PRELIMINARY QUANTITATIVE HYDROGEOLOGICAL RISK ASSESSMENT OF THE POLLUTION IMPACT FROM THE PERMANENT WASTE MANAGEMENT FACILITY AT LADY CROSS PLANTATION, NORTH YORKSHIRE

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1 INTRODUCTION

1.1 General Background

York Potash Ltd (YPL) propose to develop the Lady Cross Plantation site near Egton, North Yorkshire, for an Intermediate Shaft to a tunnelled Mineral Transport System (MTS). This proposed MTS will extend from the Minesite at Dove’s Nest near Whitby, to the port facility at Wilton. As part of that development, the Non-Inert, Non-Hazardous rock waste arisings to be generated by excavation of the Intermediate Shaft and MTS are to be accommodated for onsite within a Permanent Waste Management Facility (PWMF), for which an Environmental Permit is to be applied for.

FWS Consultants Ltd (FWSC) have prepared a Hydrogeological Baseline Report (Ref. 1) that presents the geological and hydrogeological conditions determined for the proposed Intermediate Shaft site and surrounding area, and identifies the hydrogeological receptors in the vicinity of the Lady Cross Plantation site. A Hydrogeological Risk Assessment (Ref. 2) has been prepared that presents a qualitative environmental risk assessment of the impact that the PWMF will have on the wider environment.

This preliminary quantitative hydrogeological risk assessment report has been prepared to present an initial screening calculation to identify the potential groundwater pollution impacts of the proposed Non-Inert Non-Hazardous PWMF, to the hydrogeological receptors identified within the Hydrogeological Baseline Report. To quantify the magnitude of the potential significant adverse pollution impacts of the PWMF on sensitive groundwater receptors on, and adjacent to, the site, groundwater modelling has been carried out by ESI Ltd (ESI), under the direction of FWSC, and is included in Appendix 4. This report presents the findings of this modelling and provides recommendations on further works to be undertaken as part of the Environmental Permit application for the PWMF.

1.2 Regulatory Requirements

YPL have undertaken consultation with the Planning Authority, the North Yorkshire Moors National Park Authority (NYMNPA) and their consultants (AMEC) and the Environment Agency (EA) to determine their requirements for specific information to be included in the hydrogeological risk assessment for the Planning Application stage of the development.

From that consultation, YPL were requested to provide a preliminary quantitative hydrogeological risk assessment to illustrate the lifetime risks associated with the PWMF and its potential impact on the nearby water environment.
1.3 Objectives

The purpose of this document is to:-

- Provide summary details of the conceptual model developed for the PWMF analysed as part of this assessment.
- Identify the critical receptor(s) to the PWMF considered in the pollution impact assessment.
- Present the methodology and results of the simple quantitative risk assessment screening calculation undertaken.
- To identify, where appropriate, mitigation measures that may be warranted as part of the development to minimise adverse hydrogeological impacts resulting from the PWMF.
- To provide recommendations on any further monitoring or hydrogeological risk assessment to confirm the effectiveness of the proposed groundwater controls currently allowed for.

1.4 Sources of Information

The data incorporated into this report is sourced from the following:-


2 DEVELOPMENT DETAILS OF THE PERMANENT WASTE MANAGEMENT FACILITIES

Full details of the construction works, the rock arisings that will be generated as part of this Intermediate Shaft development, layout and phasing of the Non-Inert Non-Hazardous PWMF, are presented in the design documents detailed above (Refs. 1 to 4). For the purpose of this report, summary details only are presented below.

The Non-Inert, Non-Hazardous rock waste material that will be generated for construction of the Intermediate Shaft and the MTS tunnel will comprise strata from the Whitby Mudstone, Cleveland Ironstone, and Redcar Mudstone Formations. All of the extractive waste generated by these works are to be retained onsite and contained within the PWMF.
The Redcar Mudstone Formation that will form most of these arisings comprises pyritic mudstones, siltstone and argillaceous sandstones with the potential to generate low concentrations of chloride and sulphate-rich leachate.

The PWMF is to be constructed across the northern extent of the site, as illustrated in Arup’s Master Plan (“Operational Masterplan” YP-P2-CX-441” Appendix 2). The following engineering measures have been incorporated into the design of this PWMF to prevent environmental pollution:-

- Construction of a 1 m thick artificially enhanced geological barrier, engineered to achieve a maximum permeability of less than $1 \times 10^{-9} \text{ m/s}$ using site won glacial till (clay). The footprint of these Permanent Waste Management Facilities is shown in FWSC Drawing 1433MineOD122 (Appendix 1).
- Compaction of the waste materials to minimise their porosity and permeability.
- Construction of a geo-composite drainage layer, over the final profiled surface of the extractive waste, discharging to the site’s surface water drainage system.
- Replacement of subsoil and topsoil to provide a soil cover layer with a thickness of between 1 to 2 m.

