Memorandum

Subject	Solute Transport Modelling (Groundwater), Quarry and Pond Options		
Date	15 February 2024	Pages	12
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CC			
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1.1 Introduction

Advisian (now Worley Consulting) has previously completed a high-level numerical modelling study to evaluate potential excess water infiltration options through either an infiltration pond into predominantly unsaturated surficial sands (**pond option**) or into a partially saturated sandstone aquifer situated underneath surficial sands and fericrete (the latter forming an intervening low-permeability layer - aquitard). Since under the latter option fericrete/silcrete material is to be removed for construction purposes, this option is referred to as the **quarry option**.

It is likely that water qualities/salinities of water to be infiltrated and the receiving groundwater in the sandstone aquifer are different, with an assumption that infiltrated water has comparatively higher TDS. It is therefore important to understand the fate and transport of infiltrated water with higher TDS water in the event this option was to be pursued in the future.

This memorandum presents the results of solute transport modelling of infiltration of higher TDS into the sandstone aquifer (quarry option). **Since the surficial sand aquifer is practically unsaturated, solute transport was not modelled for the pond option as there would not be any mixing processes in place**.

This memo has to be read in conjunction with the Order of Magnitude infiltration pond study, assembled by Advisian (2023) document, **Infiltration Pond Study Rev0, issued on 28 September 2023**, which outlines the hydrogeological and geotechnical conceptual understanding, assumptions considered and describes numerical modelling details. It also provides recommendations for further investigations.

1.2 Methodology

The groundwater flow model used to simulate the quarry infiltration option was updated with solute transport modules to simulate the plume migration from the quarry into the sandstone aquifer and its capture by the mining pit. The following updates to the groundwater flow model were applied to develop the solute transport simulation:

- The recharge (RCH) package was used to represent infiltration into the sandstone aquifer. The recharge rates are the equivalent of net inflows from the LAK package to groundwater calculated from the flow model, which ensures that the solute transport model has the same groundwater infiltration rates as the flow model.
- The grid cells representing the quarry in model layers 1 and 2 are assigned with a high hydraulic conductivity value (1,000 m/day) and a specific yield value of 1 – to represent water in the quarry.
- Concentration of the infiltrated water (through RCH package) was specified to be 3,740 mg/L. This value is based on pumping test data in close proximity to the proposed pit at WINU0917 (November 2023). The input concentration can be, in reality, different and can also vary in time in response to dewatering drawing water of different qualities.
- Concentration from the GHB inflow boundary representing the contribution from regional throughflow was specified to be 290 mg/L.
- Initial concentration of the sandstone aquifer is specified to be 290 mg/L based on groundwater sampling of WIDI0020.
- The longitudinal, transverse, and vertical transverse dispersivity values were specified to be 200, 20, and 2 m, respectively. The longitudinal dispersivity was representative of approximately 5% of plume length, with order of magnitude lower values for transverse components of dispersivity tensor.
- Porosity of sandstone aquifer is specified to be 0.05.

The same four scenario simulations with different combinations of hydraulic conductivity values of the upper sand and sandstone (Table 1) used in the flow model were also employed to simulate the plume migration and the associated mass loss to the open pit, which is situated downgradient of the quarry.

The simulation threshold of the flow model is year 2050, however this was extended to year 2200 for solute transport modelling, mainly to assess the time for the plume to dissipate from the peak value to the background value in the sandstone aquifer.

Input from infiltrated water to the quarry was set to be zero after year 2050, while the pit was maintained as a sink for the duration of simulation.

Table 1 Hydraulic conductivity values of the four scenarios

Scenario	K of Upper Sand (m/day)	K of Silcrete (m/day)	K of Sandstone (m/day)
Scenario 1	Kh = Kv = 5	Kh = Kv = 0.004	Kh = 2; Kv = 1
Scenario 2	Kh = Kv = 5		Kh = 1; Kv = 0.5
Scenario 3	Kh = Kv = 5		Kh = 10; Kv = 5
Scenario 4	Kh = Kv = 20		Kh = 1; Kv = 0.5

Monthly discharge rates of water disposed into pond or quarry is reproduced from Advisian 2023 as follows (Figure 1):

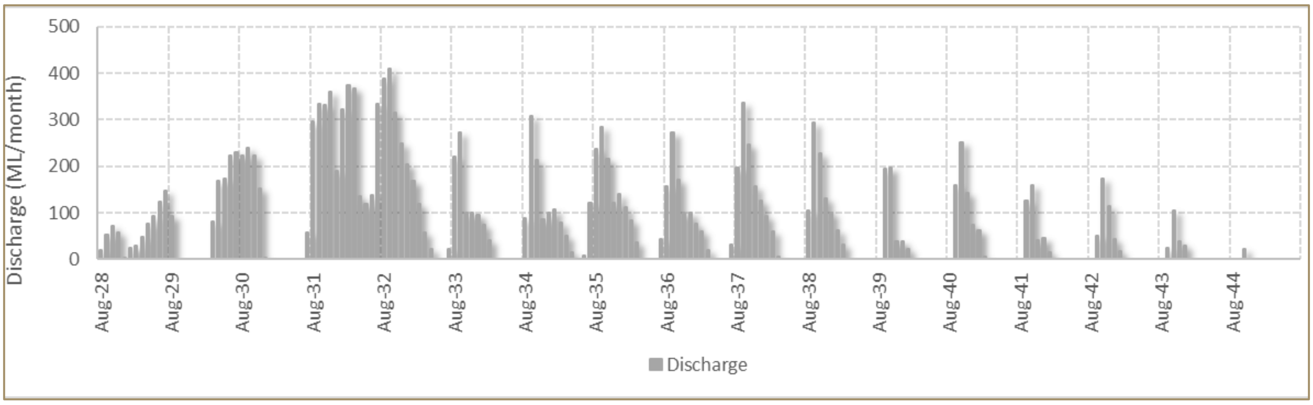

Figure 1 Monthly rates of water to be discharged into pond(s) or quarry

1.3 Groundwater quality considerations relevant for solute transport simulations

The hydrogeological conceptual setup of infiltration for both the pond and quarry options, including the technical details for construction are described in Advisian (2023). Essentially the pond construction assumes developing embankments around the current ground surface (in order to not reduce the thickness of the underlying surficial sand unit. Quarry options involves excavation of surficial sands, silcrete/ferricrete layer down to the top of the underlying aquifer, to an estimated depth of 30m bgl.

Key considerations for hydrogeochemical assumptions are:

- Top surficial sand layer, relevant for the pond option, is understood to not contain groundwater. In theory, there may be limited groundwater available after infrequent occurrences of cyclonic-related rainfall. The fate of that minor volume is unclear, part of it may be evaporated while other parts may leak to the underlying sandstone aquifer where pathway for this connectivity may occur. The existing drilling data confirm that surficial sands are unsaturated.
- Surficial sands represent a relatively homogeneous material (fine sand) composed of relatively inert quartz grains. There is no available evidence of significant clayey materials. It is therefore assumed that sand reactivity is minor, possibly limited to minor occurrence of ferric hydro-oxides that may be present in some locations. In any case, our solute transport simulations are limited to TDS (salinity), for which reactive transport considerations are not necessary.
- The underlying layer of silcrete/ferricrete practically forms a no flow boundary for further vertical migration of solutes (we are not aware of confirmed flowpaths between the surficial sand and the deeper sandstone aquifer separated by silcrete/ferricrete layer). The only sink for solutes in the current model is therefore the mining pit and evapoconcentration where mounding causes groundwater to be close to the ground surface. Extinction depth for evapotranspiration is 0.5m.
- Release of water into the pond will be similar to flood conditions resulting in quick saturation of surficial sands (due to its relatively high permeability and effective porosity), any unsaturated flow effects are not considered as these would be of a very short duration. A progressively growing

mound of groundwater will develop due to incidences of infiltration events. The mound will grow radially from the pond with a segment of it eventually captured by the mining pit.

- As with the pond option, reactivity of sandstone aquifer matrix is considered to be minor with respect to overall dissolved solids. Due to the presence of water in the sandstone aquifer with TDS approximately an order of magnitude lower than discharge, mixing processes, in contrast with pond options, will be important. A portion of discharge introduced through quarry into the sandstone aquifer will be captured by the open pit at concentrations determined by mixing with ambient groundwater.

1.4 Results

1.4.1 Quarry Scenario

Comparison of cumulative volumes from LAK and RCH packages to groundwater

The cumulative volumes from the LAK and RCH packages to groundwater are compared to ensure that the RCH approach used in the solute transport model is identical to the inflows calculated by LAK package used in the flow model.

Figure 2 shows the comparison for the four scenarios, which suggests that the inflows are the same for the RCH approach used in the solute transport model and LAK package used in the flow model.

