Leapfrog - A rapid conceptualisation and analysis tool for geology, groundwater and contaminant interception at a biosolids containment facility

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ABSTRACT

A ground model was developed using the software Leapfrog to facilitate detailed design of a biosolids containment facility on the basaltic Puketutu Island in Auckland, New Zealand. The 3-dimensional conceptual model was used to assess design requirements for a subsurface drainage system beneath the embankment of the facility, which was required to intercept any leachate that might migrate through the liner system. Data was available in report format from 132 test pits and boreholes from historical site investigations. Borehole logs were coded according to the four main lithologies and imported into Leapfrog. Contact surfaces were also generated to represent the depth of historical quarrying, the current surface of imported fill, and the proposed facility embankment and base grade. Compilation of this information in Leapfrog provided a single 3D view of the current and future ground conditions beneath the site that is readily updated as more data is received. The Leapfrog geological model was exported to the program Modflow (Groundwater Vistas) to rapidly generate a groundwater flow model for the site, which enabled efficient consideration of a number of operational scenarios to determine where groundwater interception would be most likely to mitigate any potential leakage from the liner. A viewer tool enabled communication of the 3D ground model to other parties. The 3D ground model and associated groundwater model have also been applied to address a number of other during-construction queries and have proved invaluable for the communication and interrogation of data in 3 dimensions from a range of sources.

Keywords: Groundwater, 3D Modelling, Hydrogeological Conceptual Model, Data Compilation, Leapfrog, Modflow

1 INTRODUCTION

Watercare Services Limited (Watercare) is undertaking the Puketutu Island Rehabilitation Project, which involves constructing a biosolids containment facility in former quarried and filled areas of Puketutu Island, Auckland. The biosolids will be contained by a large outer embankment with a liner system on both the sides and base of the containment area (Figure 1). The volcanic island is approximately 1.8 km x 1.1 km in area, surrounded by the Manukau Harbour, and connected to the mainland by a causeway.

Leachate generated through biosolids consolidation and rainfall infiltration will be collected by a leachate drainage layer on top of the liner, and pumped via a collection pond to the Mangere Wastewater Treatment Plant. The resource consents for the project required that a groundwater interception system be installed, in the form of 'embankment drains', that could be used to intercept any leaked leachate through the liner, although this is unlikely to occur. The concept design included a perforated pipe installed along a drainage trench beneath the liner at the perimeter of the facility (i.e. under the embankment), connected to a pumping station. This 'embankment drain' could be pumped if required during operations, to locally draw down groundwater levels and intercept potential leachate mixing in shallow groundwater beneath the facility.

As part of the detailed design, it was necessary to quickly determine where around the perimeter of the facility the drainage system would be required in the event of liner leakage, in order to meet the environmental outcomes presented during the approvals process.

A rapid analysis tool was required to predict flow paths from the biosolids containment facility and bring together data describing the geology, and it's modification from historical quarrying and filling operations. Leapfrog Hydro was used to build a three-dimensional ground model from historical and relatively disparate data sources including multiple technical reports, spreadsheets of borehole data, existing landforms and surface geology. From the ground model and these data a numerical groundwater flow and dispersion model was created to rapidly assess the effective placement of an embankment drain.

Figure 1. Aerial photo of the site in early 2014, showing the containment facility haul roads, embankment, and liner under construction (centre of photo), and Manukau Harbour surrounding the Island. Photo credit: Watercare Services Ltd.

2 METHODOLOGY

2.1 Geology Model

To determine the best location and extent of an embankment drain (a groundwater interception drain), the flow path for any potential leachate leakage needed to be understood. The flow path from the facility is dependent on the groundwater flow through the various geological materials encountered at Puketutu Island. Therefore a 3D geological model was developed using geological data collected at Puketutu Island over many investigations, and historical accounts of quarrying and filling activities.

