable levels. Level 4 is considered a special case - it must be demonstrated that: a) an impact to groundwater does not jeopardize future use of the groundwater resource; and b) the cost of remediation is disproportionate in relation to the improvement of groundwater or surface water quality that can be achieved.

4.1.1 Analytical Model

The analytical model used to calculate RTCs is represented by the Remedial Targets Worksheet (RTW) (Version 3.2) which is freely available from the EA website. The equations behind each level of the assessment are documented in an accompanying RTM guidance, and are not reproduced herein.

4.1.2 Modelling Approach

The RTW is deterministic analytical model. Each input parameter is defined by a single value based on site-specific data or literature-based sources of information. Where site-specific data were not available, suitable generic data were researched and adopted from literature. Inputs based on literature are identified and referenced throughout the report, as appropriate.

A conservative approach to the modelling was adopted to be consistent with the RTM. Most significantly, calculations assume a constant, non-declining (*i.e.* permanent) source term under steady-state conditions. As well, where ranges in input values are applicable and/or possible, conservative values were used, whereby the term “conservative” implies higher risk outcomes.

The analytical model is set up according to the CSM. Both inputs and results have been reviewed and vetted against the refined CSM for the site. Inherent uncertainty in the selection of certain parameter values has been addressed by carrying out sensitivity analyses.

4.2 Selection of CoPC

In line with the RTM, the selection of CoPC was based on the number and magnitude of screening criteria exceedances in the landfill leachate and groundwater. The following CoPC are represented:

Gravel Formation	Rickardstown Formation
Ammoniacal Nitrogen	Ammoniacal Nitrogen
Aromatic VPH >C ₈ - C ₁₀	Manganese
Manganese	
Nickel	
Chromium	

Ammoniacal nitrogen is the most prevalent CoPC at the site. The hydrocarbons that were present in the leachate were not tested for in groundwater and were, therefore, considered in the analytical model on a precautionary, exploratory basis. Metals are represented by manganese, nickel and cadmium. These were detected at their highest concentrations (and exceeding GTVs/ITVs) near the northern downgradient site boundary.

Maximum concentrations in leachate and groundwater over the two sampling rounds (November 2018 and May 2019) were used to define the source term in the GF and RF, respectively. This adds to the conservative nature of the results.

Manganese is a common constituent in Irish bedrock aquifers, especially under confined conditions. Manganese was included as a CoPC and included in the RTW calculations because concentrations in groundwater at the site are up to two orders of magnitude higher than the

natural background concentrations of both gravel and “pure limestone” aquifers that are reported by the EPA nationally (EPA, 2007).

4.3 Modelled Sources

4.3.1 Source 1 - Waste Mass

The waste mass of the legacy landfill has a footprint of 48,285 m². Sources within the waste mass are contaminated soils and landfill leachates. Modelling levels run were Levels 1, 2 and 3. The calculations pertain to the GF (only) as the GF is the first receptor of CoPC from the source, directly beneath the waste mass. Contaminants in the RF were modelled separately (see Section 4.3.2)

The maximum concentrations of the CoPC detected in samples from Source 1, represented by soils and leachate, are presented in Table 11.

Table 11: Source 1 CoPC Concentrations

Source 1	unit	Ammon- iacal Nitrogen	Aromatic VPH >C8 - C10	Mangan- ese	Nickel	Chrom- ium
Maximum Concentration in Soil	mg/kg	NT	7.5	NT	41	240
Maximum Concentration in Leachate	mg/l	40	0.139	8.3	2.9	0.0375

Note: NT - not tested (not included in the Rilta suite of analytes)

4.3.2 Source 2 - Contaminated Groundwater in the RF

For the RF, a second source was considered defined by the inferred impacted groundwater in bedrock at the site. In this instance, the source term is specified from groundwater quality data, and Levels 1 and 2 calculations are excluded. The RTM guidance document refers to this user-specified scenario as a Level 3(a) calculation.

The maximum concentrations of the CoPC detected in groundwater samples in the RF onsite are presented on Table 12.

Table 12: Source 2 CoPC Concentrations

Source 2	Unit	Ammoniacal Nitrogen	Manganese
Maximum Concentration in Groundwater (RF)	mg/l	6.2	1.83

4.4 Compliance Values and Points

The compliance value is the concentration of a specific substance that will ensure that relevant standards or threshold values are not exceeded at a compliance point. The latter could be receptor location or an otherwise agreed upon point downstream of the site. With regards to the legacy landfill site, there are three possible receptors: a) groundwater; b) seeps/springs and land drains north of the Grand Canal; and c) the Liffey. The extent of offsite contamination has not yet been established and requires that monitoring wells are installed and sampled in offsite locations. The findings could help establish appropriate compliance points in the downgradient direction.

Compliance values for each CoPC are defined by groundwater quality standards, GTVs/ITVs for groundwater, DWSs for abstractions (private wells), and surface water EQSs for the Liffey. The relevant compliance values for the site-specific CoPC are summarized in Table 13.