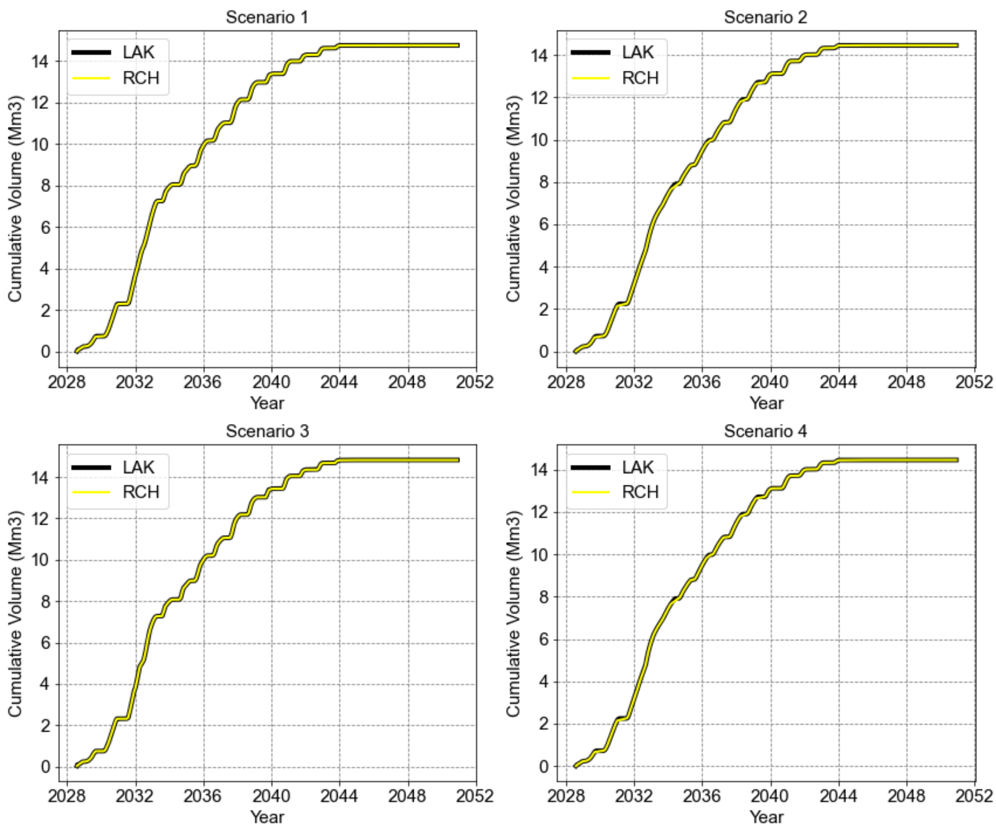

Figure 2 Comparison of cumulative volume from LAK and RCH packages to groundwater

Mass loss to the pit

The cumulative mass losses to the open pit from the infiltrated water for the four scenarios are shown in Figure 3. At the end of year 2050, scenario 3 has the highest cumulative mass loss to the pit of about 67 Tonne, whereas scenarios 2 and 4 have the lowest cumulative mass loss to the pit of about & Tonne.

This is mostly due to that sandstone aquifer of scenario 3 is the most permeable whereas it is the least permeable for scenarios 2 and 4, and therefore groundwater inflow to the open pit is the highest for scenario 3 while lowest for scenarios 2 and 4.

Predicted groundwater concentration captured by open pit

Simulated time-varying concentrations at an observation location at the rim of pit for the four scenarios are shown in Figure 4.

Peak concentration is about 3,500 mg/L for all scenarios. It takes about 22 years for the concentration near the pit to dissipate from its peak value to the background value of 290 mg/L under scenario 3.

However, this process is much longer for other scenarios: about 100 years under scenario 1 and more than 100 years for scenarios 2 and 4. Potential plume migrates faster under scenario 3 because of the highest K considered in scenario 3 among all scenarios.

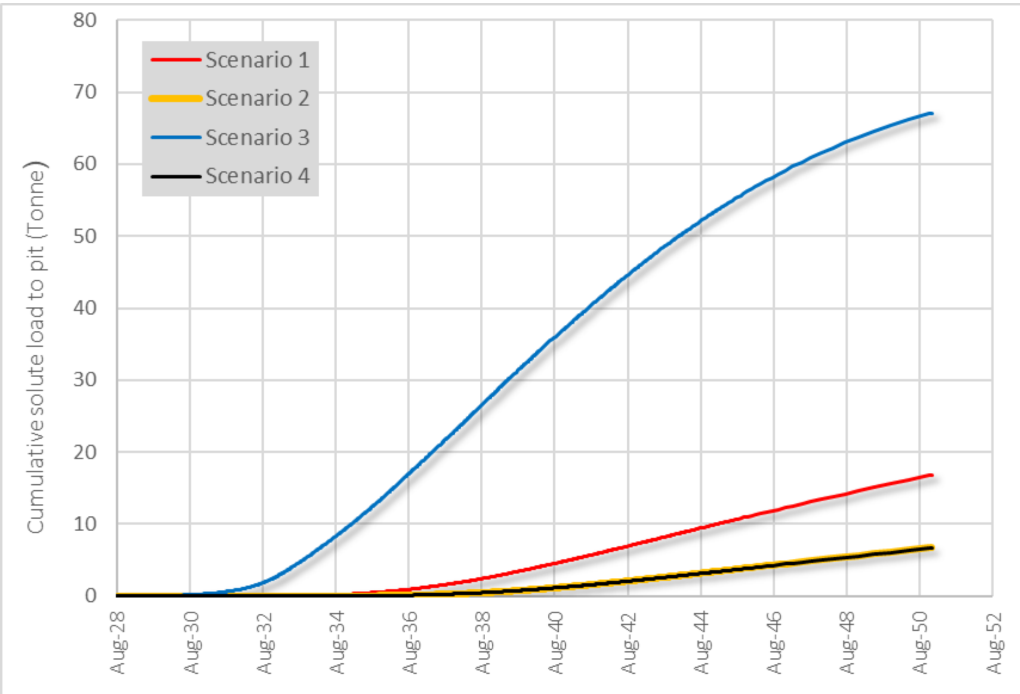

Figure 3 Cumulative solute load to the open pit for the four scenarios

Plume evolution

Figure 4 to 7 shows the concentration plume migration process from 2040 to 2200 for the four scenarios. The results suggest:

- At year 2040, the highest concentration is more than 3,500 mg/L for all scenarios (Figure 5 to Figure 8). Concentration plume dissipates since then and varies for different scenarios.
- The plume dissipation rate for scenario 1 is between that of scenario 3 and scenarios 2 and 4 (Figure 4). Plume concentration as it enters the pit in year 2100 is predicted at about 1,300 mg/L but it reaches the background value of 290 mg/L before 2200.
- Scenarios 2 and 4 show similar plume migration progress from 2040 to 2200 (Figure 6 and Figure 8) because both scenarios use the same hydraulic conductivity of the sandstone aquifer. Groundwater plume concentration as it enters the pit at year 2200 is still higher than the background value of 290 mg/L. Both scenarios show the slowest plume dissipation.
- Scenario 3 exhibits the quickest plume dissipation (Figure 7) due to the highest hydraulic conductivity of the sandstone aquifer used among all scenarios. Plume concentration near the pit declines to the background value of 290 mg/L before year 2100.