The geological model was prepared using the program Leapfrog Hydro (http://www.leapfrog3d.com) which created contact surfaces and 3D volumes describing the extent of the major geological units on the island: basalt/scoria, tuff, existing fill, hard fill (to be placed as part of construction), alluvium, and Waitemata Group.

The model was based on the following:

- All borehole and test pit data collected since 1997 (Figure 2). Approximately 132 bore logs from multiple investigation phases were reviewed and the detailed logs aggregated into the main lithological units of basalt or scoria, tuff, fill, alluvium, and sandstone/mudstone. In interpolating this data in the model, consideration was given to the changing surface elevations over time, given the quarrying and filling activities on site, therefore some earlier data points were removed from the final interpolation process.

- Other data sources describing historical quarry pit and pond extents, a previously constructed aquifer barrier trench, and surficial geological mapping and site knowledge. These were incorporated into the model through the use of interpolations and guide points, a key feature of Leapfrog enabling user interpretation and modification to the bore log interpolated geology units.
- The topographic surface based on 2012 LIDAR survey data.
- The future design of the biosolids containment facility, including the embankment surface and base grade of the liner.

The initial model creation was completed within a few days. The tool allowed for a rapid compilation of all existing data to develop a geological model which could be readily communicated and interrogated by a range of interested team members and stakeholders using the software's 3D viewer tool (Figures 3 and 4). It enabled simple presentation of complicated 3D geological information on the site, previously in a range of formats. In addition to being used for the embankment drain design, once created, the model was also useful for rapid responses to other design/construction queries on the project.

