DEMONSTRATING THE HYDROGEOLOGICAL SECURITY OF A SITE SITUATED IN KARST FOR THE NEW SOUTHLAND REGIONAL LANDFILL.

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1. Introduction

The new Southland Regional Landfill, located near Winton (Figure 1), is situated in redundant parts of a working limestone quarry. The area surrounding the landfill displays prominent karst features that are readily visible from the ground and aerial photographs as shown in Figure 2.

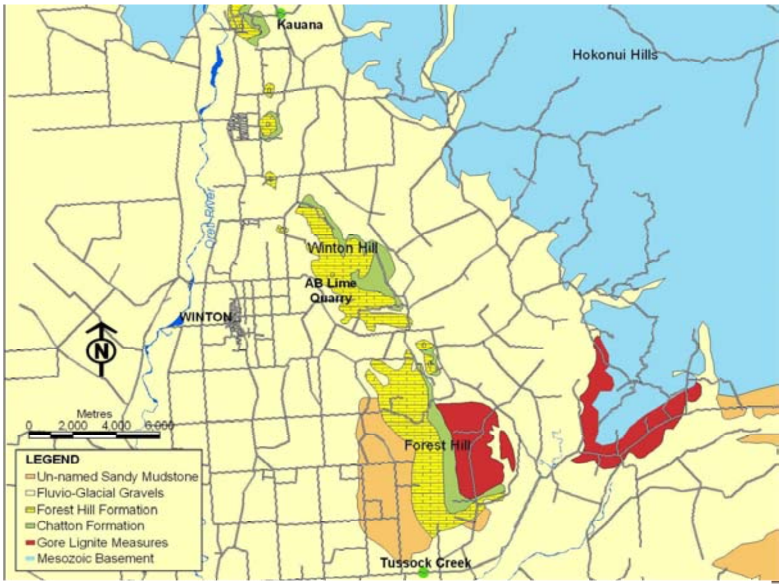

Figure 1. Locality and regional geology plan.

The Centre for Advanced Engineering (CAE, 2000) Landfill Guidelines for New Zealand suggest that it is generally undesirable to site a landfill in areas of karst geology. Landfills designed in these environments must be engineered to a higher level to avoid the hydrological features of karst that are typically detrimental to the containment of leachate or hydrogeological security of landfills.

A number of submissions were made during the public notification process associated with the resource consent application for the landfill. The primary areas of concern raised with respect to potential hydrogeological impacts included leachate collection system failure and specifically, the potential for leachate discharge into the karst system and the subsequent rapid offsite movement of possible contaminants.

This paper begins with a summary of karst hydrogeology with particular reference to the features of karst that are generally unsuitable for landfill