Figure 4 Groundwater (plume) concentration before entry into the pit

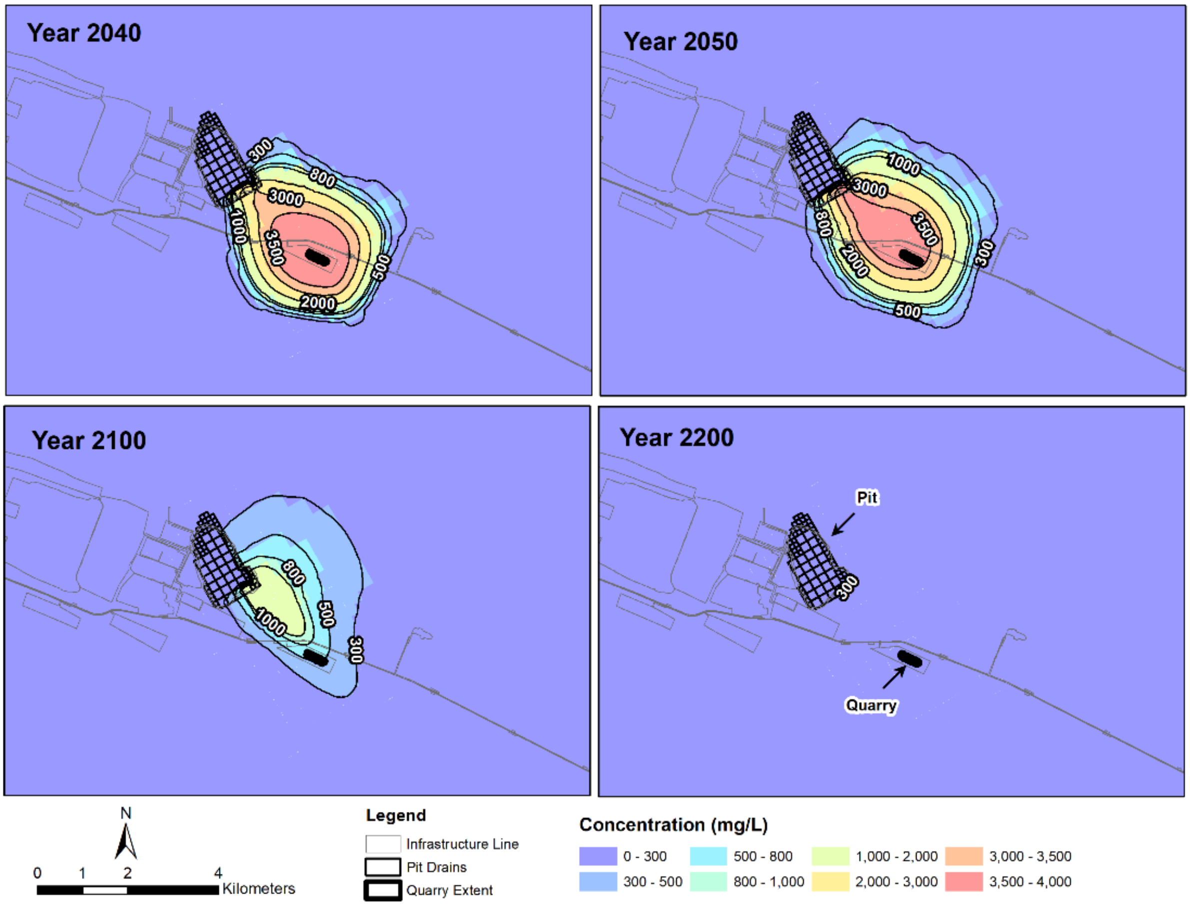

Figure 5 Evolution of plume migration process under scenario 1

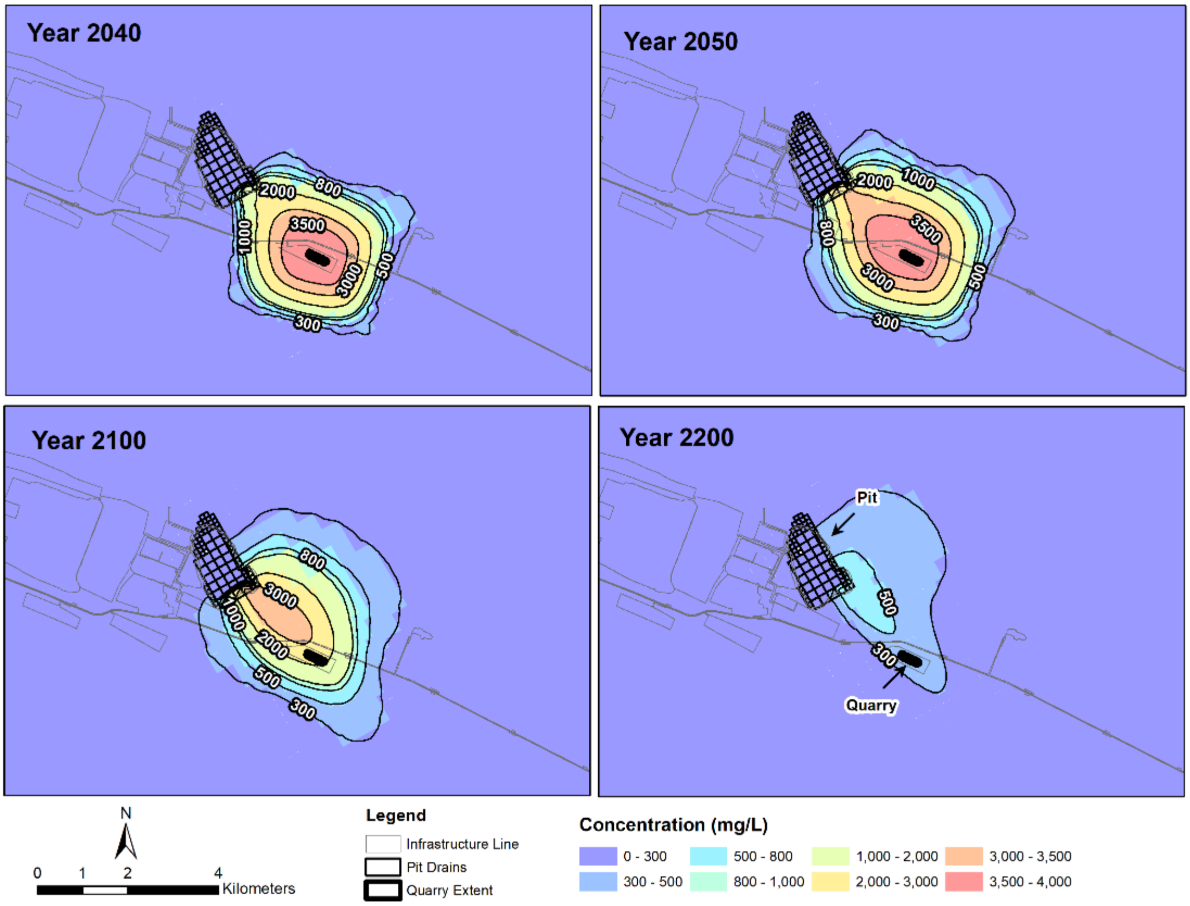

Figure 6 Evolution of plume migration process under scenario 2

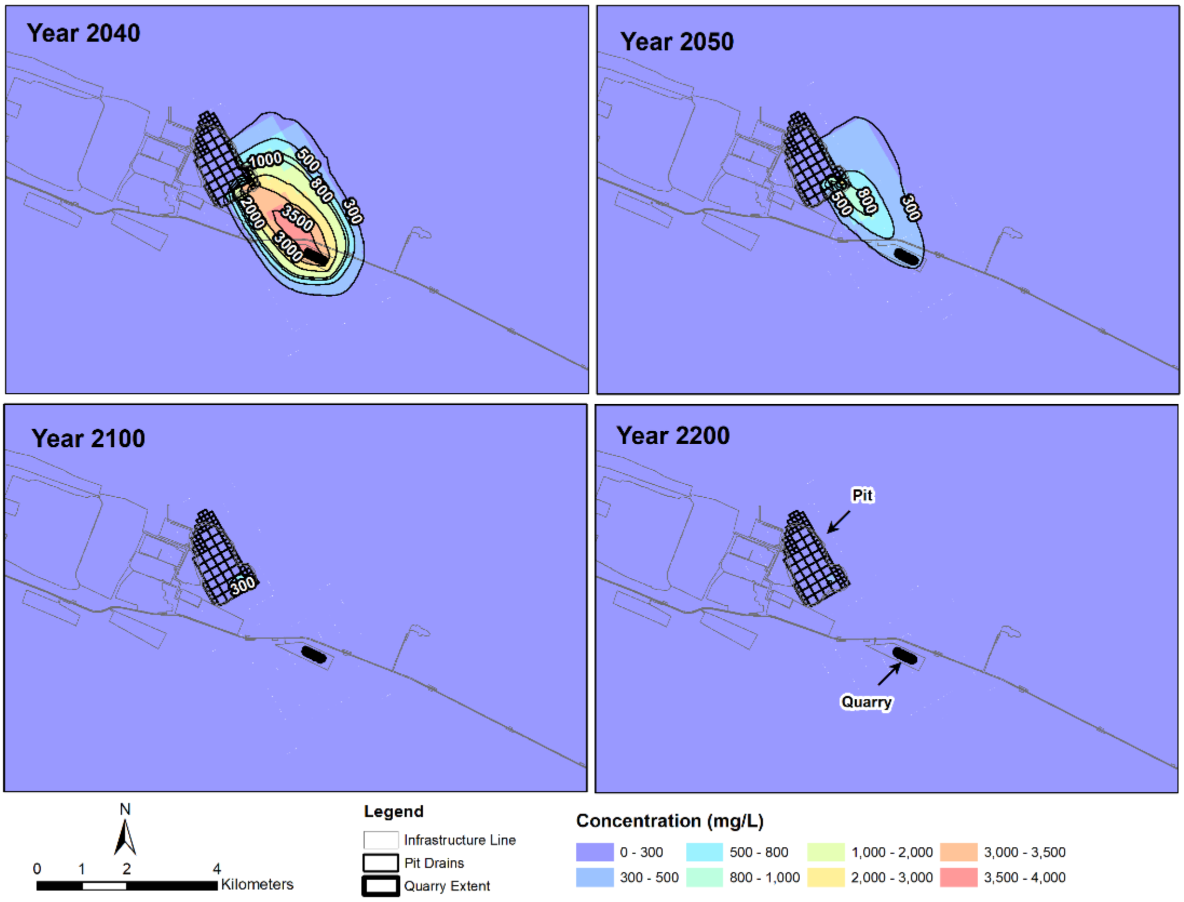

Figure 7 Evolution of plume migration process under scenario 3

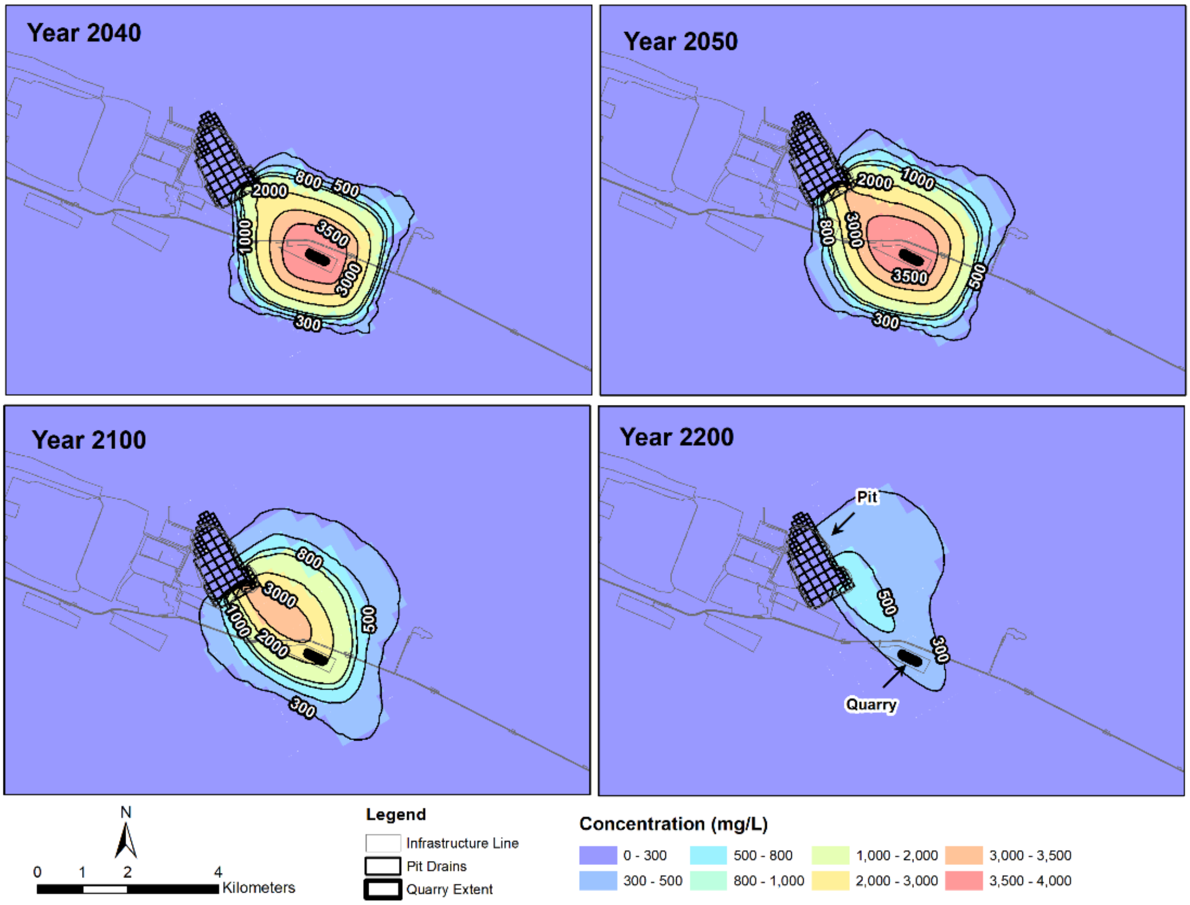

Figure 8 Evolution of plume migration process under scenario 4

1.4.2 Infiltration pond scenario

Groundwater concentrations

This scenario assumes infiltration of water from the pond (or two ponds) constructed on top of the surficial sand layer which currently has no or negligible saturation. No change to salinity of the slug of water introduced from the pond is assumed. The introduced body of water will retain the same salinity as water disposed of into the pond because no mixing processes occur due to the lack of saturation.

The resulting plume will have the same extent as the mound predicted by infiltration modelling, with no concentration gradients – unless infiltrated water concentration would vary in time, however constant concentration is assumed for the purposes of this study.

The extents of bodies of water – essentially plumes with arbitrarily uniform concentration - introduced by infiltration through pond(s), are shown in Figure 9.

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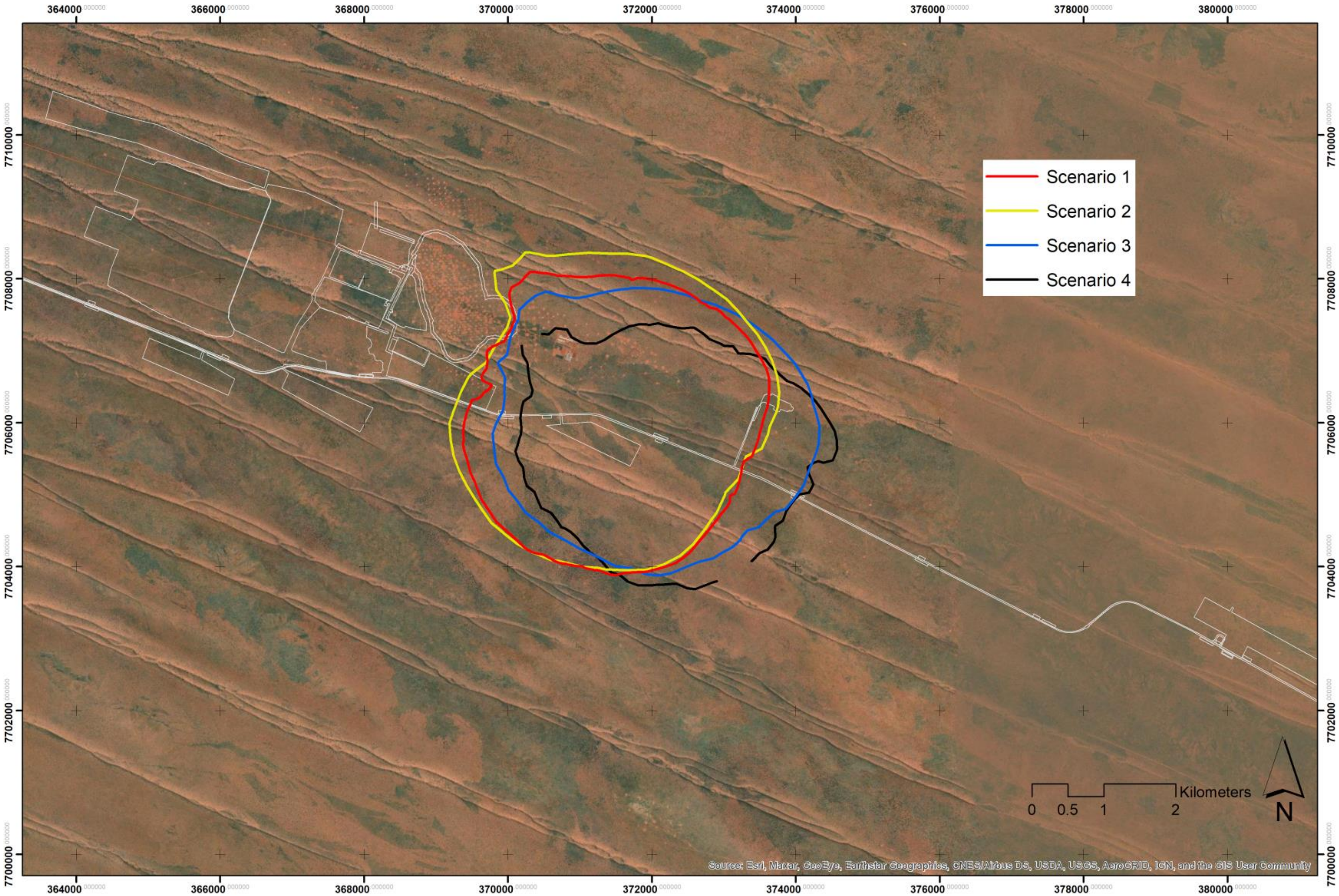