Table 13: Relevant Compliance Values

Receptor	Standard	Unit	Ammon- iacal Nitrogen	Aromatic VPH >C8 - C10	Mangan- ese	Nickel	Chromium
Groundwater - general	GTV/IGV	mg/l	0.175	0.01	0.05	0.015	0.0375
Groundwater – hazardous substances	UKTAG	mg/l	--	--	--	--	0.005
Surface Water	EQS	mg/l	0.065	--	--	0.004	0.0047
Abstraction Wells	DWS	mg/l	0.3	0.01	0.05	0.02	0.05
Most stringent value		mg/l	0.065	0.01	0.05	0.004	0.0047

Even though it represents the ultimate downgradient potential receptor of site-related contamination, the Liffey is not a practical, and may not be an appropriate, compliance point due to its distance from the site and the fact that the water quality of the Liffey is influenced by many variables within its catchment which could mask the influence of any site-related constituents discharging to the river via the groundwater pathway. Nonetheless, for the purposes of the DQRA, and for completeness, it was considered in the RTM.

4.5 Input Parameters

4.5.1 Unsaturated Zone

The groundwater level at the site fluctuates seasonally, and data collated during the Tier 2 site investigation indicates that the groundwater table is periodically in contact with the base of the waste mass. In the RTW, the unsaturated zone was given a zero thickness, which is conservative since this is not a permanent scenario.

4.5.2 Infiltration Rate

An infiltration rate of 343 mm/yr, or 9.4×10^{-4} m/d, was applied guided by the GSI national recharge map. This value is conservative (high) as the waste mass includes a cover material and less water likely infiltrates than was simulated.

4.5.3 Groundwater Flow Gradient

The groundwater flow gradients were estimated from groundwater contour maps presented in **Appendix D**. They are:

- Gravel Formation (GF): 0.028
- Limestone Formation (GF): 0.018

4.5.4 Aquifer Hydraulic Conductivity

A value of 30 m/day was assigned to the GF based on published information from the GSI for the mid-Leinster gravel bodies (Kelly *et al.* 2015). A value of 1 m/d was assigned to the RF based on Daly (2008).

4.5.5 Background Groundwater Concentrations

Concentrations of ammoniacal nitrogen and manganese exceeded respective GTVs/IGVs in the monitoring wells along the southern site boundary, indicating impact from upgradient sources.

The purpose of the DQRA is to quantify impacts from source contributions of the landfill, hence the upgradient concentrations were not included in the modelling, so as not to influence the DQRA results.

4.5.6 Biodegradation Rates

Biodegradation rates were calculated in the RTW from published values of half-lives of ammoniacal nitrogen and the aromatic VPH C₈-C₁₀. Unlike metals, these parameters are subjected to microbial attenuation processes. The selection of half-lives (which determine biodegradation rates) considered the inferred redox condition in groundwater, whereby;

- Upgradient monitoring well MW01 showed dissolved oxygen concentrations above 1 mg/l and redox values above 100 mV, indicating aerobic conditions in the GF at this location.
- Downgradient monitoring wells MW04 and MW05 showed dissolved oxygen concentrations lower than 1 mg/l with lower redox values than MW01, indicating less oxygen is available in the groundwater environment, tending towards anaerobic conditions.

Further downgradient, *i.e.* offsite, it is anticipated that aerobic conditions will be re-established, at least in the GF.

In the RF, the field parameters indicated low oxygen conditions in the single well MW08. In the downgradient direction, *i.e.* offsite, it is expected that anaerobic conditions may prevail since the RF is buried beneath glacial till along the northeasterly groundwater flow path.

The published half-life for ammoniacal nitrogen ranges from 1 to 6 years. To be conservative, the high-end value of 6 years was input. A high end published value was also used for aromatic VPH C₈-C₁₀.

4.5.7 Partitioning Coefficients (K_d)

Partitioning is an attenuation mechanism which controls the degree to which certain CoPC adsorb or desorb from soil particles. Per the RTM, site-specific partitioning coefficients (K_d) for soil and water were estimated from soil laboratory data. The derived values are presented in Table 14. The laboratory reported that soil leachate samples were prepared for a liquid:solid ratio of 10:1. According to the RTM, the preferred liquid:solid ratio for soil leachate samples is 2:1. The implication is that the site-specific K_d values may be slightly overestimated. For this reason, literature values of K_d were researched for the CoPC in question and compared against the estimated values (see Table 14: Partitioning Coefficients Used for Metals).

Table 14: Partitioning Coefficients Used for Metals

	Kd for Soil Source (l/kg)	
	Estimated Site-Specific Values	Literature Value ¹
Cadmium	483	100
Chromium	1200	480
Nickel	465	500

¹ – see Table 17 for literature references

Literature values are generally more conservative (resulting in less retardation in groundwater) and were thus selected for the RTC calculations.

4.5.8 Dispersion

Dispersion, depicted in Figure 3 (a) & (b), is an attenuation mechanism whereby contaminants are mixed/diluted in three dimensions as contaminants migrate in groundwater.

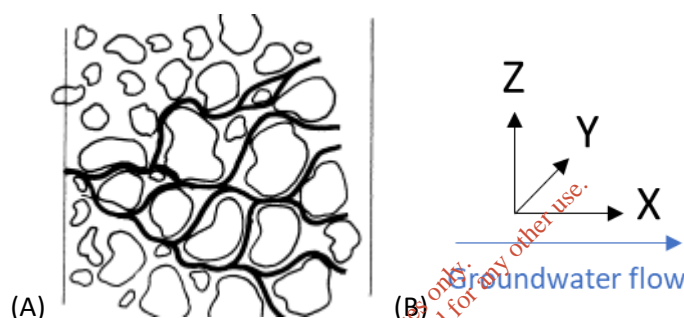


Figure 3: (A) Mechanical dispersion through a porous aquifer. (B) Axis relative to groundwater flow

The mixing (and dilution) that occurs along the groundwater flow direction (x-axis in Figure 3) is called longitudinal dispersion. The mixing that occurs transversely (y-axis in Figure 3) is called transverse dispersion. The mixing that occurs in the vertical plane (z-axis in Figure 3) is called vertical dispersion.

Selecting appropriate values for each is important as they describe the growth or spread of contaminants in the downgradient direction, which is site-specific (e.g. aquifer heterogeneity influences dispersion to a considerable extent). It is a particularly tricky parameter to quantify because dispersivity is scale-dependent.

Longitudinal dispersion is typically assumed as 0.1 times the pathway length (Domenico and Schwartz, 1990). Transverse dispersion is often assumed as 0.01 to 0.03 times the pathway length. Vertical dispersion is often assumed as 0.001 times the pathway length (because of layering of strata) (EA, 1999).

However, it is recognized that different geological materials also have different dispersive capacity. Dispersivity in fractured bedrock can be very different from dispersivity in sand and gravel aquifers. For this reason, a literature review was conducted to assign reasonable values of dispersivity, mainly based on published field studies of contaminant plumes at contaminated land sites with similar geology to the Digby Bridge site. Thus, sand and gravel-based values were used for the GF and limestone-based values were used for the RF. Relevant references are USGS (1999), Singhal and Gupta, 1999), Domenico and Schwartz, 1990), and Gelhar *et al.* (1992).

For the Digby Bridge landfill site, the values shown in Table 15 were used.

Table 15: Selected Dispersivity Values

Formation	Longitudinal Dispersivity	Transverse Dispersivity	Vertical Dispersivity
GF	100 m	10 m	1 m
RF	25.3 m	12.65 m	0.25 m

Dispersion is generally greater and more significant in the GF. The RF values are based on published values from contaminant field studies in limestones. In karst systems the ratios of longitudinal to transverse or vertical dispersivity could be significantly larger.

4.5.9 Other Fate and Transport Input Parameters

Other fate and transport parameters, and their references, are presented in Table 16.

Table 16: Physical Parameters Used for Calculations in the GF

Parameter	Unit	Value	Comment / Justification
Unsaturated Soil Source - Landfill			
Source width	m	100	Site-specific - width of site area, perpendicular to groundwater flow
Unsaturated source depth	m	6.00	Site-specific data
Unsaturated source length	m	400	Site-specific - length of waste mass parallel to groundwater flow
Infiltration rate	mm/yr	343	GSI national recharge web map
Bulk density	g/cm ³	1.0	Literature-based. Typical density of 0.8–1.2 tonnes/m ³ for municipal waste. GasSim Manual
Fraction of organic carbon	%	3.7	Site-specific (lab data)
Moisture content	%	25	Site-specific (lab data)
Air filled porosity		0.036	Calculated in RTW
Water filled porosity	--	0.25	Calculated in RTW
Saturated Zone – Gravel Formation			
Fraction of organic carbon	%	0.01	Literature-based
Aquifer saturated thickness	m	13	Site-specific
Hydraulic conductivity, K	m/day	30	Literature-based (Kelley <i>et al.</i> 2015), supported by visual examination of SI samples
Hydraulic gradient, i	--	0.028	Site-specific (from groundwater contour maps)
Bulk density	g/cm ³	1.65	Literature-based (www.SImetric.co.uk)
Effective porosity	--	0.15	Literature-based (Kelley <i>et al.</i> 2015)
Longitudinal dispersivity	m	100	Literature-based - explained in Section 4.5.8
Transverse dispersivity	m	10	Literature-based - explained in Section 4.5.8
Vertical dispersivity	m	1	Literature-based - explained in Section 4.5.8
Saturated Zone - Rickardstown Formation			
Fraction of organic carbon	%	0.01	Literature-based
Aquifer thickness	m	30	Literature-based, GSI groundwater body description
Hydraulic Conductivity, K	m/day	1.0	Literature-based (range 0.1 - 10 m/day) from Daly E. (2008)

Parameter	Unit	Value	Comment / Justification
Hydraulic Gradient, i	--	0.018	Site-specific (from groundwater contour maps)
Dry Bulk Density	g/cm ³	2.61	Literature-based (www.SImetric.co.uk)
Longitudinal Dispersivity	m	27	Literature-based - explained in Section 4.5.8
Transverse Dispersivity	m	13.5	Literature-based - explained in Section 4.5.8
Vertical Dispersivity	m	0.27	Literature-based - explained in Section 4.5.8
Effective Porosity	--	0.03	Literature-based (Daly, 2008)

4.5.10 Chemical Input Parameters

Chemical parameters, and their references, are presented Table 17.