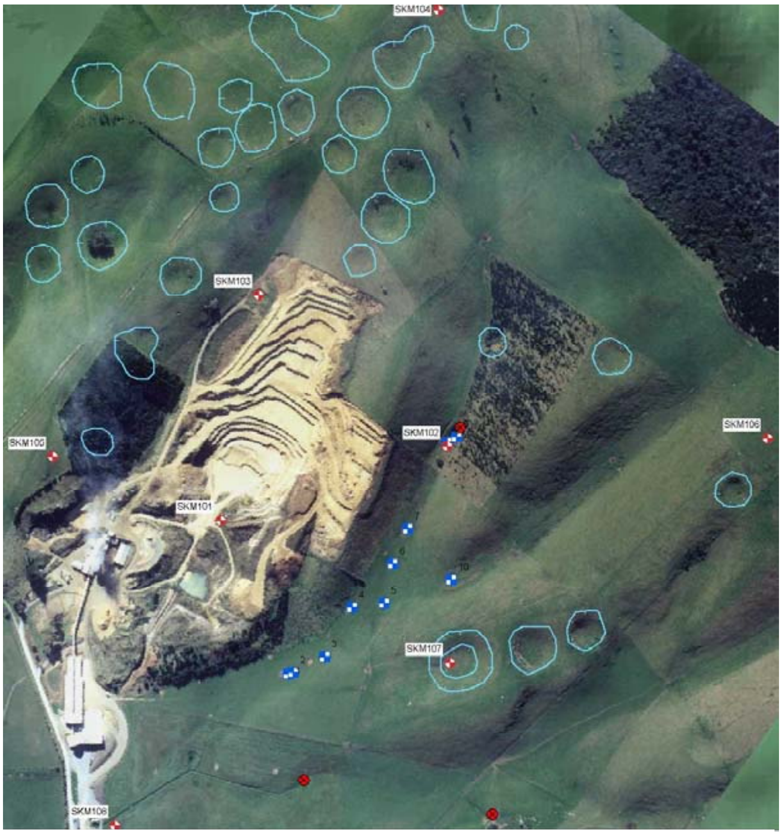

Figure 2. Aerial photograph (April, 2002) of the quarry, adjacent sinkholes and investigation sites.

development. This is followed by a discussion of the investigations that were undertaken to determine the hydrogeological security and a summary of the assessment of groundwater effects from operation of the landfill.

2. Karst Hydrogeology

Karst is the name given to areas of limestone or marble characterised by landforms developed as a result of solution processes.

2.1 Karst Forming Processes

The development of karst terrains occurs primarily when carbonate rocks are hard and relatively free from impurities (less than approximately 20% terrigenous material). Some limestone, such as argillaceous limestone north of Auckland (e.g., at Redvale and Wellsford) are pure enough to be quarried for agricultural lime but are too impure for developed karst features to arise (Williams, 1992).

2.1.1 Carbonation

Carbonation is a solutional chemical weathering process and is the fundamental chemistry of the karst forming process involving a reaction of dilute carbonic acid and calcium carbonate. Carbonic acid is formed where rainwater of low bicarbonate hardness percolates through soil absorbs CO_2 from air within the soil. In the case of limestone, H^+ ions of the mildly acidic rainwater react with calcite producing calcium and bicarbonate ions. The acidic rainwater becomes progressively weaker through removal of H^+ ions as this process continues and the residual water becomes progressively saturated with respect to calcium and bicarbonate. As the degree of water saturation increases the ability of the water to dissolve limestone decreases. This typically relates to contact time, which generally correlates to depth below the ground surface. For this reason, karst is usually more developed close to the surface with wider solution fissures nearer the surface and gradually tapering with depth.

2.1.2 Karstification

Karstification is the term used for the overall processes that increases the water bearing capacity of most carbonate rocks. Karstification is the result of the carbonation process described above, which predominantly occurs in rock defects such as bedding planes, faults and joints. The defects are gradually enlarged and over time narrow fissures can develop into very large caves.

The development of karst topography advances through stages, which may be identified as juvenile, maturity and old (Goodman, 1993). Figure 3 depicts these aspects of karst development. It should be noted that different stages of karstic development may coexist, due to climatic variations and changes in local non-limestone geology. In hard indurated limestone, the progression through these stages may take a very long time, with the progression through stages unlikely to occur in a persons lifetime (Goodman, 1993).

The individual stages of karst landscape development each have distinctive hydrological characteristics and consequently have important implications for any development and especially landfills.

2.2 Sinkhole Development

Sinkholes, which are topographically closed landforms that display a ‘pocked’ appearance (see Figure 2), are the most prominent surface karst features at this site. Sinkholes form through the following processes:

- simple solution of the limestone;
- collapse of overlying sediments into solution voids; or
- collapse of the limestone itself.