Figure 9 Estimated plume extents for Infiltration Pond Option scenarios

The details of Infiltration Pond Option scenarios are covered in Advisian (2023), however the modelling scenarios are also summarised in Table 2:

Table 2 Numerical modelling scenarios for Infiltration Pond Option

Modelled Scenarios	Pond dimensions (m)	Sand layer thickness (m)	Proportion of discharge	K (Sand) m/day
Scenario 1	Pond 1: 100 x 500	Pond 1: 11-12	Pond 1: 100%	5
Scenario 2	Pond 1: 100 x 500	Pond 1: 11-12	Pond 1: 100%	10
Scenario 3	Pond 1: 100 x 500 Pond 2: 120 x 500	Pond 1: 11-12 Pond 2: 15-16	Pond 1: 50% Pond 2: 50%	5
Scenario 4	Pond 1: 100 x 500 Pond 2: 200 x 500	Pond 1: 11-12 Pond 2: 15-16	Pond 1: 33.3% Pond 2: 66.7%	2

Pit loads from pond infiltration

The return quantities to the pit are smaller in comparison to the Quarry Option, however theoretically at unchanged concentration due to absence of dilution.

The estimated cumulative water returns to the pit are between 44,000 kL (Scenario 4) to 773,000 kL (Scenario 2) over the prediction period (Figure 10):

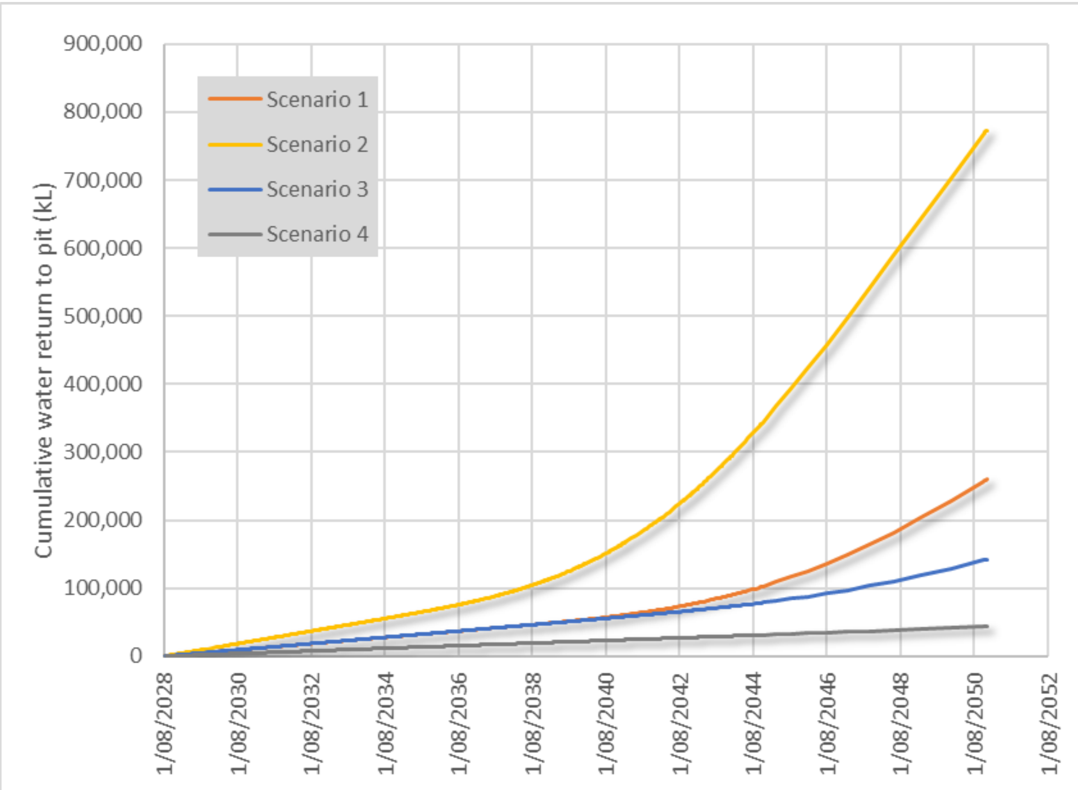


Figure 10 Predicted cumulative water returns to the pit from pond infiltration

The estimated cumulative solute load is presented in Figure 11 and sums up to a total 160 Tonne for Scenario 4 and up to almost 2,900 Tonne for Scenario 2. This is due to hydraulic conductivity contrasts between the two scenarios.