Table 17: Chemical Parameters Used for Calculations

Compound	Henry's Law Coefficient	Kd / Koc for Soil Source (l/kg)	Kd / Koc for Unsaturated Pathway (l/kg)	Kd / Koc Saturated Pathways (l/kg)	Solubility (max in mg/l)	Half-life (years)
Gravel Formation						
Chromium	-	480	480	480	>1,000,000	1.0E+10
Nickel	-	500	500	500	>1,000,000	1.0E+10
Manganese	-	50	50	50	>1,000,000	1.0E+10
Ammonium (as NH ₄)	0.00008	0.4	0.4	0.4	10,200	6
TPH Aromatic >C ₈ -C ₁₀	0.23	79	79	79	1,800	238
Rickardstown Formation						
Ammonium (as NH ₄)	-	0.2	0.2	0.2	10,200	12
Manganese	-	50	50	50	>1,000,000	1.0E+10

Environment Agency (2003a) Review of ammonium attenuation in soil and groundwater (NGWCLC report NC/02/49)
Burkhard Heuel-Fabiane (2014) Partition Coefficients (K) for the modelling of transport processes of radionuclides in groundwater; Consim Manual
Nathanail, C.P.; McCaffrey, C.; Gillett, A.G.; Ogden, R.C. & Nathanail, J.F (2015) The LQM/CIEH S4ULs for human health risk assessment. Land Quality Press, Nottingham
Environment Agency, 2008. Compilation of data for priority organic pollutants for derivation of soil guideline values. Science Report SC050021/SR7
Howard, H. 1991 Handbook of Environmental Degradation Rates
https://pubchem.ncbi.nlm.nih.gov/compound/Ammonium-ion
Lawrence, S.J., 2006, Description, properties, and degradation of selected volatile organic compounds detected in ground water— A Review of Selected Literature: Atlanta, Georgia, U. S. Geological Survey, Open-File Report 2006-1338
Conservatively, selected a long half-life double the high end for Ammonium in the GF, due to lack of published data for half-lives in confined limestone aquifer settings.

4.6 Modelling Results and Discussion

The completed RTWs for the different sources modelled are presented in **Appendix E**. Results are summarized and described below.

4.6.1 Source 1 – Waste Mass

Level 1 RTC (Soils and Leachate)

The Level 1 RTCs in soils and leachate are presented in Table 18. The compliance point for the calculation is the porewater in the soil samples.

Table 18: Level 1 Remedial Target Concentrations

Model Parameter / Output	Unit	Ammoniacal Nitrogen	Aromatic VPH >C ₈ - C ₁₀	Manganese	Nickel	Chromium
Level 1 RTC- Soil	mg/kg	0.074	0.032	2.51	2	2.26
Level 1 RTC- Leachate	mg/l	0.065	0.01	0.05	0.004	0.0047

Note: RTC values in red reflect CoPC concentrations that exceed the calculated RTCs

Level 1 RTCs for aromatic VPH >C₈ - C₁₀, chromium and nickel were exceeded in soil samples (see data in Section 3).

Level 1 RTCs for ammoniacal nitrogen, manganese, aromatic VPH >C₈ - C₁₀, nickel and chromium were exceeded in leachate samples (see data in Section 3).

Level 2 RTC (Groundwater at Source)

The Level 2 RTCs are presented in Table 19. The compliance point for the calculation is in groundwater immediately below the waste mass.

Table 19: Level 2 Remedial Target Concentrations

Model Parameter / Output	Unit	Ammoniacal Nitrogen	Aromatic VPH >C ₈ - C ₁₀	Manganese	Nickel	Chromium
Level 2 RTC- Soil	mg/kg	2.25	0.954	75.6	60.2	67.9
Level 2 RTC- Leachate	mg/l	1.95	0.301	1.50	0.12	0.141

RTC values in red reflect CoPC concentrations that exceed the calculated RTCs

Level 2 RTCs for aromatic VPH >C₈ - C₁₀ and chromium were exceeded in soil samples (see data in Section 3).

Level 2 RTCs for ammoniacal nitrogen, aromatic VPH >C₈ - C₁₀, manganese and nickel were exceeded in leachate samples (see data in Section 3).

Level 3 RTC (Groundwater Downgradient)

The Level 3 RTCs are presented in Table 20. The compliance point for the calculation is groundwater at the location of the River Liffey, approximately 1,000 meters downgradient of the site.