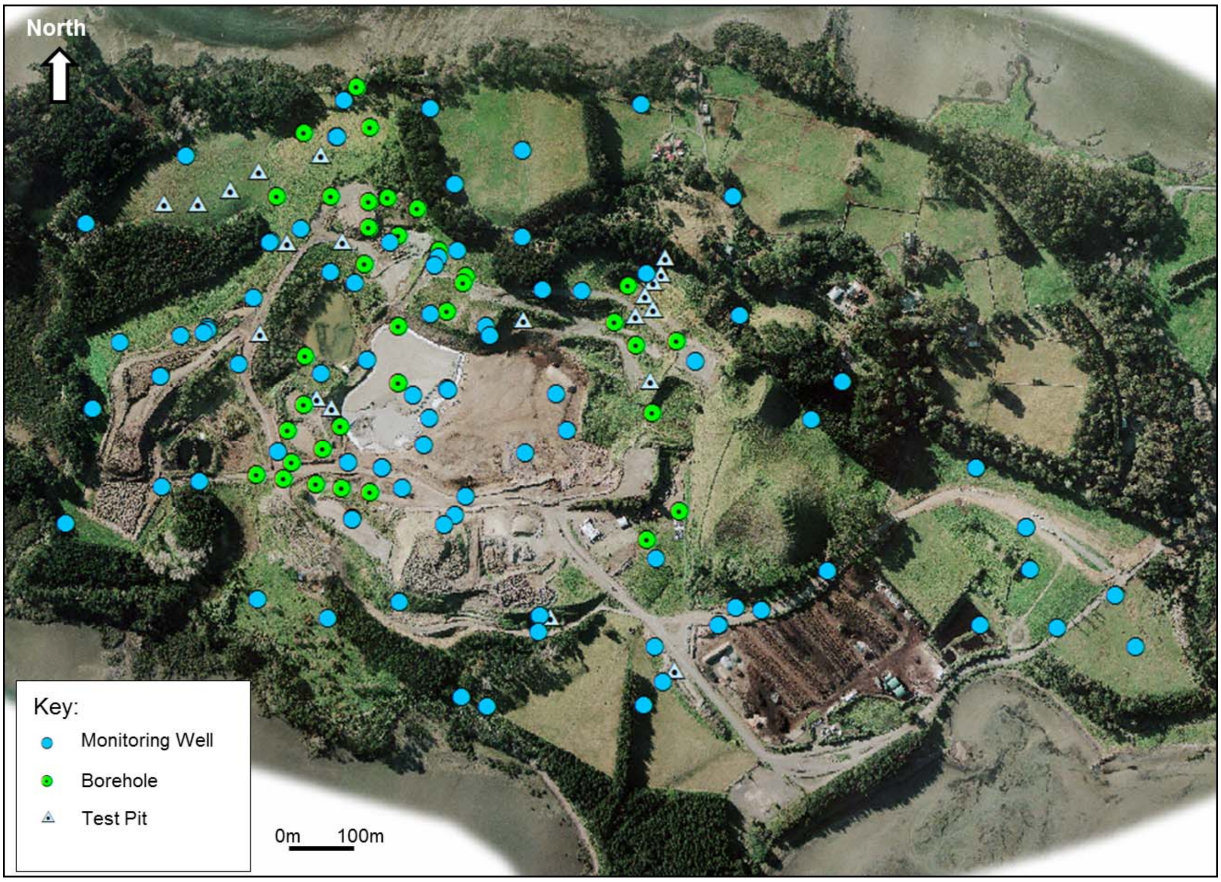

Figure 2. Bore logs from monitoring wells, boreholes and test pits completed since 1997, requiring compilation and interpretation to develop a geological model.

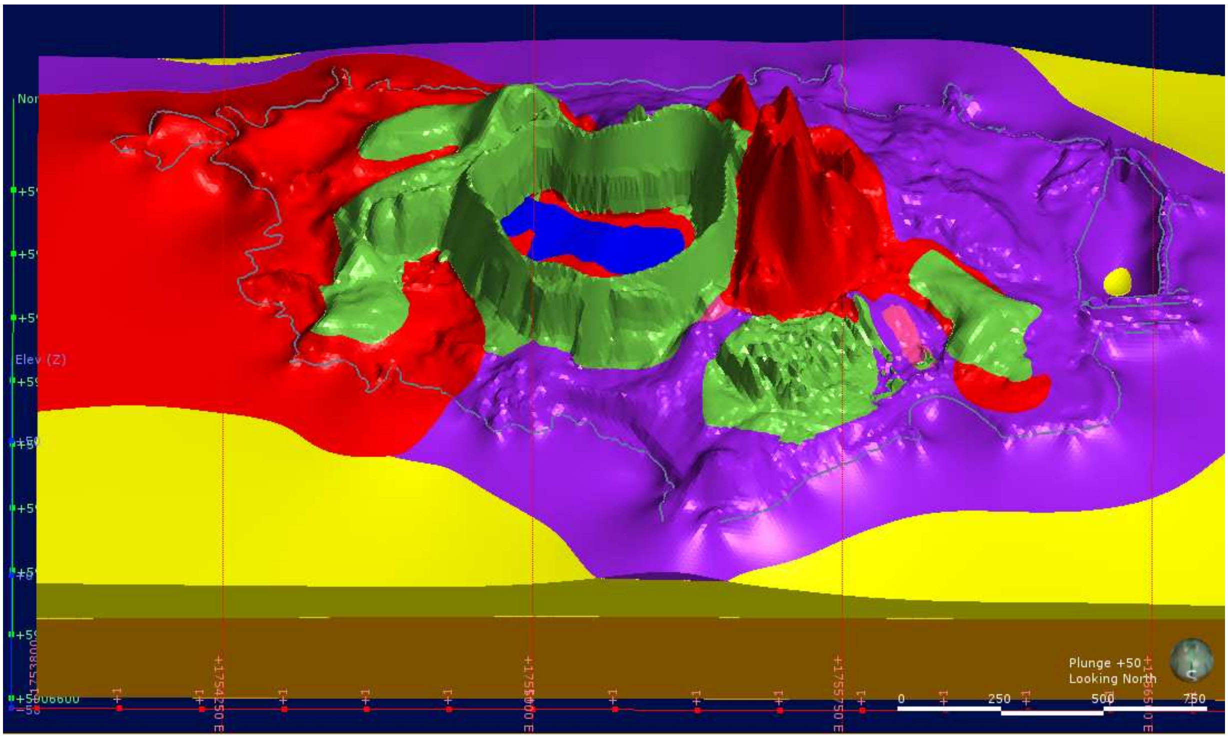

Figure 3. Leapfrog viewer output showing a 3D geological model of the site and biosolids containment facility embankment - oblique view looking north. Colours represent different lithological units. The outline of the island can be seen as a thin blue line.

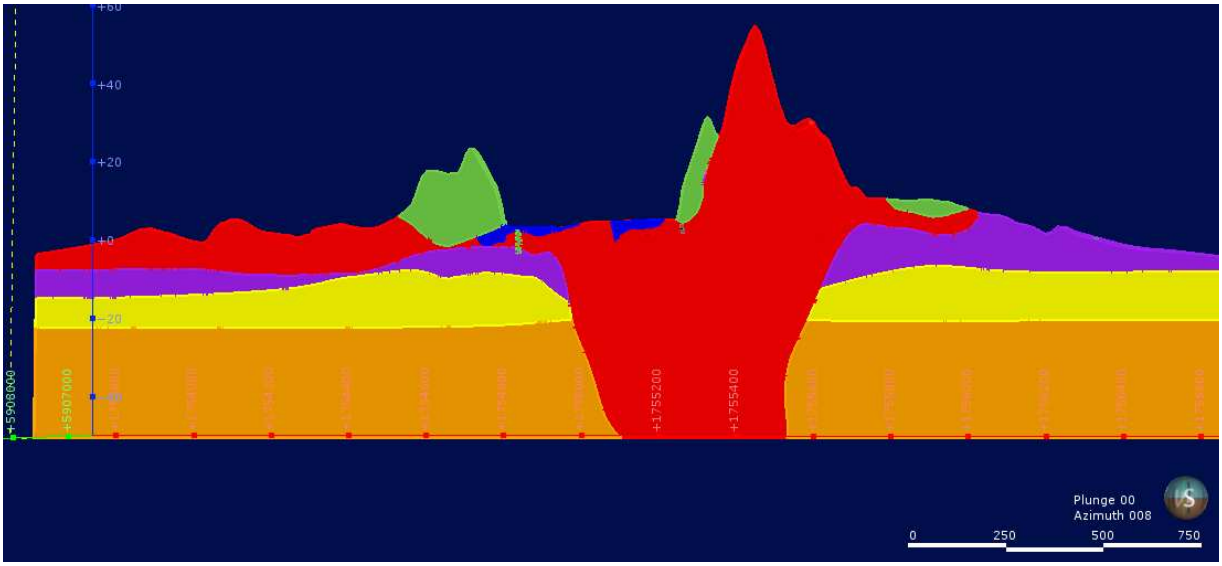

Figure 4. Leapfrog viewer output showing an example 2D cross-section through the geological model of the site and biosolids containment facility embankment. Colours represent different lithological units.

2.2 Leachate Generation and Potential Liner Leakage

In order to determine the location and extent of a groundwater interception drain, estimates of worst-case potential liner leakage had to be made. The facility liner is made up of a 300 mm thick cohesive soil (hydraulic conductivity = 1×10^{-8} m/s), overlain by a geosynthetic clay liner (GCL) and a flexible membrane liner (FML). The assessment considered maximum leachate generation rates from biosolids consolidation, potential build-up of head on the liner from failures to the leachate collection system, and liner performance (i.e. permeability and potential defects).

Leachate generation rates over time were estimated based on filling the facility in 35 years without change to the current nature of the biosolids. The peak rate of leachate production will be at the end of year 35 of biosolids placement, and following this leachate production will decrease as the biosolids become consolidated.

A network of leachate collection pipes are embedded within a drainage blanket on top of the liner, and leachate is pumped to collection points, and returned to Mangere Wastewater Treatment Plan. Failure to parts of the leachate collection system could result in the temporary build-up of leachate head on the liner. An assessment of pessimistic-case leachate head on the liner was calculated assuming a failure of the leachate collection system for a period of one year.

The rate of leakage through lining systems with FMLs is negligible compared to the rate of leakage through FML defects. Estimates of leakage through liner defects by Giroud (1997) were utilised to quantify a pessimistic case leakage through the liner, at the peak leachate generation period (year 35), after a one year failure of the leachate collection system. This liner leakage rate was used to design mitigation against potential effects on groundwater.

Concentrations of key contaminants (ammoniacal nitrogen, cobalt, copper, nickel, zinc) in the leachate were identified from previous research and reports (URS, 2008a and 2008b), and assumed no attenuation through the clay liner.

2.3 Numerical Groundwater Flow Model Development

Using the geological model developed, a numerical groundwater flow and dispersion model was set up to predict the critical groundwater flow paths from the biosolids containment facility to the coast, to determine where the leachate interception system would be most effective in the unlikely event that groundwater contamination occurred during operations.

2.3.1 Model Set-Up

Leapfrog Hydro enables rapid translation of the geological contacts and deposits to a grid and property zonation that forms the basis of a numerical groundwater flow model. In this case, MODFLOW (McDonald and Harbaugh, 1984) grid and property zonation files were generated and imported into Groundwater Vistas (ESI, 2011). The geological distribution was replicated by a combination of varying the grid elevation and assigning property zonation. This enabled complex and heterogeneous arrangements of material properties to be set up in the groundwater flow model very quickly. The property zonation is based on the 3D geological model and is shown in Figure 5.

Use of a steady state flow model was justified on the basis that the primary purpose of the model is to predict groundwater flow direction and plume migration over extended periods of time. In addition to the groundwater flow simulation, contaminant transport modelling was undertaken using MT3DMS (Chunmiao et. al., 1999) which takes into account advection, dispersion and other effects on movement of contaminants in groundwater systems.

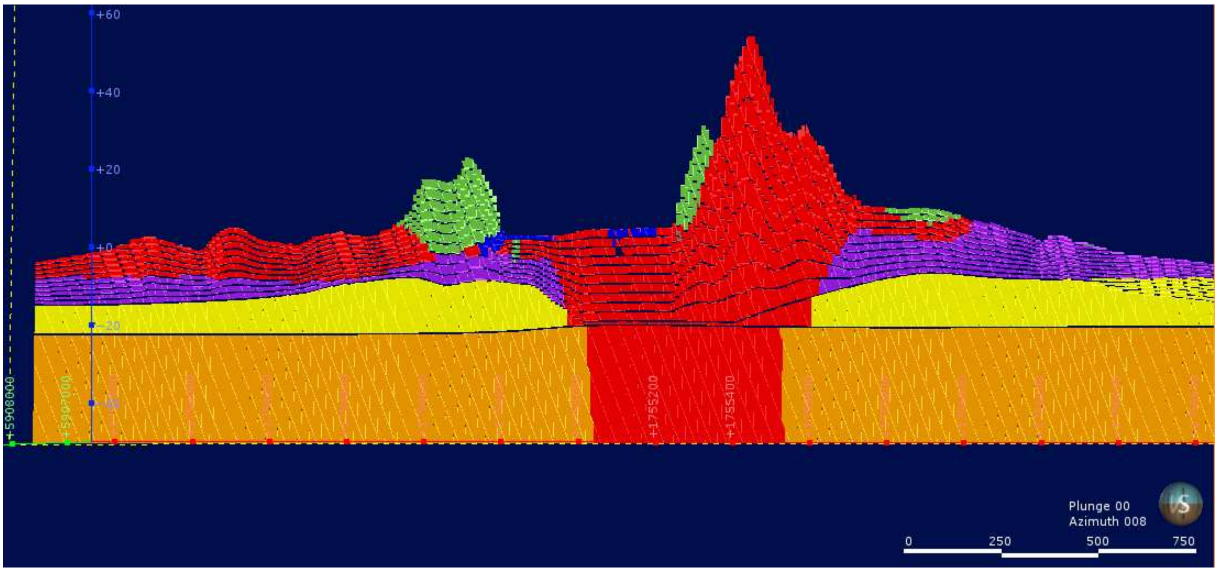

Figure 5. Groundwater flow model layer zonation in Leapfrog (same location as Figure 4). Colours represent different lithological units.

2.3.2 Model Properties and Calibration

Recharge zones were established in the model for both the facility (i.e. to represent the potential leachate leakage) and the surrounding area (i.e. rainfall recharge). The assumed leakage rates through the liner base and sides vary with each operational scenario, discussed below. The rainfall recharge rates used for the surrounding fill and other areas of the island were based on values derived from a previous investigation for average conditions.

Recharge concentrations were set using average and peak estimates of leachate concentrations of ammoniacal nitrogen, and the existing background concentrations in the surrounding lithologies based on available groundwater sampling results. Existing fill on site surrounding the future facility has elevated nitrogen concentrations, and was taken into account to predict the total future concentrations at the coast.

The initial estimates of hydraulic conductivity of site lithologies were taken from a previous investigation (URS, 2008b) and then adjusted using PEST 12.3 (Doherty, 2012). The resultant hydraulic conductivity parameter values reflected the lower end of the values reported by URS (2008b).

The groundwater model was calibrated to average groundwater levels, taken from monitoring records since 2006 in several wells across the Island. The model runs showed low mass balance errors and the solver reported low head residuals.

2.4 Embankment Drain Design Using Flow Model

A number of scenarios were run in the 3D model to determine an appropriate location and extent for an embankment drain to capture potential leachate leakage. The key scenarios assessed were:

- Leachate leakage assuming pessimistic case liner performance (i.e. large number and size of defects) during peak biosolids consolidation (i.e. peak leachate generation rates and concentrations);
- Leachate leakage during a failure of the leachate collection system above the liner, with pessimistic liner performance, during peak biosolids consolidation; and
- As above, with the proposed embankment drain added. This scenario was iterated multiple times with different drain locations and extents to optimise placement of the embankment drain.

2.4.1 Modelling results without embankment drain

During normal operations, and assuming an unlikely pessimistic case liner performance during peak biosolids consolidation, the resulting predicted plume of leachate was barely distinguishable from the background concentrations of ammoniacal nitrogen in groundwater. However, it showed several critical flow paths to the north, west and south of the liner area, and the impact of rainfall recharge through the existing fill on the site, on background concentrations.

Virtual monitoring wells were added in the flow model to show the predicted increase in concentration over time at key points along the coast. These demonstrated the concentrations at the coast peaking at lesser concentrations than those predicted at the time of obtaining project approvals.

A further scenario was run that considered the complete failure of the leachate collection system above the liner during the peak biosolids consolidation, and assuming pessimistic liner performance. This rate was applied continuously over 600 years when in reality a failure of the drainage blanket is very unlikely to continue for any extended period without intervention. While the simulated concentrations recorded were highly unlikely, they did assist in identifying the location of the critical flow paths.

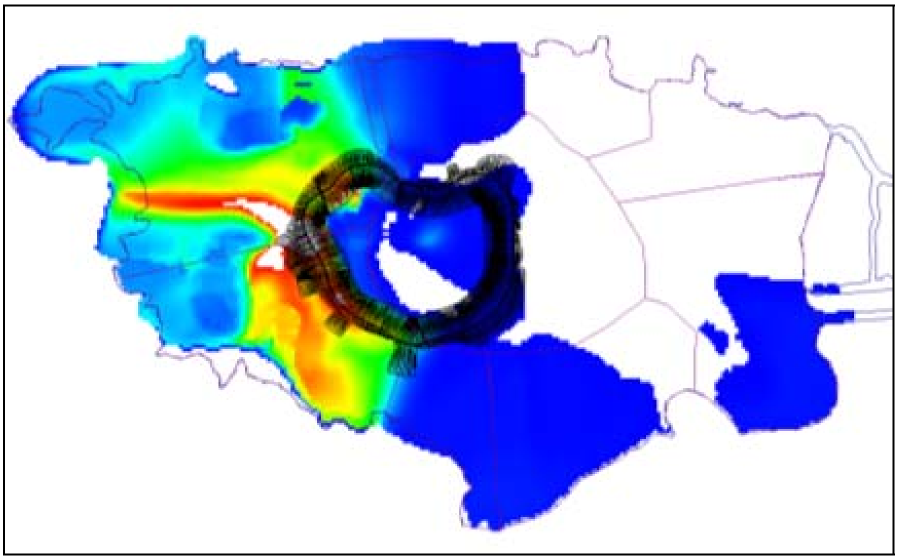

Figure 6. Groundwater Vistas model output showing concentrations of ammoniacal nitrogen in groundwater under pessimistic case conditions, without the embankment drain. The model was used to determine critical flow paths to optimise the embankment drain location.

2.4.2 Addition of embankment drain

The model was then re-run multiple times with an embankment drain added. The extent of the drain boundary in the model was optimised until the leachate plume was intercepted. The drain was located across the previously identified critical flow paths to the west and south of the facility footprint. The model showed the pessimistic case (most unlikely scenario) leachate plume would be almost completely intercepted by the drainage system and overall the predicted concentrations at the coast under this unlikely scenario would be better than were assumed during the approvals process.

3 CONCLUSION

Using the right hydrogeological analysis tools can provide timely and valuable advice to assist design decisions, and make use of all available geological data that has been collected on a site. Leapfrog Hydro is a very effective tool for rapidly creating a geological model from multiple data sources to assist in understanding ground conditions. It has also enabled efficient preparation of a numerical groundwater flow model that can be used to assess groundwater flow paths. Contaminant dispersion add-ons can then be used to assess future groundwater concentrations under a range of operating scenarios.

On the Puketutu Island Rehabilitation Project, Leapfrog was used to rapidly combine a range of valuable existing geological data and information on the site history to create a 3D geological model of the site. This was used to quickly generate a groundwater flow model which enabled design of an embankment drain that would intercept leachate even under highly unlikely future operational scenarios. The use of these tools allowed the design engineers and environmental scientists to find the right outcome for the asset owners and the environment, and to communicate the assessment with other stakeholders. The 3D geological model has also been applied to address a number of other during-construction queries.

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REFERENCES

Chunmiao Zheng, P., Wang, P (1999). University of Alabama "MT3DMS: a modular three dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems: documentation and user's guide"; prepared for U.S. Army Corps of Engineers; monitored by U.S. Army Engineer Research and Development Center.

Doherty, J (2012). "PEST 12.3". Parameter estimation software found at http://pesthomepage.org/Home.php

ESI (Environmental Simulations Incorporated) (2011), "Groundwater Vistas" www.groundwatermodels.com

Giroud, J.P. (1997) "Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects". Geosynthetics International, Vol. 4, No. 3-4, pp.335-348. 1997.

McDonald, M.G., and Harbaugh, A.W (1984) "A modular three-dimensional finite-difference groundwater flow model" U.S. Geological Survey Open-File Report 83-875, 528 p.

URS (2008a) "Technical Report C, Biosolids Leachate Production and Composition." Report prepared for Watercare Services Ltd. Technical report accompanying resource consent application.

URS (2008b) "Revised Groundwater Assessment". Report prepared for Watercare Services Ltd. Supplementary technical report during resource consent process.