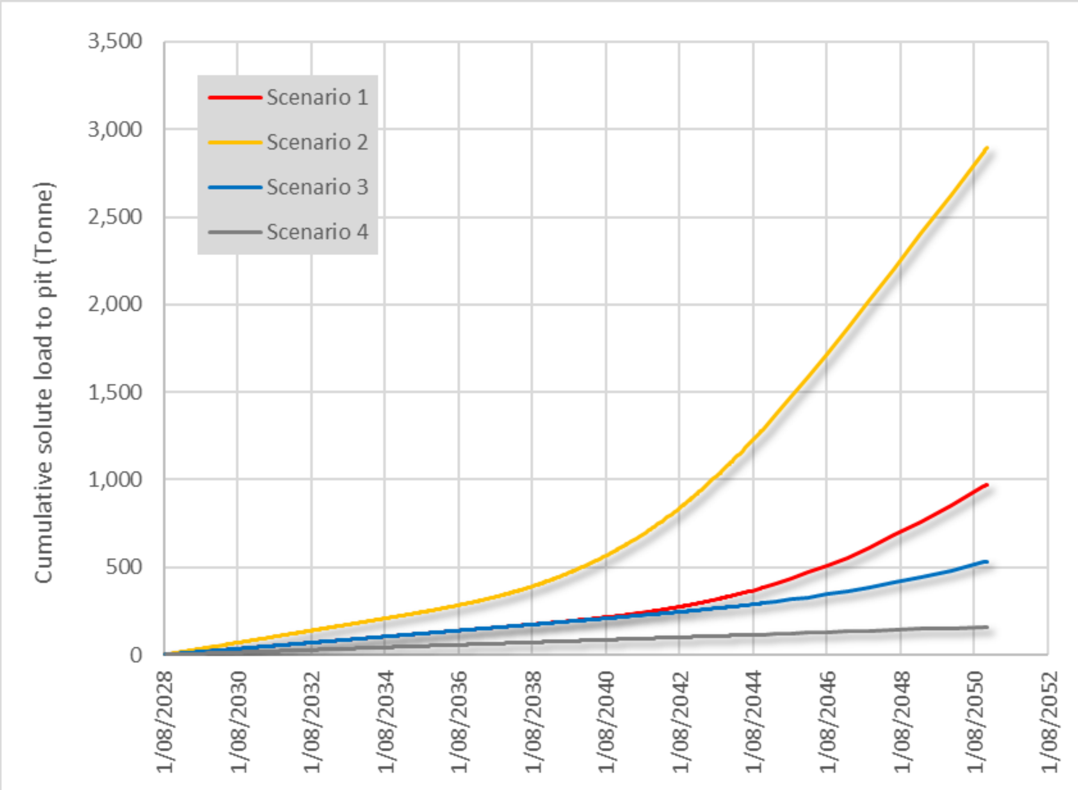


Figure 11 Predicted cumulative solute load reporting to the pit for pond options over LoM

Higher sand hydraulic conductivity will result in larger volumes reporting to the pit and consequently higher solute loads.

Predicted solute loads are directly correlated with input concentrations. This means if input concentrations are 50% of the currently used value of 3,740 mg/L, the resulting solute loads will be also reduced by 50%. Estimates of input concentrations (and their variations with time) are currently not available, but once estimated they could be used to improve estimates of solute loads reporting to the open pit.

Groundwater mounding associated with pond infiltration

Seepage of water from pond(s) will create a groundwater mound radially extending around the pond(s) and elongated in the direction of groundwater flow which will be dominated by the drawing action of pit dewatering.

Due to the variable topography characterised by the presence of NW-SE trending dunes and inter-dune depressions, depth to the groundwater surface – the mound (from ground surface) will vary. It will also vary in response to changes of volumes discharged in time, i.e. application of varying discharge rates.

Indications of depth to water for all four pond infiltration scenarios are presented in Figure 12, for presentation of differences associated with different assumptions. More detailed figures are also provided in Appendix A.

Three different time-slices are presented;

- Infiltration peak rate (February 2033)
- End of regular infiltration (January 2044)
- End of prediction period (December 2050), during that period infiltration was negligible.

Depth to water depictions extracted for pond infiltration scenarios suggest that:

- the interdune depression to the east and north-east of the two ponds are predicted to experience depth to water being less than 10 m associated with mounding.
- Relatively small depth to water will be also present underneath the ponds, during infiltration events.
- The footprint characterising the extent of shallower depth to water will increase in time as more water is introduced into surficial sands.

These predictions are directly dependent on accurate geometry of ground elevations - and also elevations of the base of surficial sands.

The latter is represented in the model as a relatively flat surface which in reality will be subject to local variations (peaks and highs) all of which could then form a different pattern or specific variations to the currently modelled extents. As with other parameters, once the base of surficial sands is better understood it can be used to improve the understanding of depth to water associated with pond infiltration options.

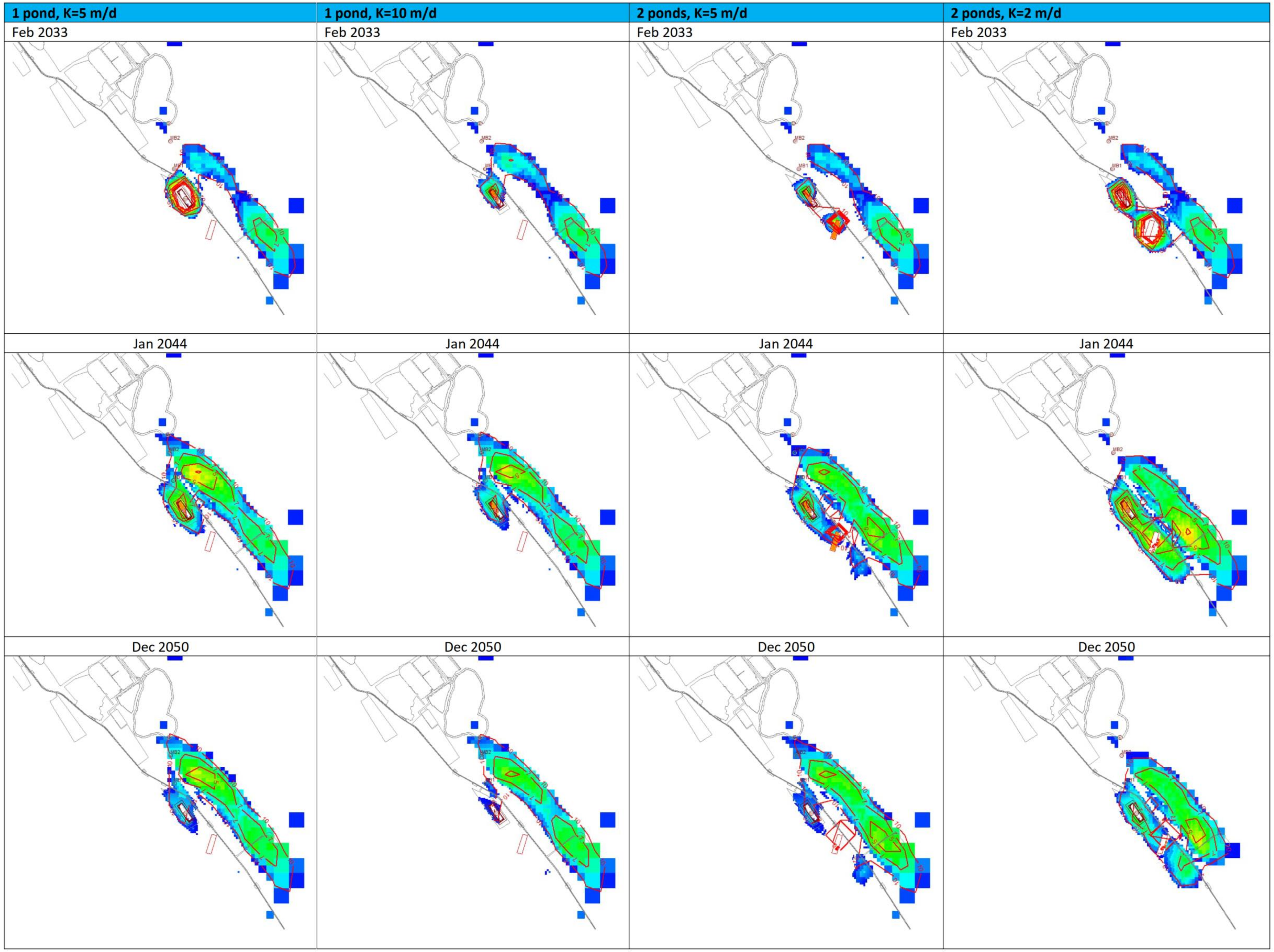
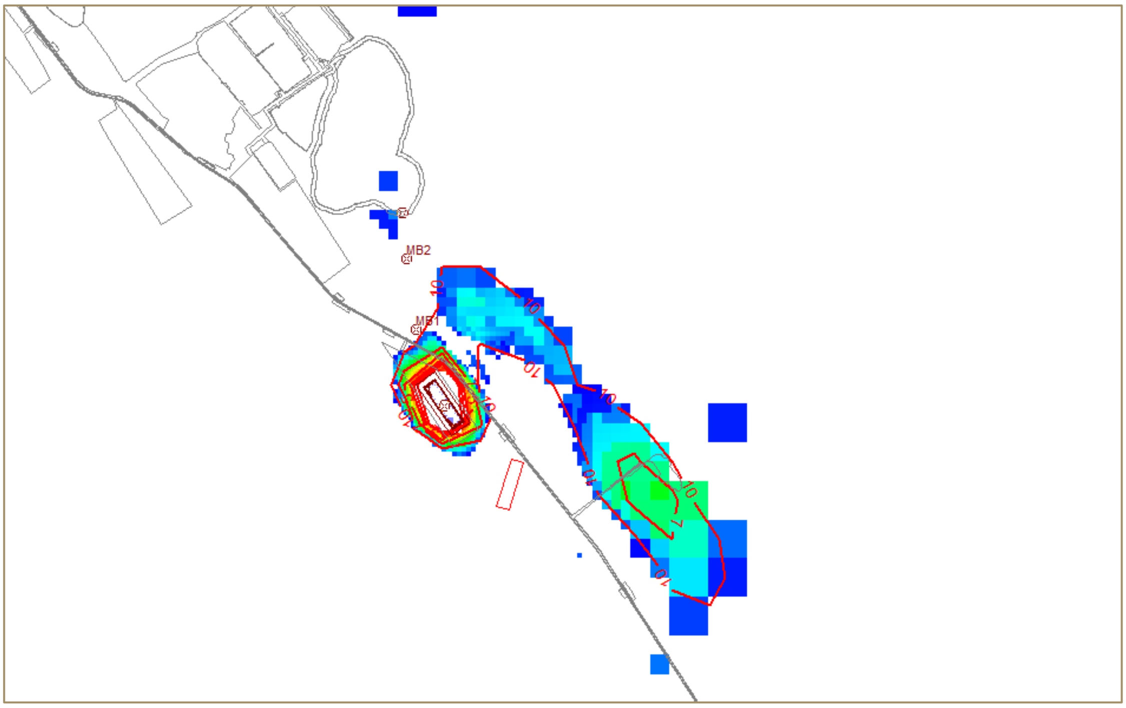