Table 20: Level 3 Remedial Target Concentrations

Model Parameter / Output	Unit	Ammoniacal Nitrogen	Aromatic VPH >C ₈ - C ₁₀	Manganese	Nickel	Chromium
Level 1 RTC- Soil	mg/kg	54.3	15.3	1,200	952	905
Level 1 RTC- Leachate	mg/l	62.5	4.82	23.8	1.9	1.89
Transport time to River Liffey	year	5.16	4.58	261	2,602	2498

RTC values in **red** reflect CoPC concentrations that exceed the calculated RTCs

The Level 3 RTCs were only exceeded for nickel in leachate samples (see data in Section 3). None of the concentrations in the soil samples exceeded respective Level 3 RTCs.

Despite the nickel exceedance in leachate, the risk of impact (of nickel) to groundwater at the River Liffey location is considered low to negligible. The calculated migration (transport) time of nickel from the site to the river in the GF is 2,602 years. This is due to the high retardation in groundwater that is computed by the RTW. The transport of nickel (and other metals) in groundwater is significantly slowed due to their high partitioning coefficients. As stated in the RTM (EA, 2006), the rates of contaminant transport for constituents with high partitioning coefficients may involve “considerable delay” (upwards of thousands of years) before the contaminant reaches a compliance point. In this case, the River Liffey is approximately 1,000 m away.

The RTM argues in these instances that it may be acceptable for no action to be taken at the source even if an RTC is exceeded. As a first step towards remedial planning, offsite verification of the downgradient extent of contamination is appropriate as a means of verifying the outcomes of the RTM presented in this report.

Because of the low risk to the River Liffey, the Level 4 assessment (dilution in the river) was not carried out. Instead, and to indicate the potential downgradient location where each CoPC would remain at concentrations above the most stringent compliance value, the RTW was applied to calculate concentrations as a function of distance from the landfill. To be conservative, the starting concentration at the source that was used was the maximum concentration recorded in leachate during the two rounds of sampling in November 2018 and May 2019.

Results are shown in Table 21. Ammoniacal nitrogen, aromatic VPH C₈-C₁₀, manganese and chromium all attenuate to below respective compliance values before reaching the river. Nickel reaches the Liffey above its groundwater GTV, but only after 2,609 years, and as such requires no immediate action.

Offsite monitoring to verify the actual downgradient extent of existing impact is recommended (see Section 6). A maximum downgradient distance of 500 m is considered as a reasonable distance to guide the installation of downgradient monitoring wells.

Table 21: Calculated Concentrations in the GF Downgradient of the Landfill

Distance from source (m)	Ammoniacal Nitrogen	Aromatic VPH >C ₈ - C ₁₀	Manganese	Nickel	Chromium
	mg/l	mg/l	mg/l	mg/l	mg/l
50	0.924	0.00231	0.197	0.067	0.0009
100	0.594		0.13	0.048	
250	0.264		0.063	0.022	
500	0.123		0.037	>1,000 years	
750	0.073				
1000	0.048				

Note: The concentration at which compliance value is reached is indicated **bold**.

4.6.2 Source 1 Results – Discussion

The attenuation of contaminant concentrations between the landfill and receptors depends on numerous variables that relate to both sources and pathways. Both site-specific and published parameter values were applied in the RTW. The Source 1 modelling results are conservative, principally because the source term is modelled as constant. In reality, leachate is generated in pulses and the source can be expected to decrease in strength over time (since landfilling ended in 1982).

Key input parameters were tested by sensitivity analysis, specifically for parameters that influence contaminant loading and the fate and transport of CoPC. The sensitivity analysis is presented in Section 5 .

4.6.3 Source 2 – Groundwater in the RF

Level 3(a) RTC

The Level 3(A) RTCs in groundwater in the RF are presented in Table 22. The compliance point is groundwater in the RF by the River Liffey, approximately 1,000 meters away.

Table 22: Level 3(A) Remedial Target Concentrations

Model Parameter / Output	Unit	Ammoniacal Nitrogen	Manganese
Level 3(A) RTC- Groundwater	mg/l	21	0.56
Transport time to River Liffey	year	68	19,868

Note: RTC values in red reflect CoPC concentrations that exceed the calculated RTCs

The Level 3(A) RTC was exceeded in groundwater for manganese only.

Like nickel in the GF, the estimated transport time for manganese to reach the Liffey is significantly large due to the combined effect of high retardation and lower groundwater velocities. Manganese is non-hazardous and would also be significantly diluted in the river. The conservative nature of inputs implies a low to negligible risk to the River Liffey.

Section 5 Sensitivity Analysis

5.1 Introduction

Sensitivity analysis was carried out on three key parameters that influence contaminant loading and fate and transport of the CoPC in groundwater:

- Infiltration rate;
- Aquifer hydraulic conductivity; and
- Biodegradation rates.

These are described in the following sections.

5.2 Infiltration Rate

The infiltration rate of 343 mm/yr that was used in the baseline calculations was taken from the GSI national recharge map. This value reflects natural hydrogeological settings, and does not consider localized effects of, for example, landfill cover materials. The landfill cover at Digby Bridge has clay content. As such, this can be expected to reduce the infiltration rate into and through the waste mass, which implies lower chemical loading to groundwater.

Without targeted field study of infiltration rates, it is not possible to precisely quantify the actual episodic or annual average infiltration rates that occur. For this reason, a sensitivity run was carried out in the RTW with the infiltration rate reduced by 50% (to account for a partially effective cover). Results are presented in Table 23.

Table 23: Sensitivity Analysis – Infiltration Rate

Compound	Maximum Leachate Concentration (mg/l)	GTV/IGV in Groundwater	Calculated Concentration in Groundwater at Level 2 (mg/l)		
			Baseline Infiltration Rate	50% of Baseline Infiltration Rate	1% of Baseline Infiltration Rate
Ammoniacal Nitrogen	40	0.175	1.33	0.068	0.0014
Manganese	8.3	0.05	0.28	0.014	0.0029

A red value indicates the calculated groundwater concentration beneath the waste mass exceeded the GTV/ITV

The effect was to lower the groundwater concentrations of both ammoniacal nitrogen and manganese in groundwater beneath the waste mass (*i.e.* at Level 2) to below respective GTVs. Covering the waste mass with a properly engineered liner/cap would reduce the infiltration rate further. Under an assumption infiltration rate of 1%, the calculated groundwater concentrations would be reduced to barely detectable concentrations.

5.3 Aquifer Hydraulic Conductivity

The baseline hydraulic conductivity values selected to represent the GF and RF were raised and lowered by one order of magnitude. Results are presented in Table 24 and Table 25.

Table 24: Sensitivity Analysis – Hydraulic Conductivity - GF

Compound	Maximum Leachate Concentration (mg/l)	Low Hydraulic Conductivity 3 m /d		Baseline Hydraulic Conductivity 30 m/d		High Hydraulic Conductivity 100 m /d	
		RTC (mg/l)	Transport Time ¹ (years)	RTC (mg/l)	Transport Time ¹ (years)	RTC (mg/l)	Transport Time ¹ (years)
Ammoniacal Nitrogen	40	122	40	54.3	5.16	121	2
Manganese	8.3	2.58	2,006	23.8	261	77.5	80

Notes:

A red value indicates the maximum leachate concentrations detected in the available samples exceeded the calculated RTC.

¹ – to the River Liffey

For ammoniacal nitrogen, lowering the hydraulic conductivity value resulted in an increase in the RTC. This is because the reduced hydraulic conductivity has the effect of lowering groundwater velocities. Hence, the CoPC is transported slower, stays longer in the aquifer, which implies more time for biodegradation of the CoPC in groundwater (*i.e.* at Level 3).

Increasing the hydraulic conductivity value also resulted in a slight increase of the RTC. This is due to the increased groundwater flux in the aquifer, which increases the dilution factor that occurs in groundwater beneath waste mass (*i.e.* at Level 2).

For manganese, lowering the hydraulic conductivity value resulted in a decrease in the RTC. This is because the dilution factor (at Level 2) was reduced, which is of greater significance numerically than the increase in the attenuation factor in groundwater (at Level 3).

Increasing the hydraulic conductivity value resulted in an increase of the RTC. This is due to increased dilution in groundwater beneath the waste mass (at Level 2). The transport time is shortened but the risk to the receptor remains low because the RTC is above the leachate concentrations.

Table 25: Sensitivity Analysis – Hydraulic Conductivity - RF

Compound	Maximum Groundwater Concentration (mg/l)	Low Hydraulic Conductivity 0.1 m /day		Baseline Hydraulic Conductivity 1 m/day		High Hydraulic Conductivity 10 m /day	
		RTC (mg/l)	Transport Time ¹ (years)	RTC (mg/l)	Transport Time ¹ (years)	RTC (mg/l)	Transport Time ¹ (years)
Ammoniacal Nitrogen	6.2	1.52E+10	685	21	68.5	0.47	6.9
Manganese	1.83	0.56	198,676	0.56	19,868	0.56	1,987

Notes:

A red value indicates the maximum groundwater concentrations (RF) detected in the available samples exceeded the calculated RTC.

¹ – to the River Liffey

For ammoniacal nitrogen, lowering the hydraulic conductivity value resulted in a significant increase in the RTC due to a lower groundwater flow velocity and increased time for biodegradation in groundwater (at Level 3).

Conversely, increasing the hydraulic conductivity value resulted in a decrease of the RTC due to less time for biodegradation in groundwater (at Level 3). The shortened transport time results in a calculated RTC which is below the ammoniacal nitrogen concentration in groundwater, implying a potential risk of impact to groundwater.

Changing hydraulic conductivity values had relatively small influences on the attenuation factors, but influenced travel times. The travel times to the River Liffey remain greater than 1,000 years. Hence, the risk to the river is considered low.

5.4 Biodegradation Rates

Biodegradation is a significant attenuation parameter for ammoniacal nitrogen. The conservative baseline half-life value of 6 years was reduced to 3 years which increases the biodegradation rate and attenuation in groundwater. Results are presented in Table 26 for the GF and Table 27 for the RF.

Table 26: Sensitivity Analysis – Lower Half-life of Ammoniacal Nitrogen in the GF

Compound	Maximum Leachate concentration (mg/l)	Half-life 50% of Baseline		Half-life Baseline	
		RTC (mg/l)	Transport Time ¹ (years)	RTC (mg/l)	Transport Time ¹ (years)
Ammoniacal Nitrogen	40	90.7	5.16	54.3	5.16

Notes:

A red value indicates the maximum leachate concentrations (GF) detected in the available samples exceeded the calculated RTC.

¹ – to the River Liffey

Table 27: Sensitivity Analysis - Lower Half-life of Ammoniacal Nitrogen in the RF

Compound	Maximum Groundwater Concentration (mg/l)	Half-life 50% of Baseline		Half-life Baseline	
		RTC (mg/l)	Transport Time ¹ (years)	RTC (mg/l)	Transport Time ¹ (years)
Ammoniacal Nitrogen	6.2	465	68.5	21	68.5

Notes:

A red value means the maximum groundwater concentrations (RF) detected in the available samples exceeded the calculated RTC.

¹ – to the River Liffey

In both instances, the calculated RTC increased since the calculated biodegradation rates were lowered.

5.5 Sensitivity Analysis – Discussion

Single-value deterministic analytical models cannot account for transient (time-varying) processes or spatial variability of input parameters. As such, conservative input values provide for worst case outcomes.

The outcomes presented in the current report are sensitive to each of the tested parameters - infiltration rates, hydraulic conductivity values, and biodegradation rates. However, in each instance, conservative input values indicate long transport times and considerable attenuation potential in both aquifers between the site and downgradient receptors.

For organic compounds, the dominant factors that determine offsite fate and transport are dilution in groundwater and biodegradation. For metals, it is dilution and dispersion.

Specific input variables that contribute to the conservative nature of the outcomes presented in this section and to the DQRA generally are:

- The infiltration rate is likely higher than actual, but this is not yet confirmed and would require field testing;
- Starting concentrations of CoPC in leachate and groundwater are based on maxima (in two rounds) rather than averages; and
- The source term is assumed to be constant. In reality, leachate generation and contaminant loading to groundwater is episodic and/or seasonal. Leachates migrate vertically in pulses (with rainfall events). The groundwater table may also come into contact with the waste mass periodically or seasonably. The understanding of contaminant loading to groundwater at the landfill site is currently constrained to two rounds of sampling. Hence, the use of a constant source term is precautionary.

An exceptional scenario which cannot be tested or checked with the RTM is the potential presence and influence of karst in the RF. Preferential transport of CoPC via karst conduits in the RF implies a higher degree of risk to downgradient receptors including springs that may be connected to a karst network. At this time, there are no specific indicators that such karst features are present, but this is not yet confirmed by field mapping or investigation offsite.

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Section 6 Conclusion and Recommendations

6.1 Conclusions

Landfill leachates and land uses both contribute to groundwater quality impact at the site. The chemical loading to groundwater is expected to vary in time, influenced by wet weather events and seasonality.

The GQRA identified 25 substances in leachate that exceed relevant screening criteria, of which 11 were classed as hazardous substances. Most of the hazardous substances were also detected in monitoring wells onsite. Groundwater quality data shows exceedances of both DWSs and GTVs/ITVs. Impacted groundwater is migrating offsite, to the northeast and east in the GF (confirmed from site-related data) and to the northeast in the RF (inferred from a limited dataset).

The base level of the Grand Canal is at a higher elevation than groundwater along the northern site boundary which means the canal is not hydraulically connected to the contaminated groundwater. There is no pathway that links leachate and the canal via either surface water or groundwater pathways. As such, there is no leachate or groundwater impact on the canal. However, runoff waters from the landfill area can reach the canal via overland flow.

A hydraulic relationship between impacted groundwater and small springs/seeps and land drains to the north of the canal is possible but has not yet been ascertained.

The Liffey River is the final downgradient potential receptor of site-related contamination. However, risks of impact are low to negligible due to: a) the approximately 1 km distance from the site; b) the attenuation that would occur in groundwater between the site and the river; and c) the significant dilution that would occur in the river due to groundwater/surface water mixing. Moreover, the water quality of the Liffey is influenced by several other potential sources of pollution within the broader catchment.

The modelling that was carried out for the DQRA followed an established methodology using conservative input values. A final tabulation of risk based on the refined CSM and SPR linkages is provided in Table 28.