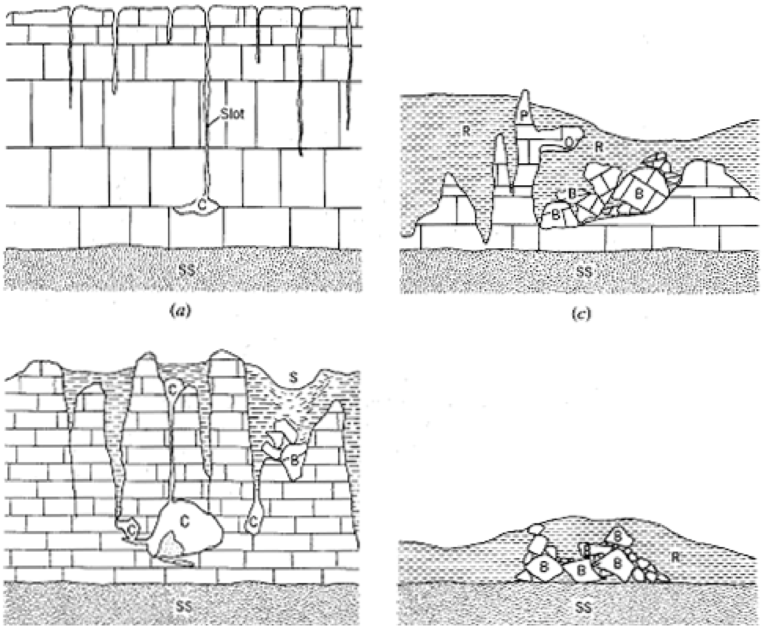

Figure 3. Development of solution cavities and karst features: (a) juvenile; b) early maturity; c) late maturity; d) old. C, cavity; S, sinkhole; SS, sandstone; B, block; R, residual soil; P, pinnacle; O, overhanging pinnacle (after Goodman, 1993).

The development of solution sinkholes (the first two processes above) is a self-reinforcing process. An initial minor weakness in the rock produces higher hydraulic conductivity and preferential flow paths. The solution potential is increased along the conduit, further enlarging the conduit. The focussing of drainage from surface waters in the vicinity of the sinkhole increases the volume of water harvested, resulting in accelerated development and continual expansion of the sinkhole.

2.3 Hydraulic Characteristics

The hydrogeology of karst systems differ from standard groundwater systems in that:

- The hydraulic networks can consist of three types of spaces; pores (aquifer matrix), fracture and channel or conduit (Motyka, 1998). For this reason, simple porous media or double porosity conceptual models of the system are not usually applicable.
- The circulation of water in a karst aquifer continually enhances the aquifer permeability over time. The hydraulic gradient will decrease through long periods of time, as the water table declines due to increases in storage and permeability (Williams, 1992).
- The piezometric surface geometry may not follow topographic lows and highs due to lowering of the water table through conduit drainage.
- The rock matrix in karst accounts for almost all of the aquifer storage, while the channels transmit almost all the groundwater flow (Worthington *et al.*, 2000)

Most classifications of karst systems (Motyka, 1998), show three primary hydraulic response zones:

i) ***Unsaturated (vadose) zone*** – comprising the soil, weathered subcutaneous (sub-surface) zone and free draining percolation zone;

ii) ***Intermittently saturated (epikarstic) zone*** – zone of water table fluctuation; and

iii) ***Saturated (phreatic zone)*** – zone beneath the true groundwater table (Williams, 1992).

The hydraulic characteristics of each of these zones depend largely on the degree of karst development.

2.4 Investigations in Karst

Investigations of karst aquifers are particularly challenging because complex networks of fractures and dissolution features can locally and regionally control groundwater flow. It is not realistic to expect to encounter all conduits during drilling because of the infrequent and heterogenous nature of conduit distribution. An approach with multiple investigative techniques is usually used to understand how permeability and porosity are distributed in the aquifer.

3. Site Hydrogeological Investigation and Findings

Hydrogeological investigations were undertaken within and surrounding the then proposed landfill site. The information gained from this investigation provided the factual data that formed the basis of the assessments of site feasibility, hydrogeological security and environmental effects with respect to groundwater.

The objectives of the site investigation were to determine:

- the stratigraphic sequence of rocks within the proposed landfill site, including thickness of the limestone and underlying materials;
- the sedimentary texture of the materials encountered during drilling including, grain size, shape and fabric, which in turn govern bulk density, porosity and permeability of the rock matrix;
- the primary sedimentary structures of the materials encountered during drilling including bedforms, lamination, and bedding planes;
- the secondary sedimentary structures (defects) of the materials encountered during drilling including fracturing and faulting, which govern secondary porosity;
- the tertiary structures that have developed through the dissolution processes of carbonation that govern tertiary porosity and in this terrain have the biggest influence on preferential flow;
- the rock matrix hydraulic conductivity of the unsaturated and saturated zones;
- the terrain geomorphology and nature of karst development;
- a conceptual hydrogeological model for the site.

The investigations conducted comprised a number of techniques to obtain the required data, including:

- aerial photograph analysis
- site walk over observing the geomorphology,
- borehole drilling (9 bores, 8 locations),

- excavation of soil testpits (10 testpits),
- hydraulic testing,
- groundwater level monitoring,
- groundwater chemical sampling, and
- groundwater numerical modelling.

3.1 Drilling Methodology and Specifications

Nine boreholes at eight locations were installed using the wire-line rotary continuous coring technique with a HQ tungsten and diamond tipped core bit. The HQ coring method produces a drilled hole diameter of 96.1 mm and a rock core diameter of 63.5 mm, and permits detailed geological analysis of the recovered geological materials. The bores were drilled to depths between 9 and 77 mBGL, depending on the ground elevation at each site and the depth to base of limestone or water table. A nested piezometer configuration comprising two 20 to 32 mm PVC standpipes, or a single 50 mm PVC piezometer was installed in each borehole to facilitate groundwater monitoring and/or sampling.

3.2 Testpits

A 12 ton excavator equipped with a 1 m diameter bucket was used for the excavation of ten testpits along a transect where small open sinkholes (shafts) were prevalent. The alignment of the shafts corresponds to a significantly incised drainage valley to the east of the existing quarry area. Several testpits were excavated to examine the extent of shaft development and drainage characteristics. Soil profile characteristics, depth of the shafts and features indicative of water soakage and sub-surface water flow were recorded. The testpits were excavated to the maximum accessible depth of the excavator, or until impenetrable limestone was encountered. Data from the testpits indicates that free water was encountered above the limestone and near the base of the colluvium. This is likely to be an interface drainage feature between the two units.

3.3 Site Geology

From analysis of drilling and testpit data and interpretation of the regional geological information, the site geology may be summarised into three bulk formations, as indicated below and summarised in the following sections:

- Overburden Material
- Limestone of the Forest Hill Formation
- Siltstone of the Chatton Formation.

3.3.1 Overburden Material

The overburden material comprises topsoil, colluvium (silt and clay) and residual limestone clasts that either remain *in-situ* or have been eroded from the slopes above. The thickness of the overburden is spatially variable, being thickest (2 to 7 m) on the lower slopes, and within valleys and sinkholes, and thinning on the upper slopes. Limestone is exposed at the surface in some places – predominantly on the steep sides of ridges.

3.3.2 Limestone of Forest Hill Formation

The limestone located on site is of the Forest Hill Formation and comprises yellow brown and light greenish grey, thin to thickly bedded, slightly weathered, bryozoan/brachiopod, biosparite that ranged in thickness between 18.4 m and 75.6 m. The formation is interbedded with moderately weathered, thin (generally <0.04 m) soft clay/silt horizons and occasional greenish grey biomicrite. The interbedding of thin soft clay/silt horizons generally occurs near the surface, becoming less frequent with depth. The light greenish grey biosparite limestone and greenish grey biomicrite limestone generally occur towards the base of the limestone.

The occurrence of fractures and dissolution features (vertical fluting and cavities) decreases with depth and is limited to above the water table. Cores recovered from the boreholes indicates that the fractures where occurring are near vertical, with a dip angle greater than 70^o.

Dissolution features were primarily encountered near the surface, as indicated by the loss of drilling fluid within the upper profile of the limestone during drilling. This finding adheres to the standard conceptual model for karst hydrology and limestone dissolution theory, with groundwater becoming more saturated with calcium and bicarbonate, and losing its power to dissolve carbonate rocks as it migrates downward through the vadose zone.

3.3.3 Siltstone of Chatton Formation

Underlying the limestone is a siltstone of the Chatton Formation, which is comprised of dark grey to dark greenish grey, slightly calcareous, slightly to moderately sandy siltstone. Occasional shell inclusions and mudstone and sandstone horizons also occur within the formation at the site. The interface between the Forest Hill Formation and the Chatton Formation is a sharp contact indicating the latter to be an erosional surface. Evidence of progressive coarsening towards the base of the limestone supports this.

3.4 Sinkhole Development On-Site

The April 2002 aerial photo of the quarry site indicates that sinkholes are predominantly located along the limestone ridges (Figure 2). The relative lack of conduit development in the lower lying parts of the catchment is a function of the sinkhole development, which require turbulent flow conditions and undersaturated water with respect to calcium and bicarbonate to develop.

In lower lying areas where the water table is closer to the surface, sinkholes are less likely to develop than on the ridges because turbulent flow conditions do not have as much potential to develop and the water typically displays greater maturity (i.e., higher degree of saturation). Karstic development in the valleys is more juvenile than on the ridges.

3.5 Aquifer Hydraulic Testing

Hydraulic testing of the rock was undertaken to gain an understanding of the water transmission potential of the rock. The objective of the testing program was to quantify the permeability of both the unsaturated and saturated zones of the rock. Preliminary testing indicated the permeability below the water was too low to permit long duration test pumping, therefore only the following two approaches were employed:

- ***Packer Tests*** – provides indicative hydraulic conductivity values for the area immediate adjacent to the pneumatic packer assembly.
- ***Slug Testing*** – provides indicative hydraulic properties for the aquifer area immediately adjacent to the saturated extent of the testing bore.

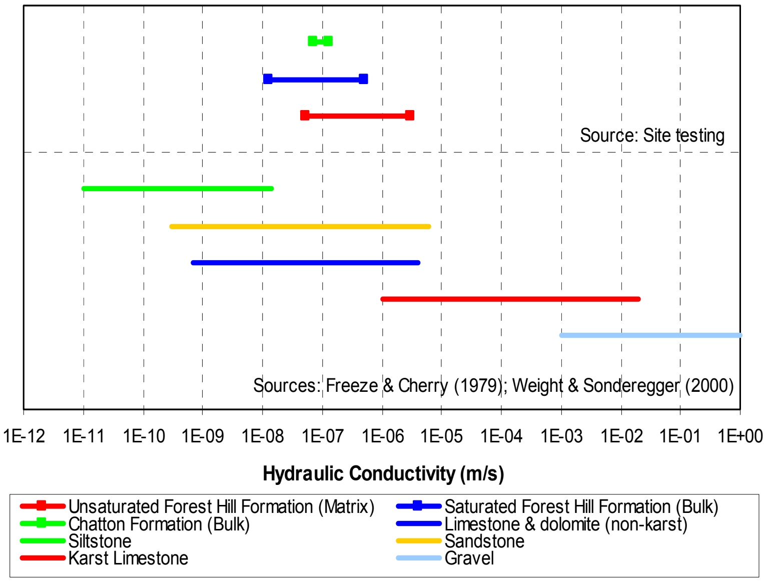

Figure 4. Comparison of site hydraulic conductivity data to typical published results.

Test results indicates hydraulic conductivity values for the (see Figure 4):

- Forest Hill Formation limestone range from 1.24×10^{-8} to 2.94×10^{-6} m/s with an average of 3.30×10^{-7} m/s.
- Chatton Formation siltstone range from 6.30×10^{-8} m/s to 1.3×10^{-7} m/s, with an average of 8.40×10^{-8} m/s.
- Hydraulic conductivity above the water table is generally greater than below, with averages of 8.61×10^{-7} m/s and 1.15×10^{-7} m/s, respectively.

The hydraulic conductivity values for the Forest Hill Formation are within the normal range of typical publicised values for non-karst limestone and lower than karst limestone. The hydraulic conductivity values for the Chatton Formation are comparable to typical published values for siltstones (Figure 4).

These findings indicate that the hydraulic properties of the limestone at this site are more indicative of non-karst than karst limestone.

3.6 Groundwater Level Monitoring

Depth to Groundwater

Groundwater is encountered at or near the surface in the quarry floor and in the valleys, and is deepest (60-70 mBGL) underneath the ridges in the upper parts of the catchment.

Vertical Pressure Gradients

Data supports the standard conceptual hydrogeological model, with downward groundwater pressure gradients in higher altitude recharge areas and upward pressure gradients in the lower discharge areas. Positive groundwater gradients currently exist beneath the base of the quarry, with groundwater seepage towards the ground surface. This provides hydrogeological security to the landfill site against leachate leakage impacting on the local groundwater resource.

Groundwater Flow Rates

Water transmission through the saturated part of the aquifer, which at this site is primarily governed by flow through the matrix or porous media, conforms to Darcy's Law. Darcy's Law describes the velocity of flow and is a function of the hydraulic conductivity, effective porosity and hydraulic gradient within the aquifer.

An average linear flow velocity of 7.988×10^{-7} m/s was calculated for limestone aquifer, which equates to a travel time of approximately 4 years for a water particle to travel 100 m downgradient of the site.

3.7 Groundwater Quality

Groundwater quality testing was undertaken but will not be discussed in this paper other than to say the groundwater quality was typical of limestone terrain and showed some influence of agricultural practices typical to many rural parts of New Zealand.

3.8 Conceptual Hydrogeological Model

The conceptual hydrogeological model has been simplified into two broad zones based on knowledge of karst hydrogeology and the hydraulic characteristics of the formation (Figure 5). These zones are described as follows:

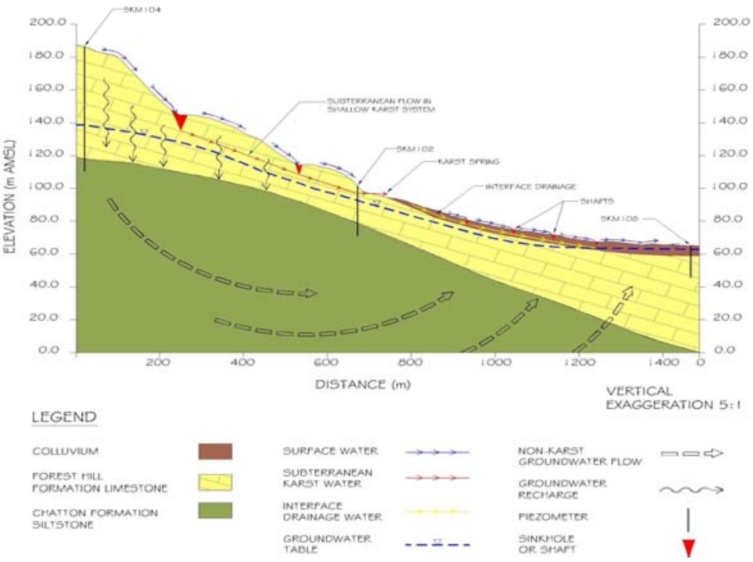

Figure 5. Conceptual hydrogeological model of the site.

- ***Karst (vadose) zone*** – water transmission zones comprising sinkholes, solution cavities and fractures within the upper 20 m and above the local groundwater table within the limestone of the Forest Hill Formation.
- ***Non-karst (saturated/phreatic) zone*** – aquifer zones beneath the local groundwater table consisting of massive low permeability limestone of the Forest Hill Formation and the underlying siltstone of the Chatton Formation. Flow characteristics of this zone conform to porous media flow governing equations.

Water may transit the system entirely within the karst zone, or may enter the deeper non-karst zone before exiting the system. The presence of sinkholes indicates that a connection exists between the recharge area and local karst springs. The exact nature of that connection is unknown. However, it is thought that the water from sinkholes travels laterally, discharging as karst springs on the valley sides and base at mid-level within the catchment.

Water flow observed in testpits excavated into the valley floor to the east of the quarry indicates the possibility of preferential flow paths along the interface between the colluvium and underlying limestone. This interface drainage feature is possibly responsible for the recent development (in geological terms) of vertical shafts extending to the surface due to the dissolution and collapse of limestone at the colluvium contact.

3.9 Groundwater Numerical Modelling

Groundwater flow and contaminant transport models were developed for the non-karst limestone using the USGS MODFLOW and MT3DMS codes, respectively.

The objectives of the groundwater-modelling component of this study were as follows:

- To develop a model that accurately simulates groundwater flow and contaminant transport processes for the deeper non-karst limestone aquifer, where porous media flow governing equations are valid.
- To determine the effect on groundwater flow rates through quarrying and subsequent landfilling.
- To determine the groundwater level impact through quarrying and subsequent landfilling.
- To determine the groundwater seepage rates to the quarry and landfill underdrains.
- To evaluate potential contaminant plume distribution and movement from the landfill under worst case liner failure scenarios.

Simulation results are discussed in the following assessment of effects.

4. Assessment of Groundwater Effects

This chapter describes the anticipated effects of the quarry and landfill on the groundwater system beneath and downgradient of the landfill.

4.1 Effect of Quarrying

Groundwater Depressurisation

Quarry excavation will progressively impinge upon the groundwater table. However, based on historical observations within the quarry, the low hydraulic conductivity of the rock, small number of conduits in the vadose zone and the progressive nature of the quarrying operation, groundwater seepage rates will be low and easily manageable.

The net effect of the quarry on the groundwater flow regime is a reduced hydraulic gradient, resulting in groundwater flow rates reduced by approximately 1.2% from the existing situation.

Continued lowering of the local water table by quarry excavation may inactivate a number of upper springs and seepages fed primarily by fracture flow in the epikarstic zone. These springs only become active during wetter conditions, with a higher water table – therefore the effect also occurs naturally. The effect of the landfill is to increase the probability of this phenomenon occurring.

4.2 Effect of Landfilling

Landfill Shadow Effect

Construction of an impermeable barrier over the landfill footprint area will reduce rainfall recharge to the groundwater system. The effect of reduced recharge is that the groundwater in the immediate area of the landfill will be depressurised. The extent of measurable impact (i.e., > 0.05 m) was modelled to be limited to within approximately 750 m of the site due to the low permeability of the aquifer. The net effect on the groundwater flow regime is similar to that described in the previous section, with a reduced hydraulic gradient resulting in lower groundwater flow rates by approximately 12%.

Effect of Liner Leakage on Groundwater Quality

It is extremely unlikely that any significant leakage through the liner would occur because the proposed leachate collection and composite liner system provide a robust form of security against leakage. There are two possible outcomes that could eventuate, should the worst case scenario materialise and significant leakage through the liner occurred:

i) under normal conditions the positive upward groundwater pressures from the underlying aquifer would prevent downward percolation of leachate to the underlying aquifer, resulting in leachate collection in the groundwater underdrains, and

ii) under prolonged dry conditions when the underlying groundwater pressures are likely to be less than normal, leachate may percolate through the unsaturated zone to the water table. This is considered unlikely because the path of least resistance for water flow beneath the liner system would be along the underdrain collection system, rather than entering the low permeability limestone. In the extreme case that leachate reached the aquifer system, groundwater modelling has demonstrated that plume movement would be extremely slow and limited in extent due to the low aquifer hydraulic conductivity and the natural process of advection, dispersion, sorption, and chemical decay.

4.3 Effect on Bore Users

The distance to the closest bore is greater than 600 m. Given the low permeability of the limestone and low groundwater seepage rates to the adjacent alluvium, the groundwater quantity and quality effects of quarrying and landfilling is anticipated to be limited to less than 500 m from the site. This will not affect any bore users.

5. Conclusions

Site investigations undertaken by Sinclair Knight Merz demonstrated a high degree of hydrogeological security at the site. Positive (upward) groundwater pressures were evident in areas of lower ground elevation such as the existing quarry floor. This provides a form of hydrogeological security or natural containment of potential leachate as any leakage through the liner system is likely to be trapped against the landfill underdrain system and unlikely to migrate downwards to the underlying aquifer. The limestone displays distinctly variable permeability with depth below the ground surface with solution features and fractures becoming less prevalent with depth and being practically non-existent beneath the groundwater table. The degree of karstification or sinkhole development decreases with depth due to the reduction in the ability of percolating rainwater to dissolve limestone with distance from the surface as the water becomes progressively saturated in calcium and bicarbonate resulting in a general lack of conduit features beneath the groundwater table. This indicates that the deeper limestone is non-karstic and groundwater flow is predominantly governed by porous media characteristics. Due to the morphological and hydrological features encountered at the site, the nature of the karst terrain is considered juvenile, which suggests that the likelihood of intersecting large solution conduits at the base of the quarry is low. The permeability of the rock is reasonably low with a site-wide average hydraulic conductivity value from aquifer testing of approximately 3.30×10^{-7} m/s, which is more indicative of non-karst than karst limestone. Due to the low hydraulic conductivity and natural attenuation process, the anticipated maximum extent of a conservative element contaminant plume has been estimated at approximately 2,300 m from site after 100 years of continuous discharge.

6. References

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