3 WASTE TYPES AND POLLUTION POTENTIAL

3.1 Waste Types

The excavation arisings that are to be generated by the proposed shaft and tunnel construction works at the Lady Cross site are of a similar nature to those described for the Whitby Mudstone, Cleveland Ironstone, and Redcar Mudstone Formations within the Extractive Materials Management Statement for the Dove’s Nest minesite development (Ref 3). That report identified that the three principal rock types (sandstones, mudstones and siltstones) to be generated by the deep excavations will characterise as Non-Inert, Non-Hazardous waste, and are chemically and geotechnically suitable for containment onsite within a PWMF.

The total unbulked quantity of Non-Inert, Non-Hazardous rock waste to be generated by the Intermediate Shaft development is determined to be 195,500 m$^3$ (Ref. 4). An estimated analysis of the total quantities of each of the rock types to be generated by the excavations has been undertaken, as summarised below, to determine the relative proportions of each strata in relation to the total unbulked volume to be generated by the works.

<table>
<thead>
<tr>
<th>Extractive Material</th>
<th>Strata</th>
<th>Percentage by Volume of Total Rock Waste to be Stored in the Permanent Waste Management Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mudstone</td>
<td>Whitby Mudstone Formation</td>
<td>3%</td>
</tr>
<tr>
<td>Sandstones and Siltstones</td>
<td>Cleveland Ironstone Formation</td>
<td>1%</td>
</tr>
<tr>
<td>Mudstones and Siltstone</td>
<td>Redcar Mudstone Formation</td>
<td>96%</td>
</tr>
</tbody>
</table>

As illustrated by the table above, the Redcar Mudstone Formation will comprise the principal rock waste component (96% by volume) to be generated from the works and the primary source of this material will be from the Mineral Transport System tunnel.
The remaining Non-Inert, Non-Hazardous waste materials are to be generated from the Whitby Mudstone and the Cleveland Ironstone during the shaft excavation, which comprise around 4% by volume of the total unbulked Non-Inert, Non-Hazardous waste to be generated from these works.

3.2 Pollution Potential

Based on the visual descriptions and published data, these rock waste materials are considered to have a low potential to generate leachates in the form of hydrocarbons, heavy metals, acidic and alkaline pH, sulphates and chlorides. As part of the Dove’s Nest minesite investigation, preliminary laboratory analysis has been undertaken to determine the chemical properties of the principal strata to be encountered in the works. The results of the testing on rock and leachate samples, including WAC testing, are presented in Appendix 3.

In relation to the Non-Inert, Non-Hazardous rock waste that is to be deposited in the Lady Cross Plantation PWMF, the preliminary testing to date has been undertaken on samples from the Whitby Mudstone, Cleveland Ironstone, and Redcar Mudstone Formation. This preliminary testing determined that the rocks generally contained only low leachable concentrations of metals, hydrocarbons, organic content and inorganics with only marginally elevated concentrations of sulphate and chloride determined in the Whitby Mudstone, Cleveland Ironstone and Redcar Mudstone Formations.

For the purpose of this report, to provide a preliminary indication of the pollution potential of leachates that may be generated from these rock wastes, two indicator parameters have been considered; sulphate and chloride. Two sets of leachability data have been utilised to determine the “source term” leaching potential of the two indicator parameters within the rock arisings to be stored onsite. These are the water soluble sulphate and chloride results determined from 2:1 soil water extract analysis and the results of WAC testing determined from 10:1 water to soil extract. In compliance with the Environment Agency’s recommended test (Ref. 5), to present the pollution potential of these results in a standardised form, the 2:1 results have been recalculated to provide equivalent 10:1 liquid to solid ratio values.

Based on the available test data (Appendix 3), the following “average” leaching potential values have been calculated for the principal strata to be disposed of within the PWMF at Lady Cross Plantation.

<table>
<thead>
<tr>
<th>Strata</th>
<th>Chloride Average Leachability (mg/l)</th>
<th>Sulphate Average Leachability (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whitby Mudstone Formation</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Cleveland Ironstone Formation</td>
<td>Not Available</td>
<td>16</td>
</tr>
<tr>
<td>Redcar Mudstone Formation</td>
<td>230</td>
<td>70</td>
</tr>
</tbody>
</table>

On the basis that 96% of the materials to be stored onsite at Lady Cross are to comprise Redcar Mudstone, the average leachability concentration for those strata has been adopted as the worst case “source term” concentrations within the pollution modelling.
4 SENSITIVE RECEPTORS

Assessment of the most critical hydrogeological receptors that may be impacted on by pollution emanating from the PWMF has been determined based on the information presented in the Hydrogeological Baseline report (Ref. 1).

The PWMF is underlain by perched discontinuous groundwater in cohesive glacial till and then by a shallow groundwater table within the Scalby Formation Secondary A Aquifer. As illustrated in Drawing 1433WasteOD04 (Appendix 1), the hydraulic gradient in the Scalby Formation, beneath, and in the vicinity of, the PWMF is to the southwest. There are no sensitive groundwater receptors, in the form of source protection zones, groundwater abstractions, or hydrogeologically supported ecosystems immediately down hydraulic gradient of the PWMF. This aquifer, however, provides baseflow to spring L, which is located 830 m southwest of the PWMF. For the purposes of this preliminary quantitative hydrogeological risk assessment, based on the hydraulic gradient in the WMF and the proximity of hydrogeological receptors, spring L is taken as the critical receptor to the pollution impact from this PWMF (FWSC Drawing 1433WasteOD04, Appendix 1).

5 CONCEPTUAL MODEL

A PWMF is to be constructed in the northern area of the site (Drawing YP-P2-CX-441, Appendix 2) to contain Non-Inert, Non-Hazardous extractive waste materials of low leachable content. Chemical testing of the Non-Inert, Non-Hazardous extractive waste materials has determined that these specific rock types are of low polluting potential and contain only a low leachable content of sulphate and chloride contaminants.

This facility will be underlain by a geological barrier comprising a 1 m minimum thickness of low permeability clay and will include compaction of the waste materials to minimise their porosity and permeability. On completion, the waste surface is to be profiled to promote drainage and a geo-composite surface drainage layer will be incorporated into the 1.2 m thick soil cover system, to reduce infiltration in these areas during their operational and long term decommissioned phases. By implementation of these engineering measures, it is anticipated that only minimal leachate generation will arise that could collect in the waste above the engineered clay barrier.

The ground conditions underlying the PWMF comprise 2.3 to 3.7 m of low permeability cohesive glacial clay, beneath which are mudstones, sandstones and siltstones of the Long Nab and Moor Grit Member Secondary A Aquifers. Perched discontinuous groundwaters exist in the superficial deposits at depths of 1.44 to 1.99 m bgl and the water level within the Long Nab Member ranges between 205 and 211 m AOD, with an apparent hydraulic gradient of 0.027 to the southwest.

Down hydraulic gradient of the Permanent Waste Management Facilities, the principal sensitive hydrogeological receptor is determined as spring L (monitored as SWQ2), that’s source is the Long Nab Secondary A Aquifer.

6 QUANTITATIVE HYDROGEOLOGICAL RISK ASSESSMENT

6.1 Scope of Quantitative Risk Assessment

As agreed by YP with the EA, the scope of this preliminary quantitative risk assessment is to develop a simple risk assessment model to present the likely
Maximum concentrations and breakthrough curves of potential contaminants at key sensitive receptors.

6.2 Source of Model Data

The input data for the contamination source dimensions and pathway properties used within the model, and the justifications for this data have been prepared by FWS Consultants Ltd, in consultation with ESI Ltd, and are presented in the ESI Report Table 3.1 (Appendix 4).

For the purpose of this preliminary screening model, the source term concentrations for the contaminants of concern (Chloride and Sulphate) are based on the leachable components of the Redcar Mudstone Formation waste materials, as detailed in Section 3.2 above.

It is recognised that the largest uncertainty in the model input parameters is the leachate head. In this regard, the key parameter controlling the drainage of water from the base of the bunds will be the hydraulic conductivity of the engineered geological barrier, which for this site is to be specified to achieve a permeability of $1 \times 10^{-9}$ m/s. If the permeability of the waste or the unit flux through the capping layer is lower than this basal permeability, then it is unlikely that any leachate head would develop on the clay liner, as it would be easier for water to drain out of the base than to gain entry through the top and sides. On the basis that a unit flux of $1 \times 10^{-9}$ m/s is equivalent to an infiltration rate of 32 mm/a, in view that the effective rainfall in this area (Ref. 2) is typically between 150 to 270 mm/a, it is evident that the combined effects of drainage within the cap subsoils and cap drainage layer will only need to reduce the effective rainfall by a factor of less than 10 in order to ensure that the water inputs to the bund do not exceed its capacity for free drainage. As such, by placing an engineered cap, including a soil cover layer and a surface water drainage layer, water ingress into the waste should be controlled to ensure that no leachate head will actually develop above the clay liner. On this basis, in view that the rock waste is to be engineered to reduce its porosity and permeability, and as an engineered cap incorporating a geo-composite drainage layer is to be adopted, no significant leachate heads are expected to build up. As such, for the purpose of this preliminary screening model, conservative assumed leachate heads of 0.25 m, 0.5 m and 1.0 m have been adopted to provide an indication of possible worst case leachate heads that may arise.

6.3 Environmental Assessment Criteria

In accordance with Regulatory Guidance (Ref. 6), site specific environmental assessment criteria have been developed by consideration of natural background concentration and Environmental Quality Standards (EQS) for fresh water and drinking water values.

As detailed in Section 4, groundwater in this area is present in a Secondary A Aquifer that is not utilised for drinking water abstractions down hydraulic gradient of the PWMF and will only locally contribute to surface water flows via spring discharges. As such, groundwater at this location is considered a Low Sensitivity receptor but will act as a pathway to other controlled water receptors, the most sensitive of which for this location is identified as spring L.
By consideration of the background groundwater quality, fresh water EQS, and the contaminants of concern determined from the rock waste materials, environmental assessment criteria have been set as Sulphate 400 mg/l and Chloride 250 mg/l in this assessment.

### 6.4 Modelling Approach

The modelling of contaminant transport along the pathways to the sensitive hydrogeological receptors has been carried out by ESI (Appendix 4) using a numerical solution of the one-dimensional advection-dispersion-retardation-degradation (ADRD) equation. The modelling has been undertaken using RAM Version 2 (ESI, 2008) and the results are presented in Appendix 4 of this report.

The analysis along each pathway takes account of the geometry of the pathway, but is essentially one-dimensional, with a simple description of the physical parameters affecting the contaminant migration along the pathway. The default case does not take any transverse dispersion into account and is, therefore, a conservative calculation of concentration along the pathway. The effects of vertical dispersion are included by defining the equivalent dilution along the pathway.

### 6.5 Results of Pollution Modelling

The results of the pollution modelling are presented in Appendix 4 (Section 4 of the ESI Report), and are summarised below in terms of the maximum concentrations and breakthrough curves of potential contaminants at the key sensitive receptor for each of the three leachate heads analysed.

The results of the modelling determined the following maximum concentrations and peak breakthrough times on groundwater quality in the Scalby Formation Aquifer at Spring L for the three leachate head conditions analysed.

<table>
<thead>
<tr>
<th>Leachate Head Condition Analysed</th>
<th>Contaminant of Concern</th>
<th>Environmental Assessment Criteria</th>
<th>Maximum Concentration of Pollutant at the Critical Receptor (i.e. Groundwaters in the Scalby Formation Aquifer at Spring L)</th>
<th>Maximum Time for Pollution Breakthrough at the Critical Receptor (i.e. Groundwaters in the Scalby Formation Secondary A Aquifer at Spring L)</th>
<th>Back Ground Concentration in the Scalby Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 m</td>
<td>Chloride</td>
<td>250 mg/l</td>
<td>50 mg/l</td>
<td>34 years</td>
<td>25 mg/l</td>
</tr>
<tr>
<td></td>
<td>Sulphate</td>
<td>400 mg/l</td>
<td>24 mg/l</td>
<td>34 years</td>
<td>18.9 mg/l</td>
</tr>
<tr>
<td>0.5 m</td>
<td>Chloride</td>
<td>250 mg/l</td>
<td>52 mg/l</td>
<td>32 years</td>
<td>25 mg/l</td>
</tr>
<tr>
<td></td>
<td>Sulphate</td>
<td>400 mg/l</td>
<td>25 mg/l</td>
<td>32 years</td>
<td>18.9 mg/l</td>
</tr>
<tr>
<td>1.0 m</td>
<td>Chloride</td>
<td>250 mg/l</td>
<td>56 mg/l</td>
<td>29 years</td>
<td>25 mg/l</td>
</tr>
<tr>
<td></td>
<td>Sulphate</td>
<td>400 mg/l</td>
<td>25 mg/l</td>
<td>29 years</td>
<td>18.9 mg/l</td>
</tr>
</tbody>
</table>

From the results of the modelling summarised above, it has been determined that the pollution impact, of the chloride and sulphatic leachates that may be generated from the Whitby Mudstone Formation, Cleveland Ironstone Formation and the Redcar Mudstone Formation to be contained within the Waste Facility, is below the environmental assessment criteria for both contaminants of concern at each of the leachate heads analysed.
The results demonstrate that the greatest pollution impact would occur where a leachate head of 1 m develops above the basal engineered clay liner and the breakthrough of this impact would be expected to occur after a period of 29 years, which would then decline over a period of the following 20 years. The magnitude of the sulphate and chloride concentrations that would occur in the groundwaters in the Scalby Formation Aquifer at the Location of spring L would, however, be below the fresh water EQS and would present no significant pollution risk to Controlled Waters or to the wider environment.

The sensitivity analysis undertaken by varying the hydraulic head, has demonstrated that an increase in leachate head from 0.25 m to 1.0 m would result in only a low corresponding increase (10%) in the potential maximum pollution impact of both contaminants of concern.

7 CONCLUSION

The proposed Intermediate Shaft development at Lady Cross Plantation will generate rock waste materials that are to be stored within a PWMF within the site boundary. Preliminary chemical testing of these rock materials has demonstrated that these wastes generally contained only low leachable concentrations of metals, hydrocarbons, organic content and inorganics with only marginally elevated concentrations of sulphate and chloride determined in Redcar Mudstone Formation materials. From the current test data available two principal contaminants of concern have been identified (Chloride and Sulphate), for which leachable concentrations below environmental assessment criteria can be generated from this rock waste.

The PWMF will contain rock waste principally derived from the Intermediate Shaft excavation and from the tunnelling excavations. As such, this facility will encapsulate Non-Inert, Non-Hazardous Whitby Mudstone, Cleveland Ironstone, and Redcar Mudstone Formation rock waste materials. Based on the hydrogeological conditions determined for this facility, groundwater discharging at Spring L from the Scalby Formation, down hydraulic gradient from the PWMF, has been identified as the most sensitive hydrogeological receptor to the PWMF.

The results of the modelling and the sensitivity analysis, by varying the modelled leachate heads, has determined that there is no significant pollution impact from the long term storage of Non-Inert Non-Hazardous extractive waste within the PWMF to the sensitive hydrogeological receptor down hydraulic gradient of the facility.

Based on the results of these preliminary screening calculations, it has been demonstrated that the proposed engineered containment of Non-Inert Non-Hazardous waste as part of the minesite development presents no significant adverse pollution risk to the environment or to controlled waters and no additional mitigation measures are considered warranted, above the current containment measures included for.

As part of the detailed development design for the PWMF, additional rock testing is ongoing. This is being carried out to provide further information on the total and leachable concentrations for the full range of potential contaminants in the rock wastes that will be generated by the works and are to be stored in the PWMF. The results of that testing will be evaluated as part of the hydrogeological risk assessment in support of the Environmental Permit application for waste storage on this site. Further consultation will then be undertaken with the Environment Agency and, where necessary, more complex
probabilistic risk assessment models, with the cap engineering explicitly simulated and utilising input parameter distributions, will be prepared for the detailed hydrogeological assessment as part of the Environmental Permit application.

K WELLS
GEOLOGIST

R IZATT-LOWRY
DIRECTOR

11 September 2014
8 REFERENCES


APPENDIX 1

DRAWINGS
APPENDIX 3

CHEMICAL TEST DATA FOR NON-INERT NON-HAZARDOUS ROCK WASTE
<table>
<thead>
<tr>
<th>Formation System</th>
<th>Site</th>
<th>T8</th>
<th>Medium Depth</th>
<th>pH</th>
<th>EC</th>
<th>Water Potential</th>
<th>Soluble Sulfate</th>
<th>Chloride</th>
<th>Sodium</th>
<th>Calcium</th>
<th>Magnesium</th>
<th>Potassium</th>
<th>Total (Acid Extractable + Solution)</th>
<th>DEts</th>
<th>%</th>
<th>%</th>
<th>%</th>
<th>90% Total Indication in solutions of</th>
<th>90% Total Indication in solutions of</th>
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<th>90% Total Indication in solutions of</th>
<th>90% Total Indication in solutions of</th>
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<tbody>
<tr>
<td>Banded Ironstone and Pyritis shales</td>
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APPENDIX 4

ESI POLLUTION MODELLING RESULTS
York Potash Extraction Waste Risk Assessment: Lady Cross

Prepared for FWS Consultants Limited

Report reference: 61415AATN5, September 2014

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<tr>
<td>Author</td>
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</tr>
<tr>
<td>Checked by</td>
<td>Robert Sears</td>
</tr>
<tr>
<td>Reviewed by</td>
<td>Robert Sears</td>
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</table>
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1 INTRODUCTION

1.1 Background

York Potash Ltd proposes to develop the Dove’s Nest site as the minehead for the extraction of evaporite minerals using underground mining techniques to depths of 1.6 km. The project also incorporates a tunnelled mineral transport system from the minehead to the associated support facilities in Teesside, including an intermediate shaft site at Lady Cross.

The extraction waste from the intermediate shaft and tunnel has been characterised as Inert and Non Inert Non Hazardous of low polluting potential and will be retained onsite within an engineered bund. This will be constructed to incorporate a 1 m thick engineered clay barrier, designed to provide an attenuation layer between the extraction waste and the underlying natural strata to prevent the discharge of hazardous substances or causing pollution from non-hazardous substances.

This bund will also have an engineered cap overlying the extraction waste comprising an engineered drainage layer (geofin or geocomposite) with transfer drains to a perimeter re-infiltration drain. This will be overlain by 1.2 m of subsoils and topsoils.

1.2 Scope of work

The scope of work is to develop a simple risk assessment model for each of the Extraction Waste bunds. For this simple risk assessment, the engineered cap is not explicitly modelled, rather a leachate head within the bund is assumed, which creates a downwards head acting on the engineered / natural geological barrier.

This preliminary screening calculation has been developed to identify the potential groundwater pollution impacts of the proposed non inert non-hazardous waste facilities to specific hydrogeological receptors identified by FWS Consultants Ltd. The pollution impact, which has been run as a deterministic model, adopts preliminary input parameters defined by FWS Consultants Ltd. that have been derived from the Hydrogeological Baseline Report FWS (2014c). It is recognised that conservative choices of input parameters may not always have been selected and the model results, therefore, may not be conservative.

It is understood that development of more complex probabilistic risk assessment models with the cap engineering explicitly simulated and utilising input parameter distributions will be undertaken for the detailed hydrogeological assessment as part of the Environmental Permit application.

The conceptual model developed for the bund is presented in Section 2. The modelling approach and input parameters is discussed in Section 3. The model results, comprising breakthrough curves and times to the maximum concentration are presented in Section 4.

This report describes the model for Lady cross

2 CONCEPTUAL MODEL

The conceptual model is based on an identification of source, pathway and receptor linkages. Figure 2.1 shows a schematic conceptual model of the bund.

2.1 Source

Rainwater is assumed to infiltrate the engineered cap and percolate down to the base of the bund where it collects on the engineered / natural barrier forming a head of leachate. As it migrates through the bund contaminants present within the rock waste leach into this water. This forms the source of contamination.

The mass of contaminant is estimated in the model from the basal area multiplied by the height and the field capacity of the waste. The field capacity is equivalent to the fraction of water that remains in the source by volume under free draining conditions.
As fresh water flushes through the source and along the pathway segments, the total mass of contamination in the waste decreases. This is represented in the model using a declining source term where the rate of decline is proportional to the contaminant flux along the pathway segments.

Two contaminants of concern have been identified by FWS: chloride and sulphate.

### 2.2 Pathways

The natural stratum below the barrier is assumed to be unsaturated. Thus there is a positive head acting on the geological barrier which causes leachate to migrate through the geological barrier and into the underlying unsaturated zone. For the purpose of this preliminary screening calculation three leachate head conditions have been modelled at 0.25m, 0.5m and 1.0m above the upper surface of the engineered geological barrier. The geological barrier is considered to be the first pathway segment and the unsaturated zone is the second pathway segment.

The volumetric flux across the barrier and unsaturated zone is estimated from Darcy’s law, using the leachate head on top of the barrier, the barrier thickness, the barrier hydraulic conductivity and the barrier basal area.

\[
Q_{\text{path}} = \left( \frac{h_l + t_b}{t_b} \right) K_b A 
\]  
(Equation 1)

where:

- \( Q_{\text{path}} \) is the contaminant flux through the barrier (m\(^3\)/s),
- \( h_l \) is the definite leachate head (m),
- \( t_b \) is the thickness of the barrier (m),
- \( K_b \) is the hydraulic conductivity of the barrier (m/s) and
- \( A \) is the barrier basal area (m\(^2\)).

The pore water velocity through the barrier is estimated from:

\[
\bar{v} = \frac{Q_{\text{path}}}{A\bar{\theta}} 
\]  
(Equation 2)

where:

- \( \bar{\theta} \) is the effective porosity of the stratum (unitless).

The volumetric flux through the unsaturated zone is the same as the flux through the barrier as there are no additional sources or sinks of water. The pore water velocity through the unsaturated zone is also estimated from Equation 2, using the effective porosity of the unsaturated zone. As both the contaminants represented in the model are conservative (i.e. they do not degrade to other contaminants and sorption of the contaminants to the surrounding soil matrix is not considered to be significant), attenuation processes are not considered by the model.

Thus the barrier and unsaturated zone’s only role is to delay the breakthrough of contaminants at the identified receptor.

The contaminant migrates downwards within the unsaturated zone until it reaches the water table. The contaminant then moves laterally within the groundwater system and this is considered to be the third pathway segment. Within this segment, attenuation processes are not considered, but dilution of the contaminant with the receiving groundwater is considered. The receiving groundwater already contains background concentrations of the contaminants of concern and these are taken into account when determining the amount of dilution.

### 2.3 Receptors

The receptor is taken to be groundwater present adjacent to the Spring at location L. As this spring is some distance from the source, dilution in the receiving groundwater is taken into account.
account but no additional dilution within the spring is considered. As both the contaminants are non-hazardous pollutants it is not necessary to consider a receptor at the water table as would be required for hazardous substances.

**Figure 2.1 Schematic conceptual model**

![Schematic conceptual model](image)

### 3 MODELLING APPROACH

#### 3.1 Methodology

Contaminant transport along the pathway is modelled using a numerical solution of the one-dimensional advection-dispersion-retardation-degradation (ADRD) equation.

The analysis along each pathway takes account of the geometry of the pathway, but is essentially one-dimensional, with a simple description of the physical parameters affecting the contaminant migration along the pathway.

The default case does not take any transverse dispersion into account and is, therefore, a conservative calculation of concentration along the pathway. The effects of vertical dispersion are included by defining the equivalent dilution along the pathway.

This risk assessment has been undertaken using RAM Version 3 (ESI, 2008). This software uses a spreadsheet model to solve a detailed site specific water balance for the Site. The ADRD equation is then solved using a Laplace transform solution method by calling an external solver to the spreadsheet.

ESI benchmarked a number of groundwater risk assessment tools for the Agency and used a similar approach to benchmark RAM. Additionally, the equations used in RAM have been verified by comparison between direct evaluation of an analytical solution and the semi-analytic transform approach applied for more complex pathways, and by comparison with published solutions used for verification as part of the nuclear waste industry code comparison exercise INTRACOIN (Robinson and Hodgkinson, 1996).

#### 3.2 Input parameters

Input parameters were provided by FWS Consultants Limited and are presented in Table 3.1.
<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter (unit)</th>
<th>Value</th>
<th>Source / Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Base Area (m²)</td>
<td>81995</td>
<td>Arup Drawing YP-P2-CX-447-REV-2 / FWS (2014c)</td>
</tr>
<tr>
<td></td>
<td>Max width of site perpendicular to groundwater flow (m)</td>
<td>250</td>
<td>FWSC Drawing 1433AmtsOD122. July 2014. (2014e)</td>
</tr>
<tr>
<td></td>
<td>Waste Thickness (m) (Based on max. thickness)</td>
<td>5</td>
<td>FWS (2014c)</td>
</tr>
<tr>
<td>Source Term</td>
<td>Concentration: Water soluble sulphate (mg/l) (based on weighted average value calculated from proposed waste volumes)</td>
<td>68.21 (based on 100% Redcar Mudstone Formation)</td>
<td>FWS (2014a)</td>
</tr>
<tr>
<td></td>
<td>Concentration: Water soluble chloride (mg/l) (based on weighted average value calculated from proposed waste volumes)</td>
<td>230.24 (based on 100% Redcar Mudstone Formation)</td>
<td>FWS (2014a)</td>
</tr>
<tr>
<td></td>
<td>Leachate head (m) (3 values selected for sensitivity analysis)</td>
<td>0.25, 0.5, 1.0</td>
<td>FWSC Assumed value</td>
</tr>
<tr>
<td></td>
<td>Waste Field Capacity</td>
<td>0.4</td>
<td>Waste is predominantly mudstone and clay minerals will attract water molecules restricting ability to free drain</td>
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<td></td>
<td>Receptor Target Concentrations (mg/l)</td>
<td>Cl: 250  SO₄: 400</td>
<td>Freshwater EQS</td>
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<td></td>
<td>Free water diffusion co-efficient (m²/s)</td>
<td>2.00E-09</td>
<td>Fetter (1999)</td>
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<td>Engineered Barrier</td>
<td>Thickness (m)</td>
<td>1</td>
<td>FWS (2014b)</td>
</tr>
<tr>
<td></td>
<td>Permeability (m/s)</td>
<td>1 x 10⁻⁹</td>
<td>FWS (2014b)</td>
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<td></td>
<td>Effective Porosity</td>
<td>0.01</td>
<td>1% is a typical effective porosity for an engineered low permeability barrier</td>
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<td>Tortuosity</td>
<td>5</td>
<td>Marsily (1986) P233</td>
</tr>
<tr>
<td>Unsaturated Zone</td>
<td>Thickness (m)</td>
<td>2m Cohesive Glacial Till</td>
<td>FWS (2014c)</td>
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<tr>
<td></td>
<td>Permeability (m/s)</td>
<td>&gt;1x10⁻⁹</td>
<td>Saturated permeability &gt; overlying barrier so parameter not required by model.</td>
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<td>Effective Porosity</td>
<td>0.1</td>
<td>Assumed value for moderate permeability superficial deposits.</td>
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<td>Tortuosity</td>
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<td>Marsily (1986) P233</td>
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<td>Aquifer</td>
<td>Minimum thickness (m)</td>
<td>12.5 m of combined Long Nab and Moor Grit Scalby</td>
<td>FWSC Borehole Logs - Dove's Nest</td>
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<td>Component</td>
<td>Parameter (unit)</td>
<td>Value</td>
<td>Source / Justification</td>
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<td>Formation</td>
<td>Average Permeability (m/s)</td>
<td>5.6 x 10^-6 (Moor Grit - no data for Long Nab)</td>
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<td>Hydraulic Gradient to Receptor</td>
<td>0.027</td>
<td>FWS (2014d)</td>
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<td>Effective Porosity</td>
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<td>Assumed value for moderate permeability sandstone.</td>
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<td>Tortuosity</td>
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<td>Marsily (1986) P233</td>
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<td>Distance to receptor from midpoint of landraise (m)</td>
<td>830</td>
<td>FWS (2014b). Measured from centre of permanent waste disposal facility to Spring L monitored as SWQ2</td>
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<td>Average Aquifer Baseline</td>
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<td>Groundwater quality</td>
<td>Sulphate SO₄ (mg/l)</td>
<td>18.9</td>
<td>FWS (2014b)</td>
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<td>Chloride Cl (mg/l)</td>
<td>25</td>
<td>FWS (2014b)</td>
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4 MODEL RESULTS

Model results are presented as breakthrough curves and maximum concentrations for each of the three scenarios representing three different leachate heads of 0.25, 0.5 and 1 m.

The results represent the predicted pollution impact on groundwater quality in the shallow bedrock aquifer adjacent to the spring at Location L.

4.1 Leachate head: 1 m

Table 4.1 Maximum concentration and time to maximum concentration

<table>
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<th>Max Cl</th>
<th>Max SO4</th>
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<td>56 mg/l at</td>
<td>29 years</td>
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<tr>
<td>25 mg/l at</td>
<td>29 years</td>
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Figure 4.1 Breakthrough curves: leachate head = 1 m
4.2  Leachate head: 0.5 m

Table 4.2  Maximum concentration and time to maximum concentration

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<tr>
<th></th>
<th>Max Cl</th>
<th>52 mg/l at</th>
<th>32 years</th>
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<tbody>
<tr>
<td>Max SO4</td>
<td></td>
<td>25 mg/l</td>
<td>32 years</td>
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</table>

Figure 4.2  Breakthrough curves: leachate head = 0.5 m

![Graph showing breakthrough curves for chloride and sulphate concentrations over time.](image-url)
4.3 Leachate head: 0.25 m

Table 4.3 Maximum concentration and time to maximum concentration

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<th>Max Cl</th>
<th>Max SO4</th>
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<td>Concentration (mg/l)</td>
<td>50</td>
<td>24</td>
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<tr>
<td>Time (years)</td>
<td>34</td>
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Figure 4.3 Breakthrough curves: leachate head = 0.5 m
5 REFERENCES