Table 28: Final Risk Assessment Based on Refined CSM and SPR Linkages

SPR	Linkage	Tier 3
Leachate migration through combined groundwater and surface water pathways		
SPR1	Leachate => surface water	No Leachate to on-site drainage or run-off pathway
SPR2	Leachate => SWDTE	No Leachate to on-site drainage or run-off pathway
Leachate migration through groundwater pathway		
SPR3	Leachate => human presence	Mitigation provided by provision of public water supply
SPR4	Leachate => GWDTE	N/A
SPR5	Leachate => Aquifer	Groundwater is impacted within landfill and migrating offsite

SPR	Linkage	Tier 3
SPR6	Leachate => Surface Water	Impacted groundwater potentially connected to drains north of the canal and River Liffey
SPR7	Leachate => SWDTE	Impacted groundwater shown not to relate to surface water
Leachate migration through surface water pathway		
SPR8	Leachate => Surface Water	No pathway
SPR9	Leachate => SWDTE	No pathway
Risk Rating by Colour		
Lowest Risk (Class C)	Moderate Risk (Class B)	Highest Risk (Class A)

Thus, the refined CSM and DQRA considers that:

- Groundwater quality is impacted and CoPC are migrating offsite. Calculations suggest that impact is localized, within approximately 500 m of the site boundary;
- The risk to drinking water is mitigated because public water supply has been provided in the area;
- An inferred risk to small springs/seeps and land drains to the north of the Grand Canal remains; and
- Risks to the River Liffey are low to negligible.

Despite the low risk to offsite receptors, the conclusions are tempered by knowledge that contaminated groundwater is migrating offsite. Verification or confirmation of the downgradient extent of contamination is recommended through offsite field work, as outlined below.

6.2 Recommendations

It is recommended that the risks identified for the Digby Bridge legacy landfill site in the refined CSM are addressed through a programme of adaptive monitoring. This includes recommendations for further offsite work including:

- To establish conclusively, from sampling, the distance downgradient where DWSs or GTVs/ITVs are no longer exceeded;
- To confirm whether the downgradient springs/seeps and associated land drains may be hydraulically linked to the site; and
- To verify that existing private wells within groundwater pathways are not used for potable water, at least within the established distance of groundwater quality impact.

Similarly, further onsite work is recommended:

- To verify if hydrocarbon compounds (which are classed as hazardous substances) are present in groundwater at the site;

- To build a database that allows for patterns and trends with regards to chemical loading and associated groundwater quality to be established. It is noted that, in the two rounds of sampling to date, the maximum concentration of ammoniacal nitrogen in groundwater is greater the maximum concentration in leachate. This implies that monitoring to date has not captured the leachate loading that generated the maximum concentration in groundwater; and
- To quantify seasonal groundwater level fluctuations and determine whether the waste mass becomes saturated (periodically or otherwise).

Specific recommendations for the Adaptive Monitoring Programme are presented in Table 29 and this is presented in more detail with proposed locations of the offsite monitoring wells and costings in the Remediation Plan.

Table 29: Specific Recommendations

Recommendation	Detail	Comment
Onsite		
Routine sampling of leachates	Chemical sampling, including hazardous substances, quarterly	
Routine sampling of groundwater	Chemical sampling, including hazardous substances, quarterly	
Routine monitoring of groundwater levels	Quarterly measurement of water levels with a water level meter	Timed with wet or dry weather events to the extent possible.
Installation of pressure transducers (x4) in monitoring wells	Continuous recording of leachate and groundwater level fluctuations	One well at the upgradient site boundary One well at the downgradient site boundary One (leachate) well in the waste mass One groundwater well near the waste mass
Offsite		
Drilling and installation of offsite monitoring wells	Two nested well pairs (GF/RF) Two individual wells in the GF One individual well in the RF	At suitable locations between the site and Liffey. Will require landowner agreements. Placement of wells have to consider the existence of potential offsite sources of pollution
Routine sampling of groundwater	Chemical sampling, including hazardous substances, quarterly	Duration and scope of sampling may be reduced in time depending on results
Initial sampling of the shallow springs and seep and land drains north of the Grand Canal	Chemical sampling assumed at three locations.	Done during dry weather conditions so that the samples are not influenced by surface run-off.
Installation of pressure transducers	Continuous recording of groundwater level fluctuations	One well in GF; One wells in RF
Offsite reconnaissance and topographic survey	Ground-truthing of springs and seeps, as well as land drain details, to the north of the Grand Canal, with measurements of flow and other karst features in a wider area downstream of the site	One-time field activity

6.3 Discussion

The findings and recommendations outlined in the current report broadly satisfy the EPA guidance on discharges to groundwater (EPA, 2011) which states that:

“For historical inputs (e.g. contaminated land or accidents/spills/losses) where pollutants, including hazardous substances, are known to have already entered groundwater and are causing pollution to a receptor, the examination and review process will determine the need for, and scope of, remediation that is appropriate for the situation, while considering technical feasibility and costs. “

The scope and intent of the recommended work is to address open questions and remove uncertainty about the nature and extent of offsite contamination, as well as future risks of contamination. Per the EPA CoP, the aim of the Remediation Plan is to break SPR linkages. Monitored natural attenuation may be sufficient if it can be verified that extent of offsite migration and nature of offsite impact is limited. It is noted that there is a public water main supplying water to the residents living in proximity of the landfill, which mitigates a risk to water users which existed when groundwater sources were utilised.

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Section 7 References

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