Figure 12 Predicted depth to water footprints associated with mounding from pond infiltration

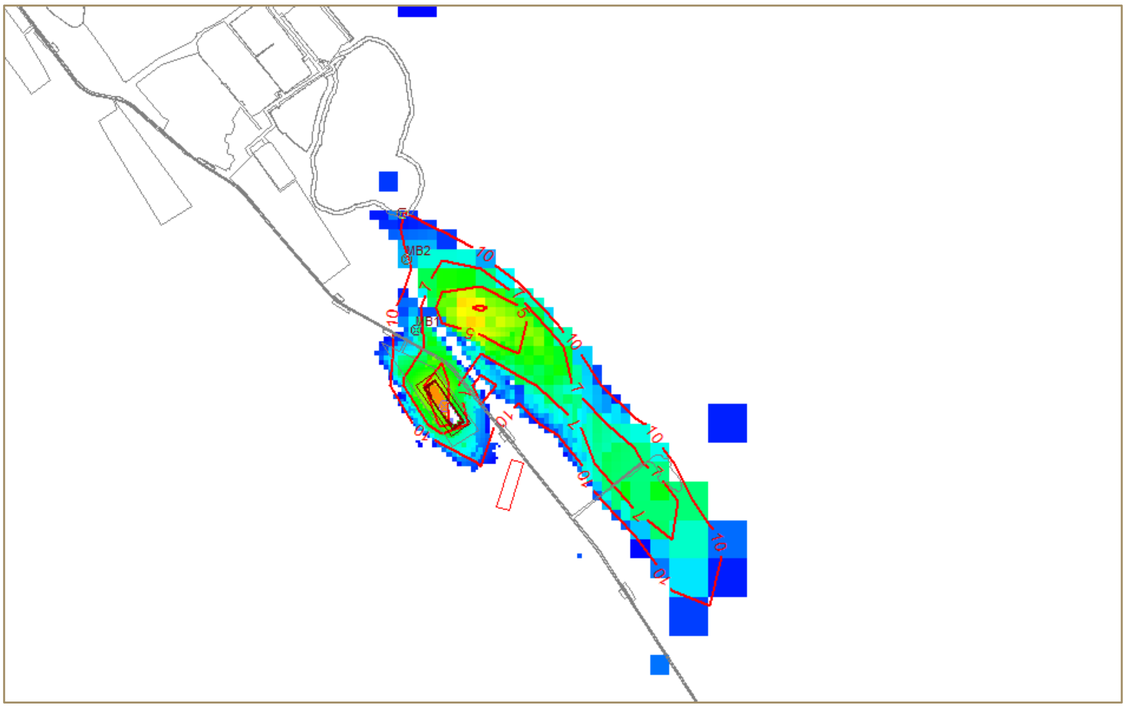
Appendix A Predicted Depth to Water Contour Scenarios (Pond Options)

1 pond, K=5 m/d

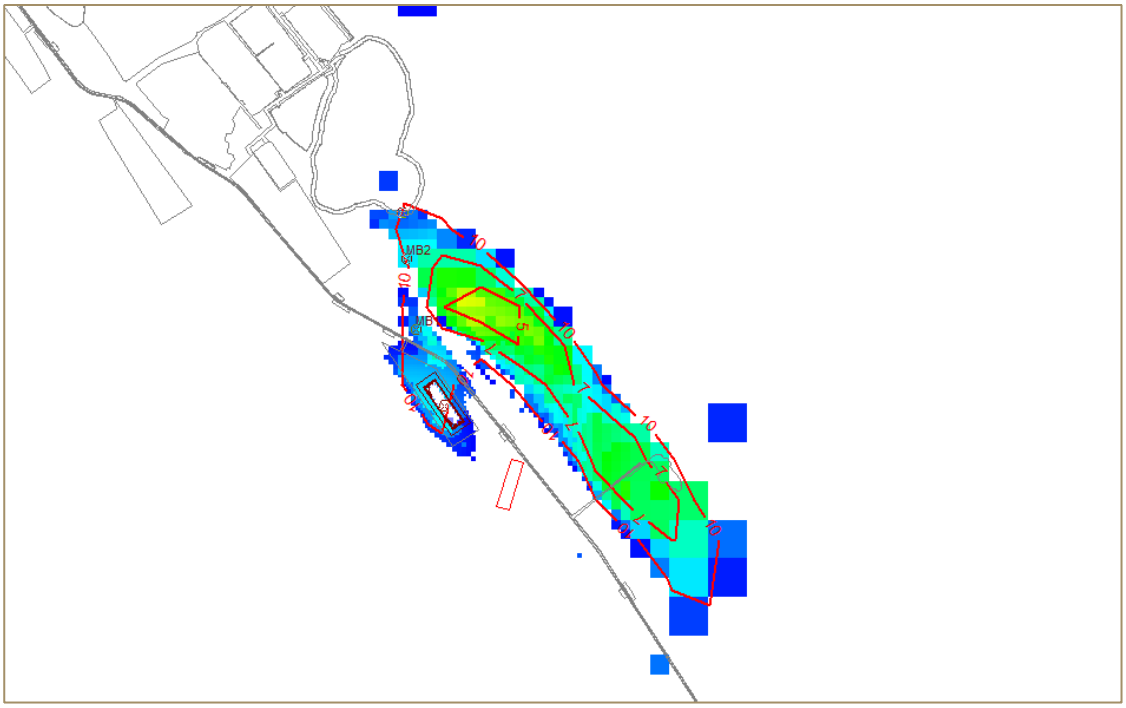
February 2033:



January 2044:

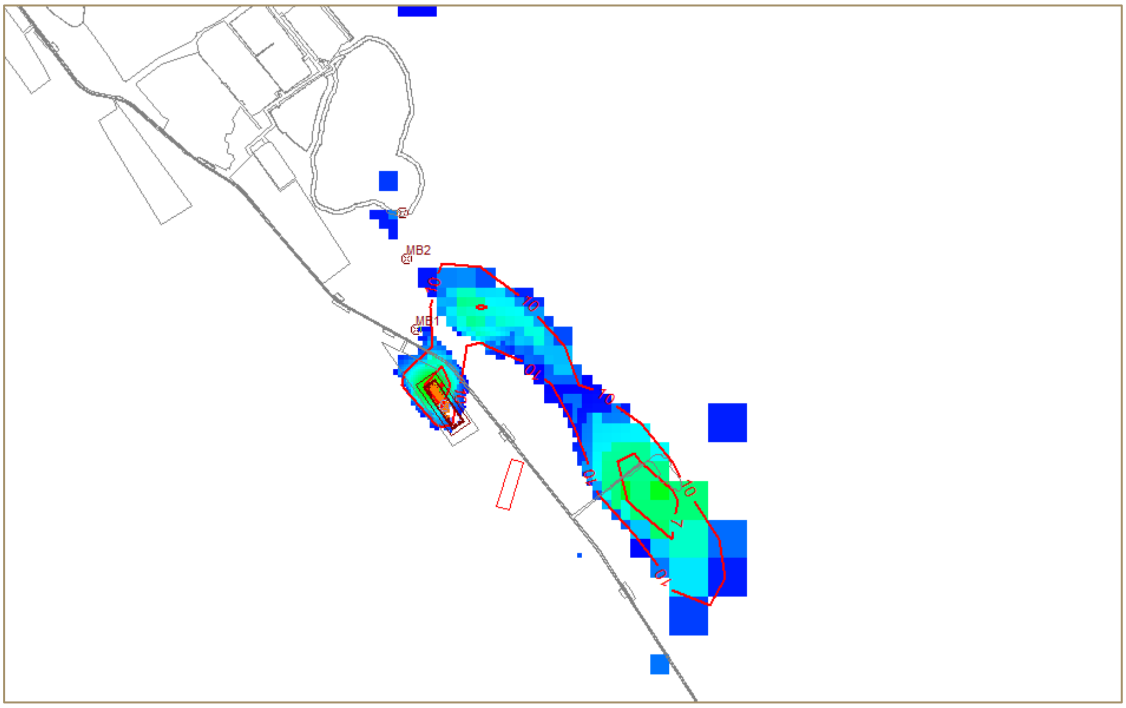


December 2050:

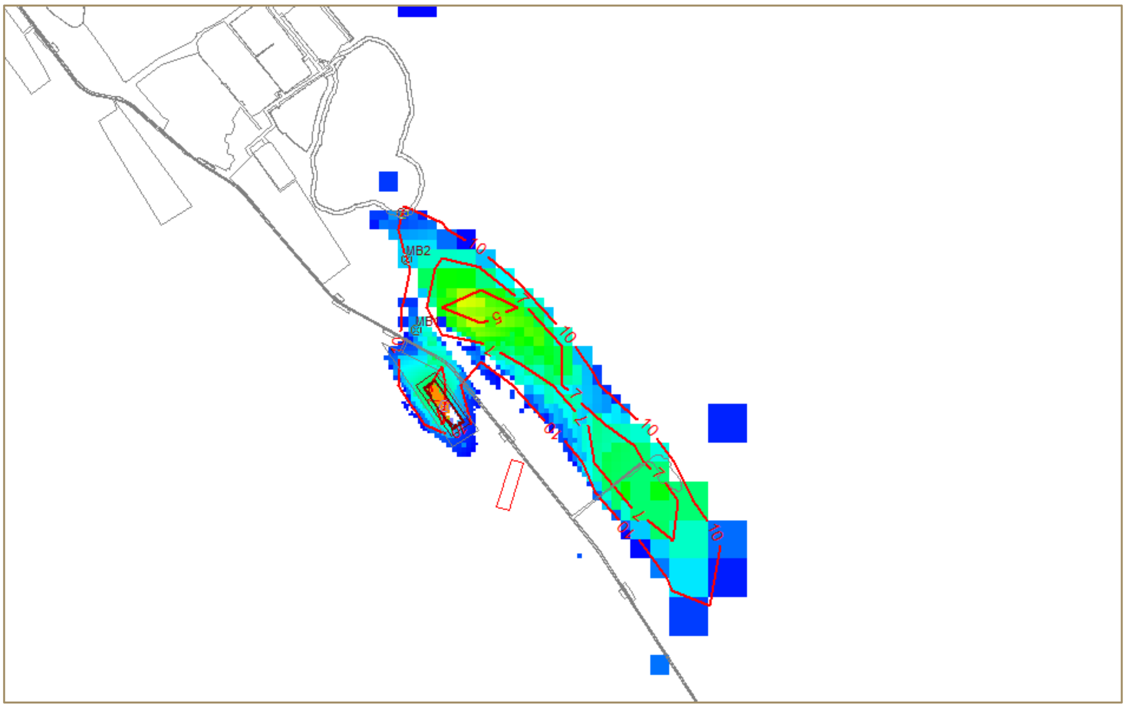


1 pond, K=10 m/d

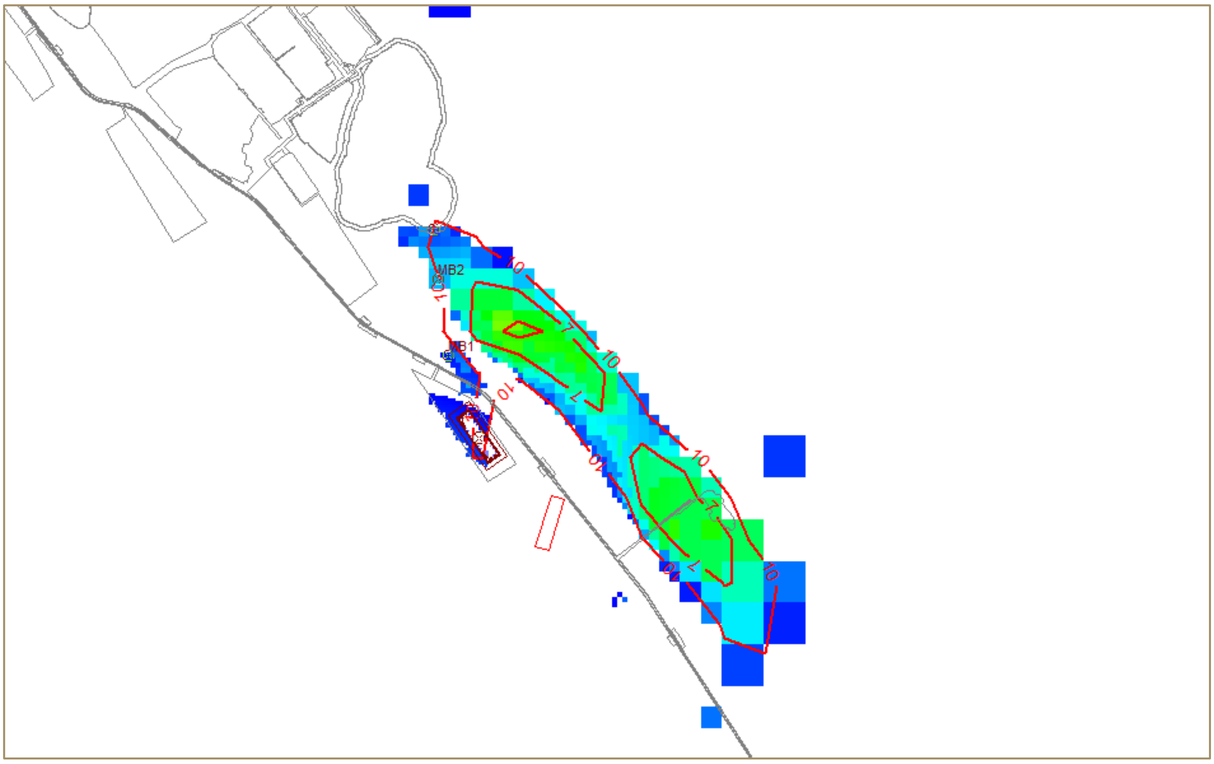
February 2033:



January 2044

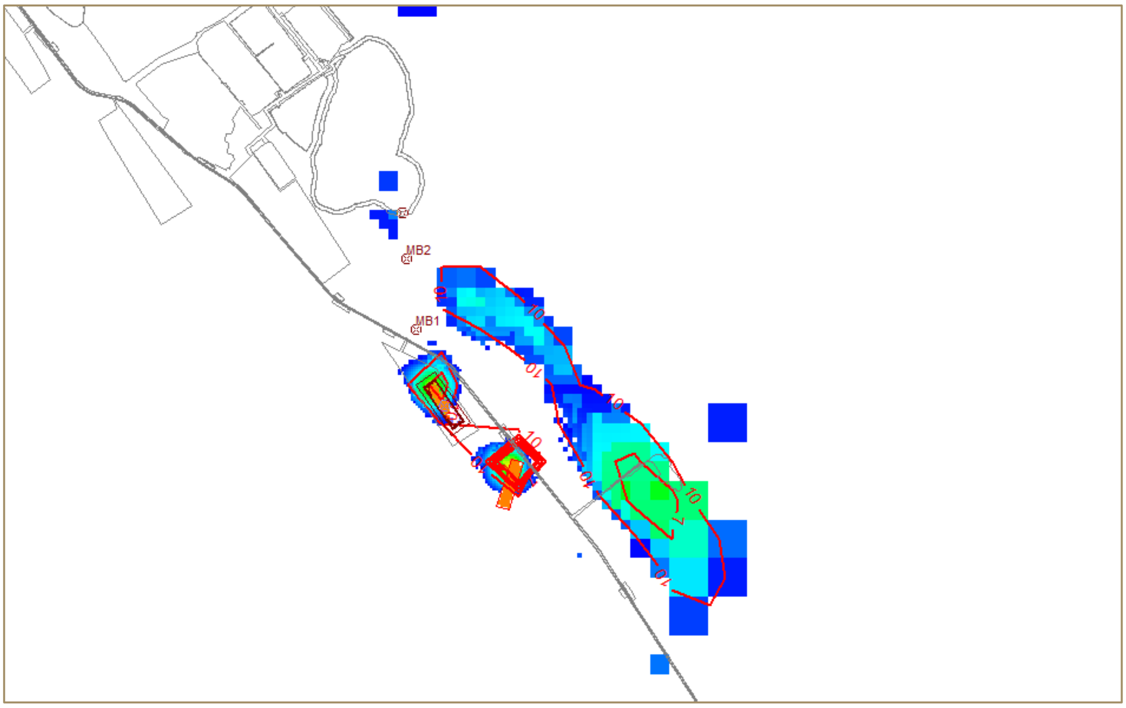


December 2050:

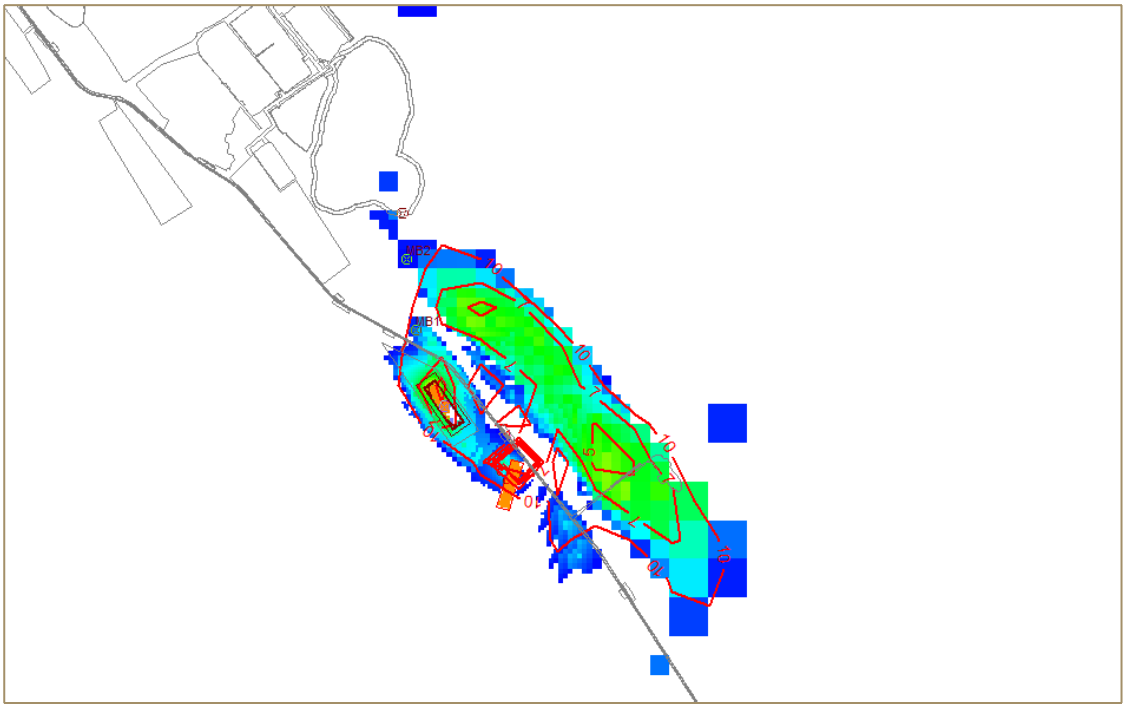


2 ponds, K=5 m/d

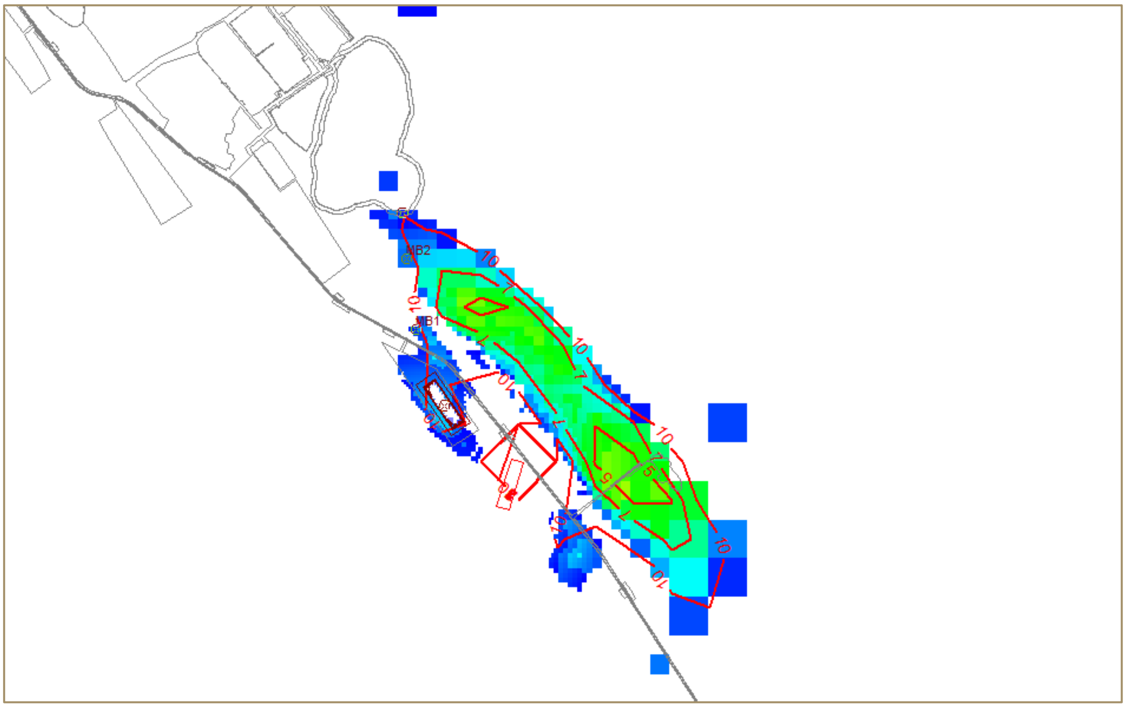
February 2033:



January 2044):

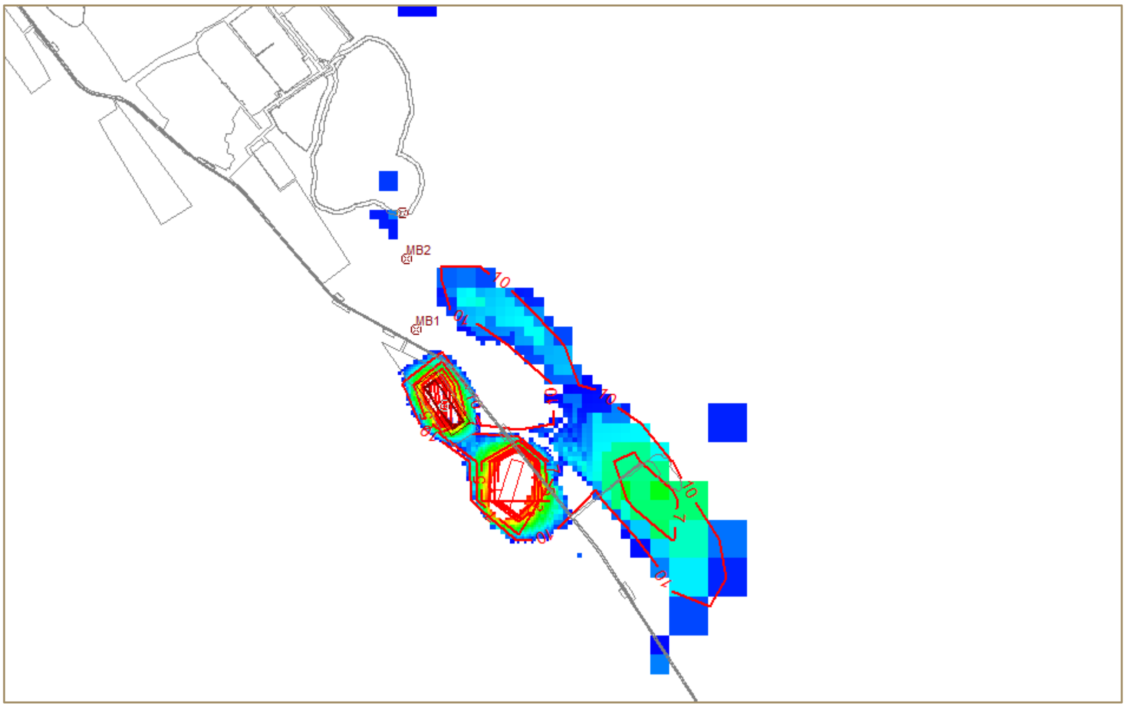


December 2050:

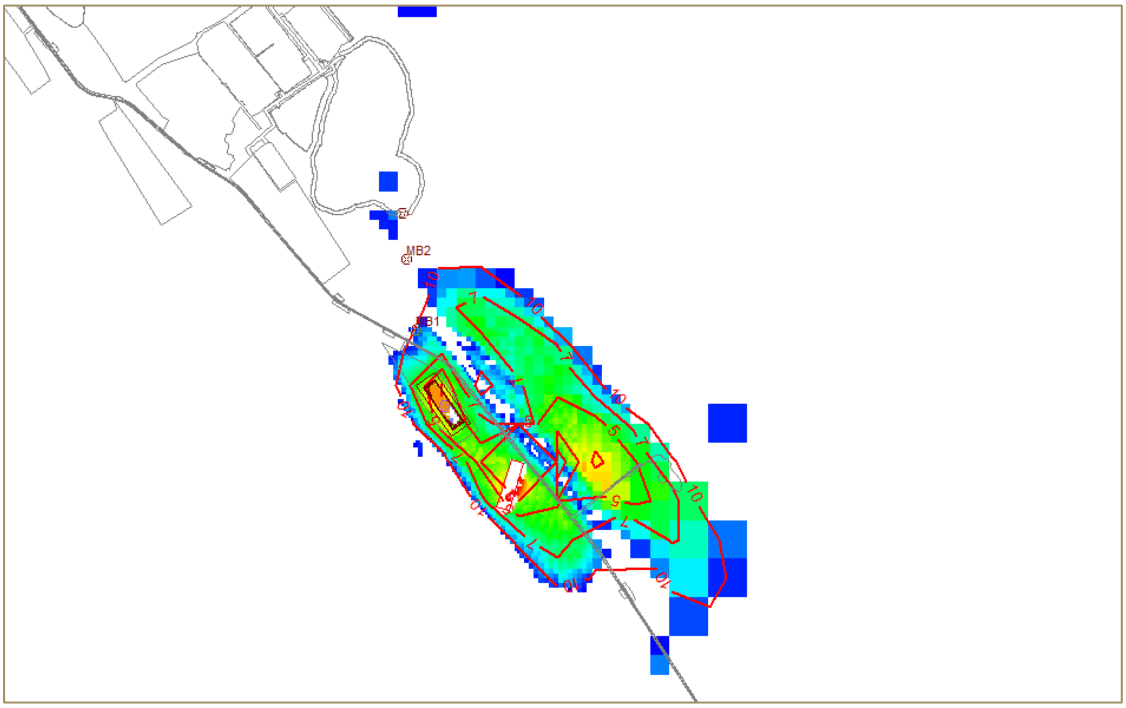


2 ponds, K=2 m/d

February 2033:



January 2044:



December 2050: