PLUME STABILITY ANALYSIS
METHODS OF CONVENIENCE OR METHODS OF NEED?

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OUTLINE

1. Overview of common approaches to assess plume stability
2. Trend analysis methods
3. Concentration contours (heat maps)
4. Ricker Method
5. Groundwater modelling
6. Key takeaways

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CONCEPTS AND METHODS OF PLUME STABILITY ANALYSIS

- Definition (US EPA 1999)
  - Plume stability analysis is the evaluation of monitoring data over time to determine whether a groundwater contaminant plume is **expanding, stable, or shrinking** in terms of its spatial extent and concentration trends, typically as a line of evidence for risk-based management and attenuation-based remedies

Reference:: "US EPA (1999) *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites*, OSWER Directive 9200.4-17P"

- Reference (CSAP 2024)
  - The overall purpose of a plume stability assessment is to use quantitative data to understand the behavior of a groundwater plume with regard to future risks related to groundwater contamination migration. This is accomplished by demonstrating that a groundwater contaminant plume will **not expand or migrate** such that the conceptual site model is no longer accurate or that unacceptable risks are actually or potentially created

Reference: "Groundwater Contamination Plume Stability, Review of Assessment Methods. Submitted to CSAP Society, Submitted by WSP Canada Inc. CA0038290.6960-001-R-Rev1 December 3, 2024"

- Plume stability assessment methods (modified from CSAP 2024)
  - Qualitative methods
    - Concentration vs. time plots
    - Concentration vs. distance plots
    - Concentration isopleth maps
  - Well-by-well analysis methods
    - Mann-Kendall analysis
    - Linear regression
  - Plume-based methods
    - Plume area; Average concentration: Total mass; Centre of mass
    - Mass flux and mass discharge
  - Modelling methods
    - Analytical model
    - Digital model

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SELECTION OF PLUME ANALYSIS METHODS

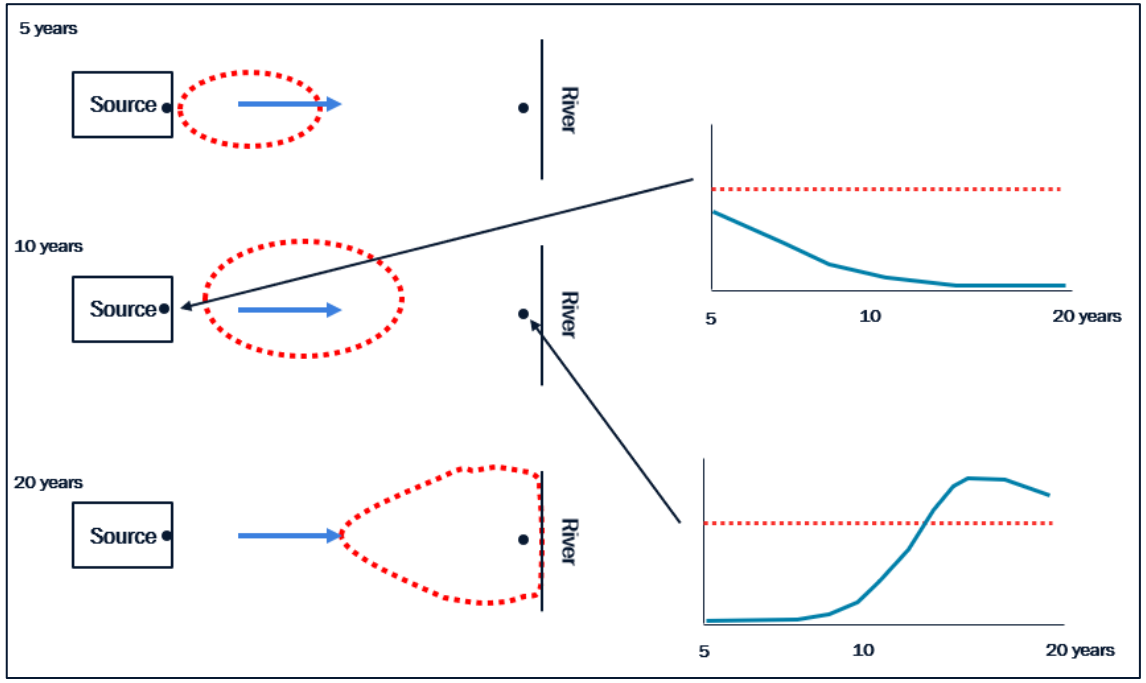
- Principles for method selection
  - Plume stability analysis methods should be chosen based on the project's decision objectives and the amount and quality of available data. Start with simple qualitative and well-by-well trend tools, and add plume metrics, flux analysis, or modelling only when the questions or regulators require that level of detail
- It is critical to clearly define the **objectives** of plume analysis
  - In some cases, plume analysis can be appropriately conducted with only partial delineation (e.g., assessing migration to off-site areas at site boundaries)
  - Changes in plume extent do not necessarily indicate changes in total mass, and vice versa. Both plume extent and plume mass should be evaluated explicitly rather than relying on only one line of evidence
  - Understanding changes in mass is essential for evaluating remediation performance or demonstrating natural attenuation but may not always be required to confirm regulatory compliance

Objective	Method
Plume delineation	Plume delineation maps
Assess trends at points of compliance or site boundaries	Concentration vs. time plots and trend analysis
Assess trends in plume extent (stable / shrinking / expanding / migrating)	Time-sequenced delineation maps to show plume evolution
Assess changes in contaminant mass within the plume	Plume mass estimation using delineation maps and average concentrations (Extent * Average concentration =Mass)
Predict future plume behaviour and test remediation or risk management scenarios	Analytical and numerical groundwater flow and transport models

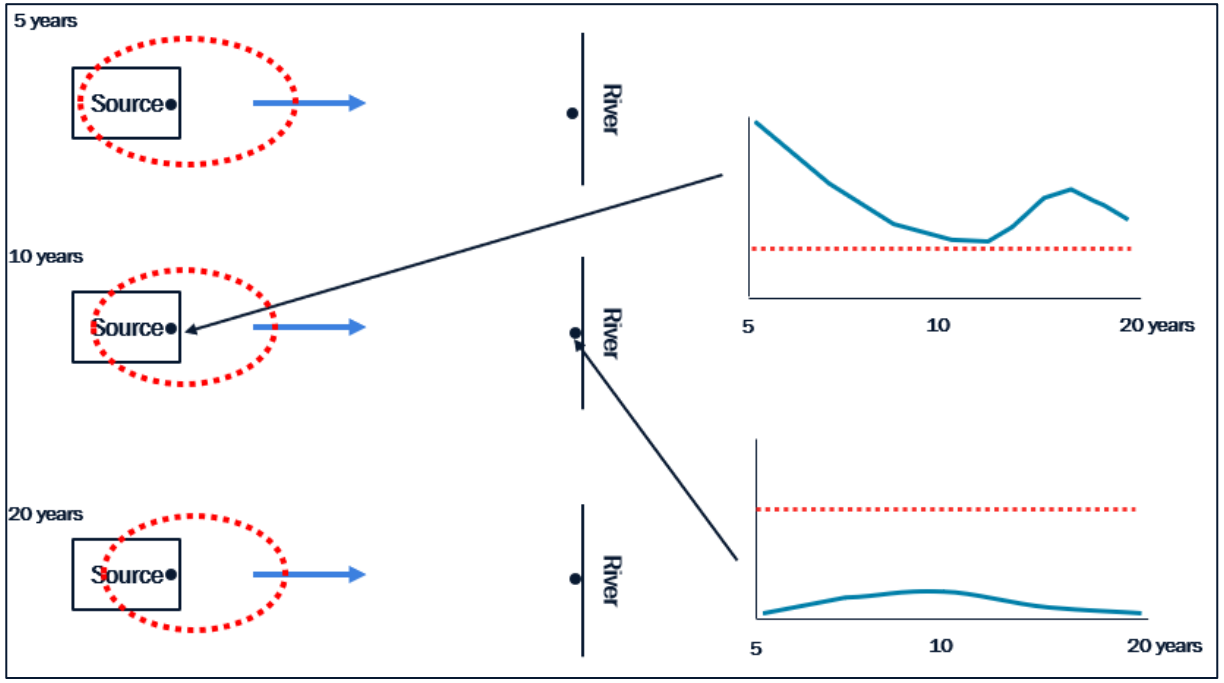
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PLUME EXTENT AND PLUME MASS

- Conceptual example 1
  - There is no changes in total mass of plume, but the plume is expanding and migrating towards receptors

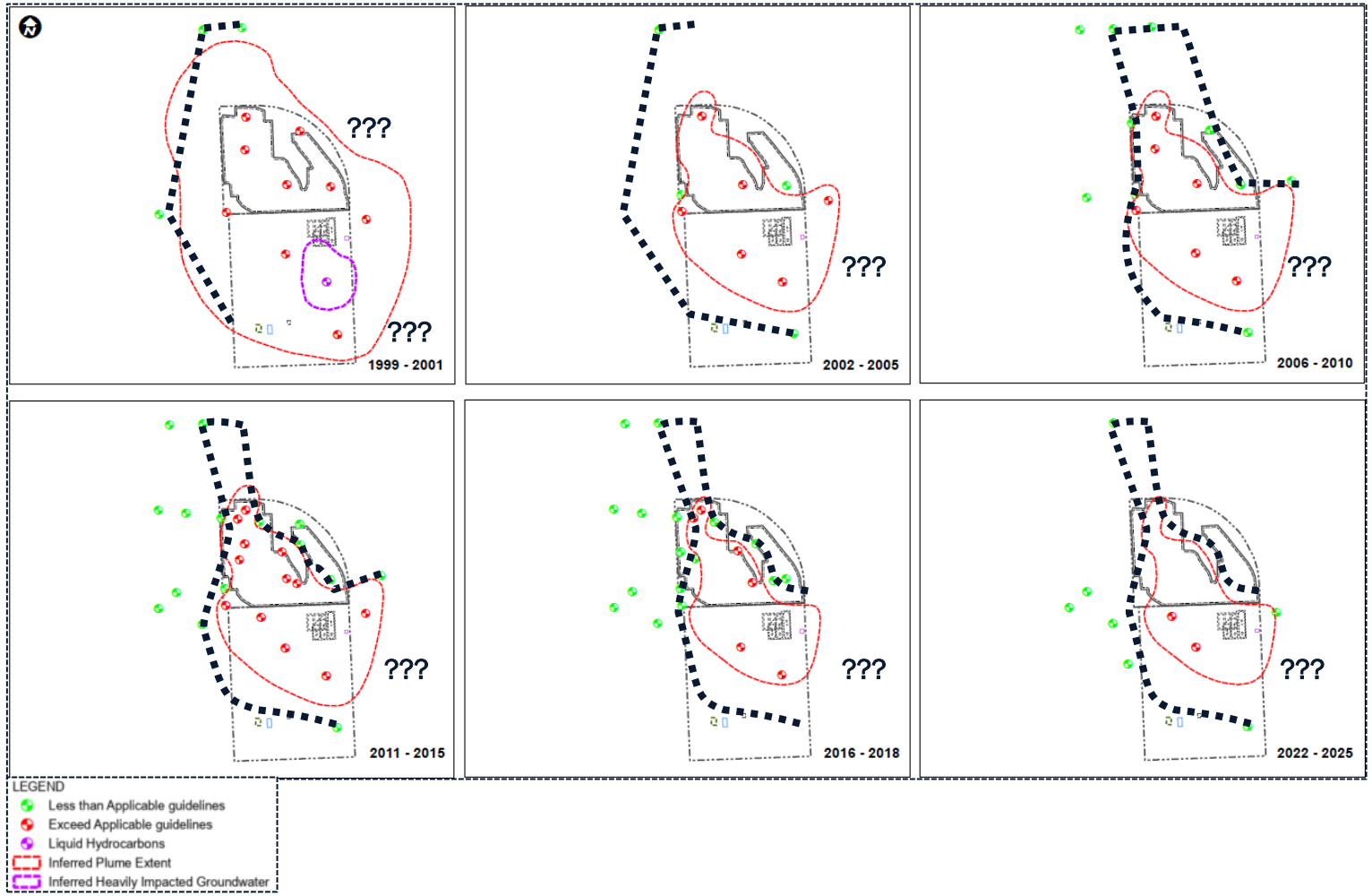


- Conceptual example 2
  - The total mass of plume changes and may increase during a period of time, but the plume extent is shrinking.



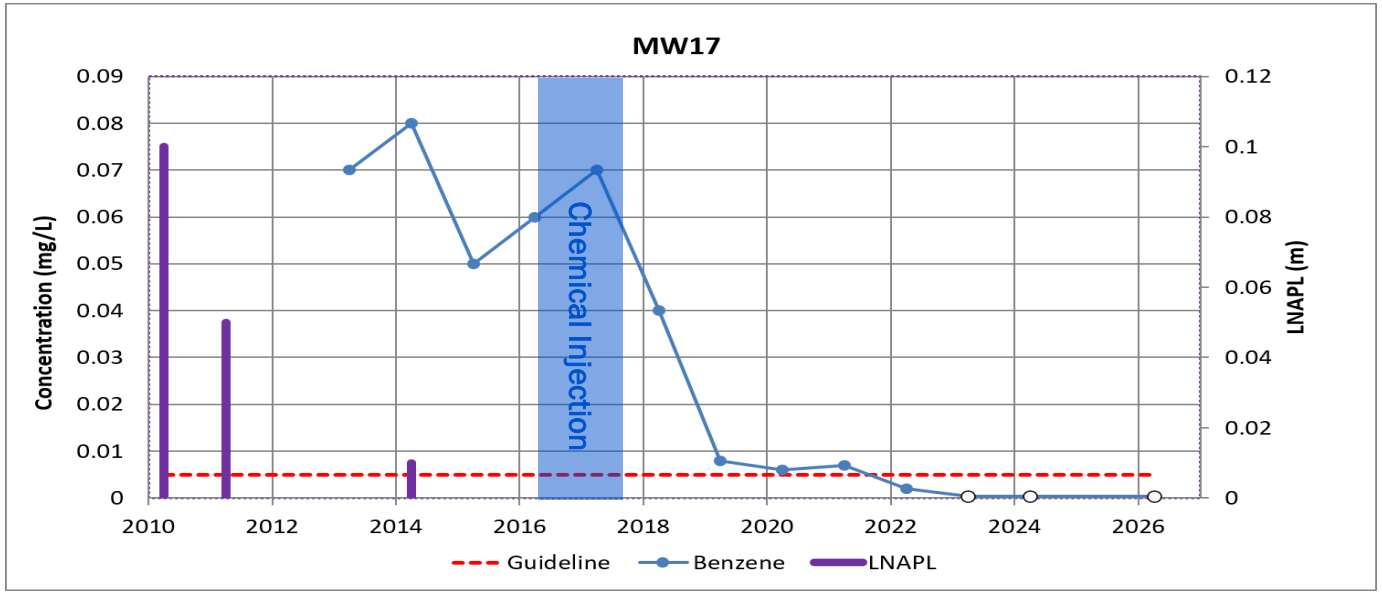
CONCENTRATION DELINEATION MAPS

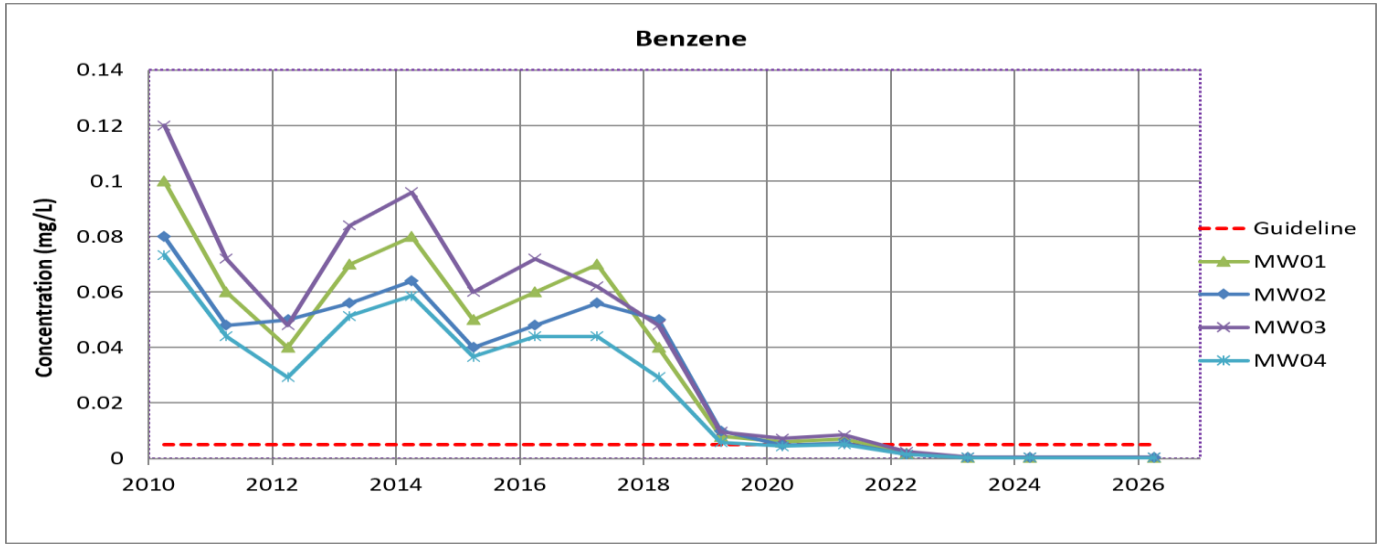
- Common method
  - A map shows exceedances or non-exceedances for a group of contaminants based on the guidelines
- Some issues
  - Selection of the chemical groups
  - Selection of the guidelines
  - Delineate to clean points or based on interpolation?
  - Background issues
- There is no simple “press-button” solution, despite what many of us assume or wish



TREND ANALYSIS– TIME-SERIES PLOTS

- Usefulness of time-series plots
  - Powerful visualization of concentration trends
  - Allow comparison between monitoring wells or chemical parameters
  - Help identify trends, exceedances, and potential seasonal variability
  - Support evaluation of key locations, including site boundaries and points of compliance
  - Can incorporate contextual information such as remedial efforts, groundwater levels, or LNAPL
- Limitations of time-series plots
  - Do not directly characterize overall plume mass, geometry, or extent
  - Can be difficult to interpret at complex sites with heterogeneous hydrogeology or multiple source areas
  - Do not provide spatial context when viewed in isolation

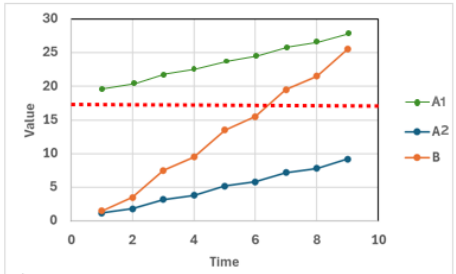




TREND ANALYSIS - MANN-KENDALL

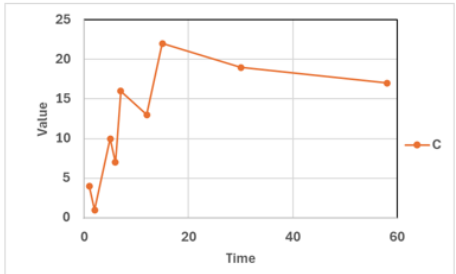
- Usefulness of Mann-Kendall statistical analysis
  - Relatively simple to calculate and interpret
  - Nonparametric; does not require the data to follow a normal distribution
  - Evaluates whether a statistically significant monotonic trend is present
- Limitations of Mann-Kendall statistical analysis
  - Does not provide an indication of the magnitude of change or concentrations – impact of trend needs to be assessed beyond the output
  - Trends may be variable over time (e.g., historically increasing, but decreasing in recent data)
  - Results can be influenced by numerous factors such as sampling frequency, outliers, or treatment of non-detect data.
  - Standard approach does not take seasonal variability into account, needs sufficient data to compare seasons separately.

Magnitude and Relevance of Change



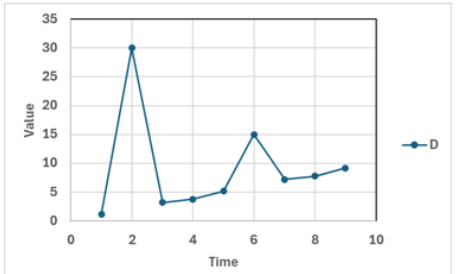
Statistically significant evidence of an increasing trend at the specified level of significance.

Change in Trend and Sampling Frequency



Statistically significant evidence of an increasing trend at the specified level of significance.

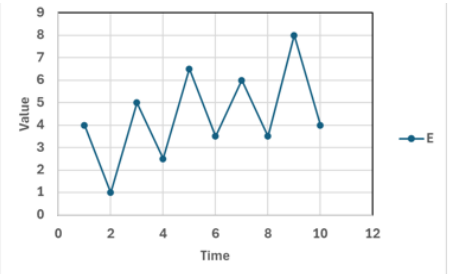
Outlier Bias



Insufficient evidence to identify a significant trend at the specified level of significance.

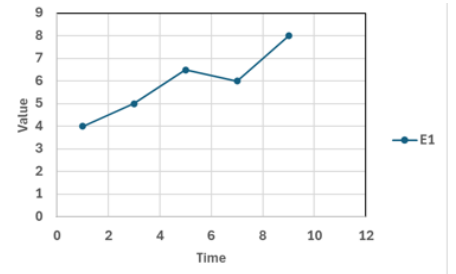
Seasonal Variability

Spring and Fall



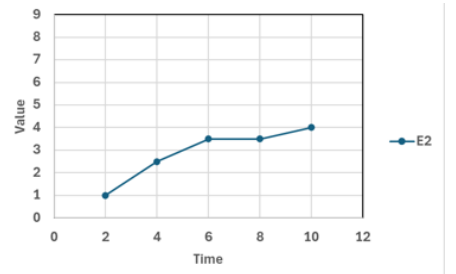
Insufficient evidence to identify a significant trend at the specified level of significance.

Spring



Statistically significant evidence of an increasing trend at the specified level of significance.

Fall

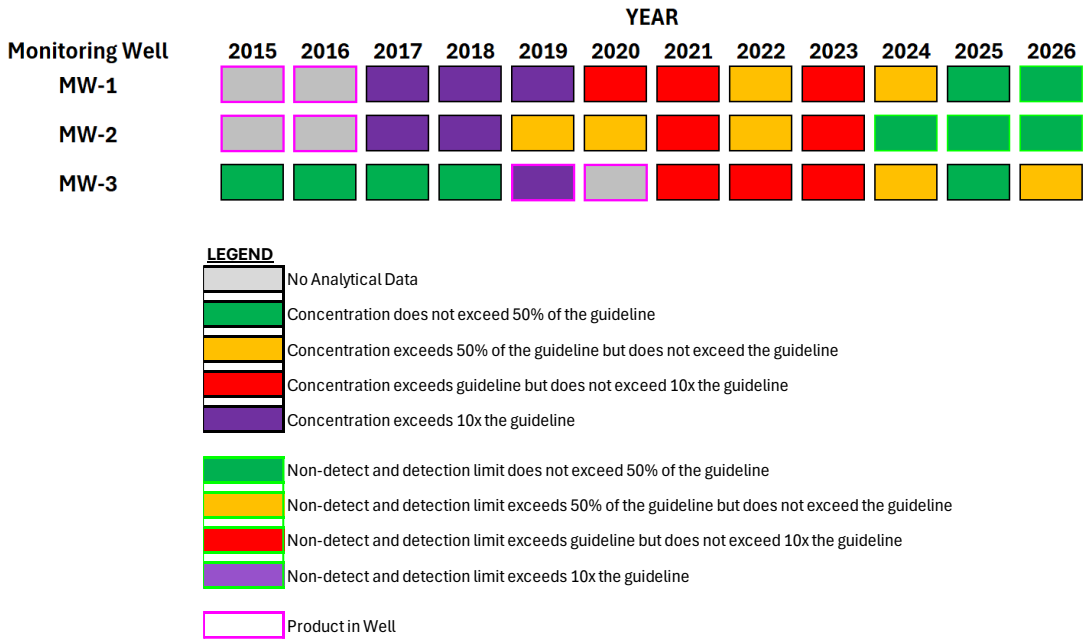


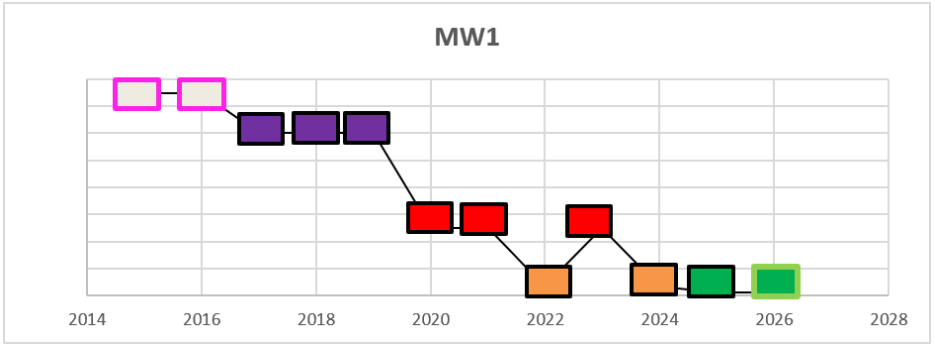
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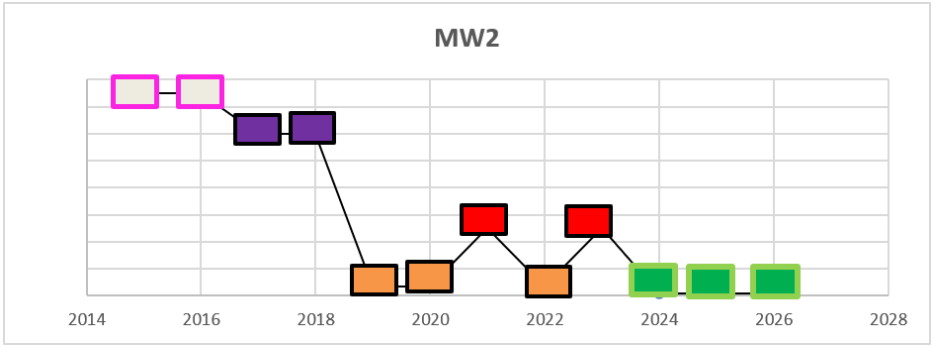
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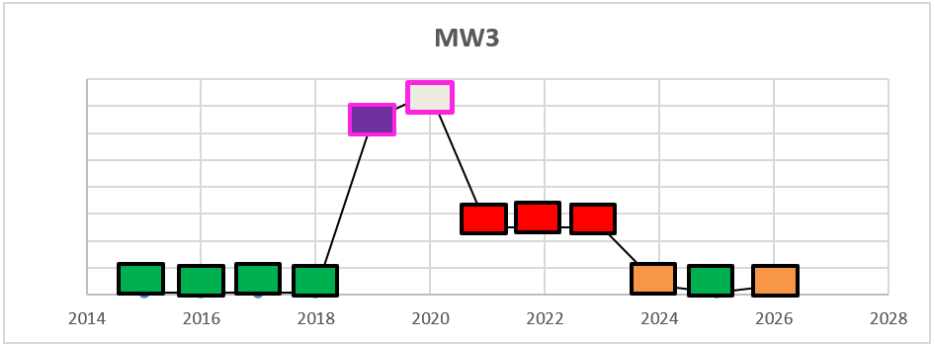
TREND ANALYSIS – ALTERNATE METHODS

- An alternative way to summarize concentration trends
  - Displays maximum normalized concentrations for monitoring wells over time.
  - Normalized concentrations allow presentation of individual chemical parameters or groups of parameters
  - Provides a quick way to assess project objectives
  - Easy to automate and tailor for project objectives



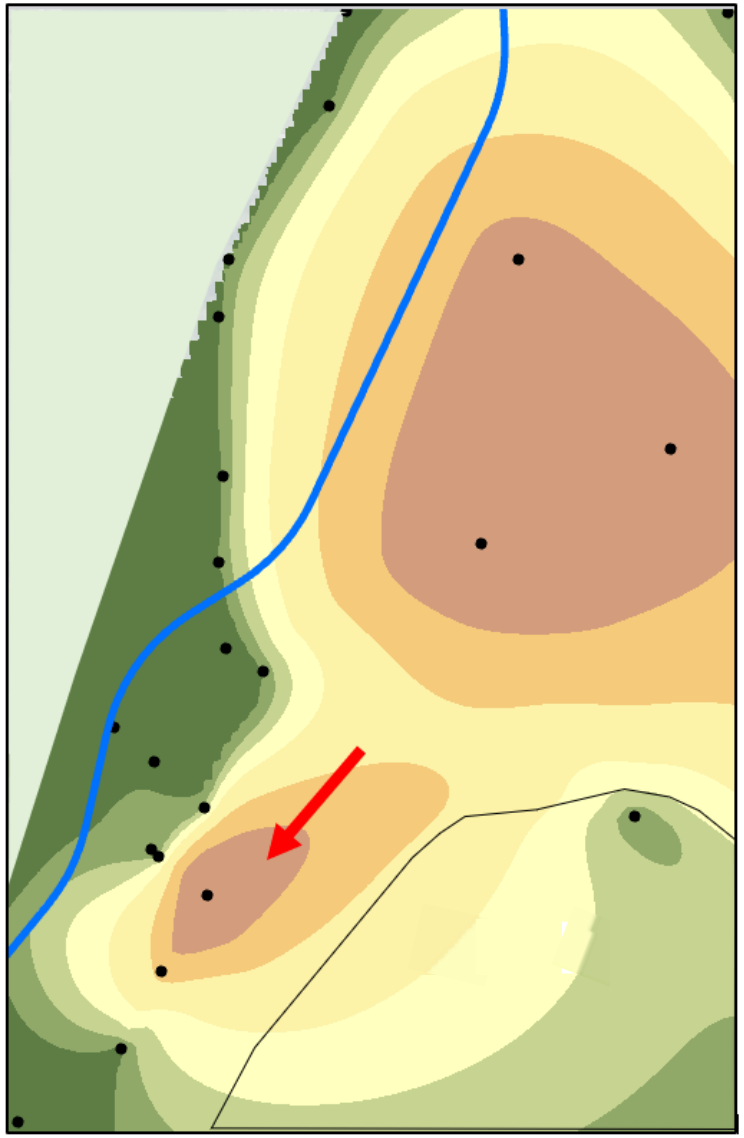






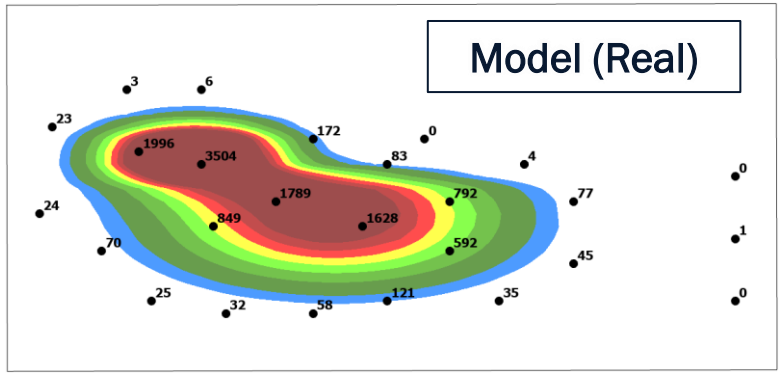
CONCENTRATION CONTOUR MAPS - OVERVIEW

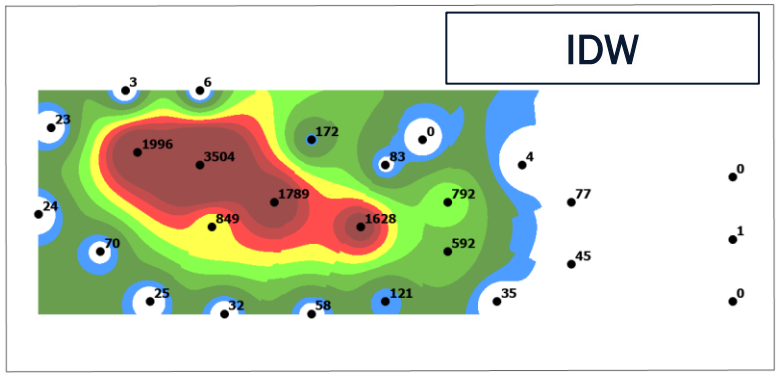
- Concentration contour maps (concentration isopleth maps or heat maps) are becoming increasingly popular
  - Because they provide vivid presentations and are easier to create with computer tools
- Usefulness of heat maps
  - Easy to understand and can aid decision making.
  - Clearly illustrate spatial patterns and the magnitude and distribution of impacts across a site.
  - Can show apparent plume development, migration, or changes in extent when presented as a series over time.
- Limitations of heat maps
  - Require depth- and time-specific considerations.
  - Rely heavily on the density, distribution, and quality of the available data.
  - Interpolated and extrapolated areas may appear reliable even though they are associated with substantial uncertainty.
  - Can be visually persuasive but must be carefully constructed and interpreted within the appropriate hydrogeologic and statistical context.

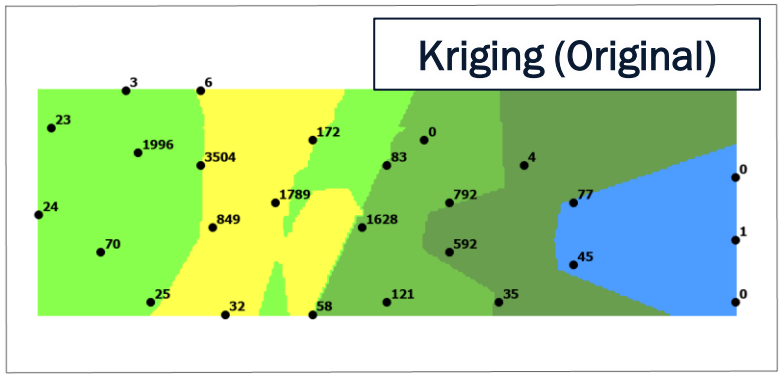


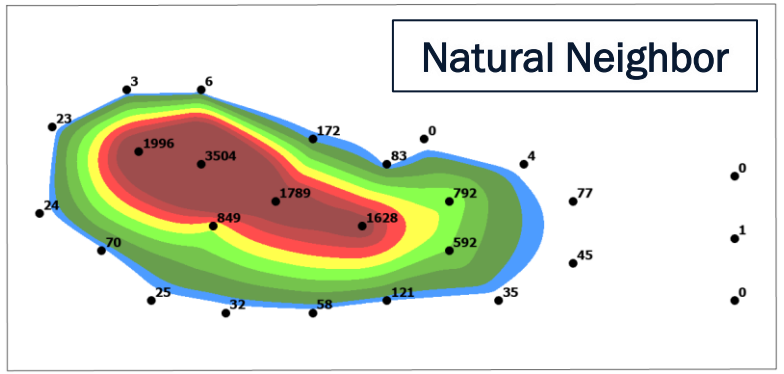
CONCENTRATION CONTOUR MAPS – INTERPOLATION METHODS

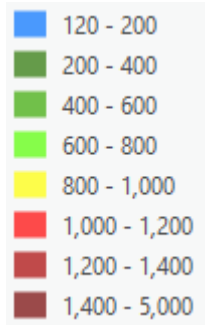
- Different interpolation methods to create heat maps
  - Interpolation methods can provide dramatically different results
  - In this case, Natural Neighbor and TIN are “best” interpolation methods
  - Requires an understanding of the methodology and interpretation based on the conceptual site model and hydrogeologic setting

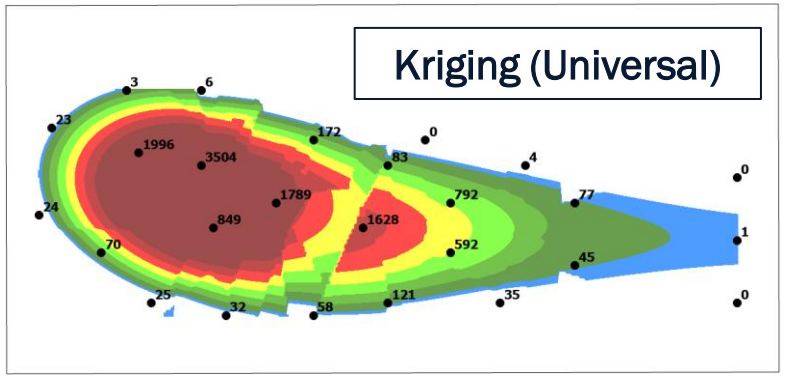


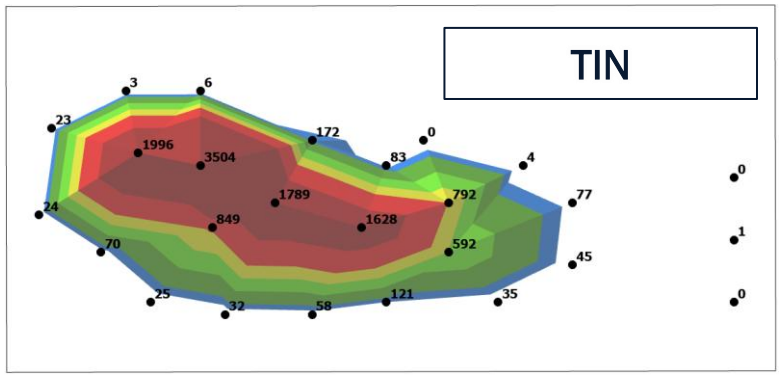








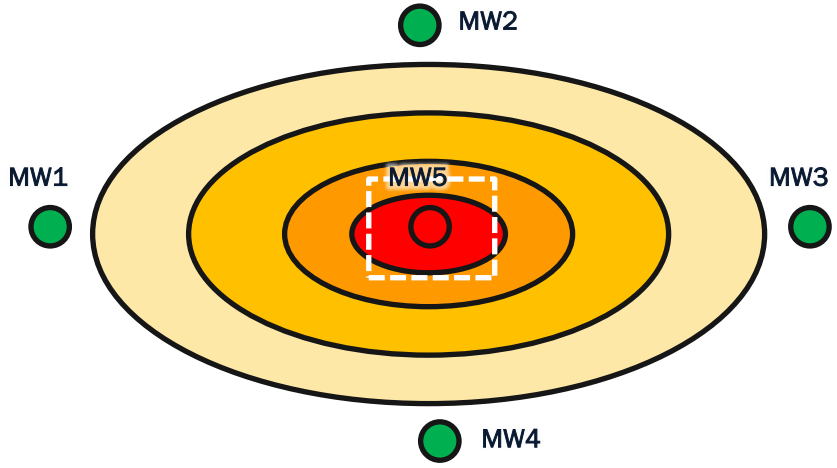




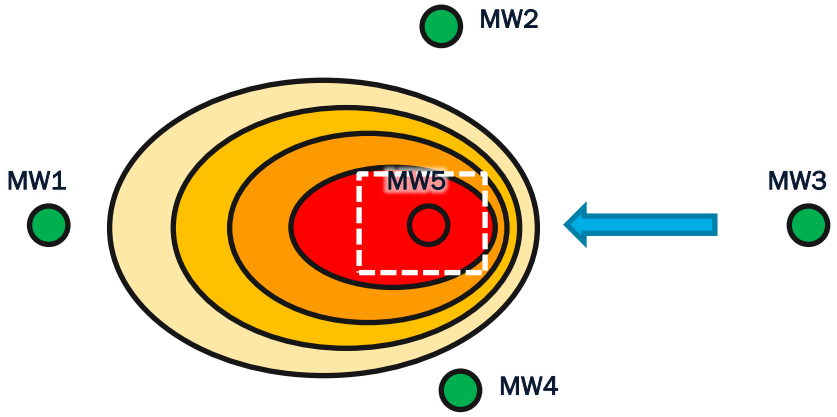
CONCENTRATION CONTOUR MAPS – HYDROGEOLOGIC INTERPRETATION

- Defensible heat maps should be consistent with the conceptual site model and hydrogeologic setting.
  - Conventional interpolation methods represent an estimated spatial pattern based on the available concentration data but do not integrate hydrogeologic concepts.
  - Additional inaccuracies may result from limitations in the monitoring-well network, such as spatial extent, well spacing, screen depths, and network geometry.
  - Initial statistical interpretations can be adjusted to create a heat map that is consistent with conceptual understandings of the site conditions.

Initial Computer Interpolation

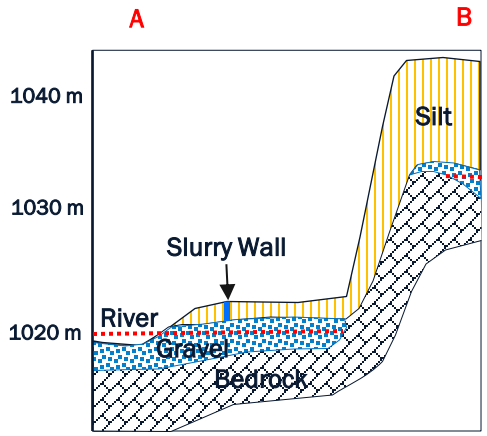


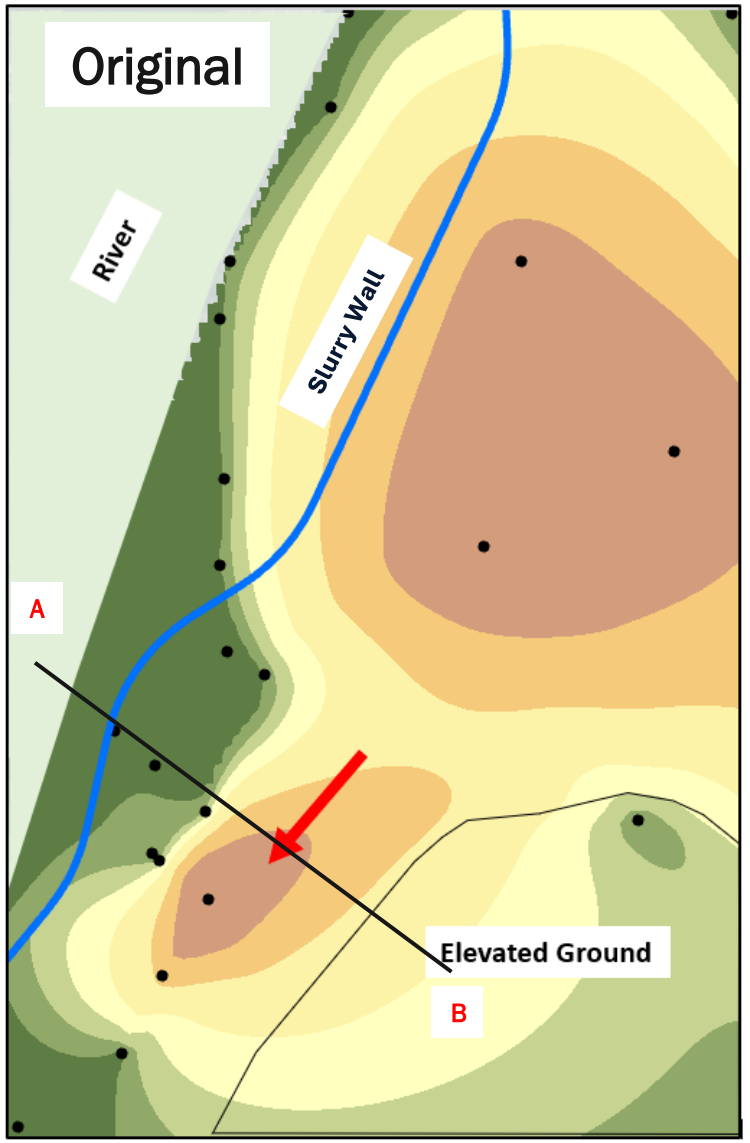
Adjusted Hydrogeological Interpretation

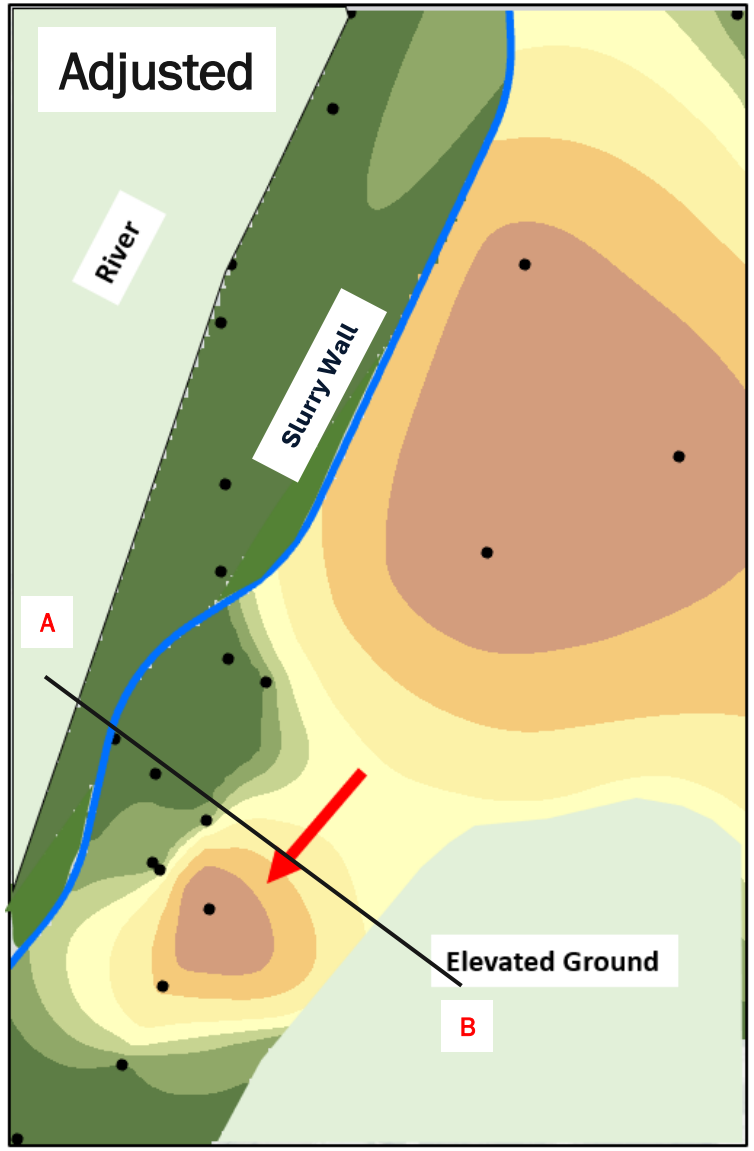


CONCENTRATION CONTOUR MAPS - EXAMPLE

- Computer-generated heat maps may not be consistent with the conceptual site model and hydrogeologic principles, requiring adjustment by experienced hydrogeologists
  - Break at slurry wall
  - Break at hydrogeological boundary
  - Remove apparent migration against groundwater flow direction
- Limited manual adjustments were applied, and in some cases, a more robust representation of concentration distribution and migration may require modelling

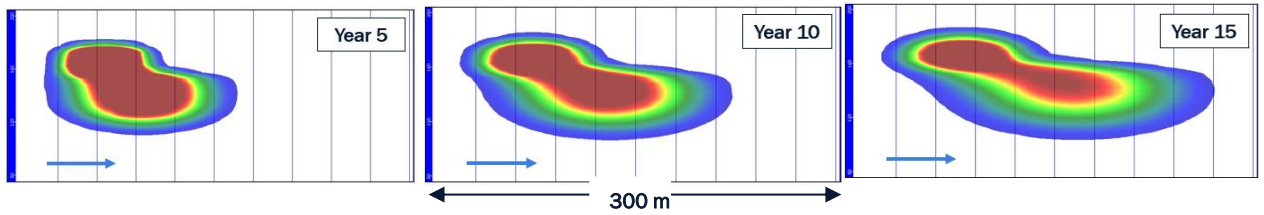


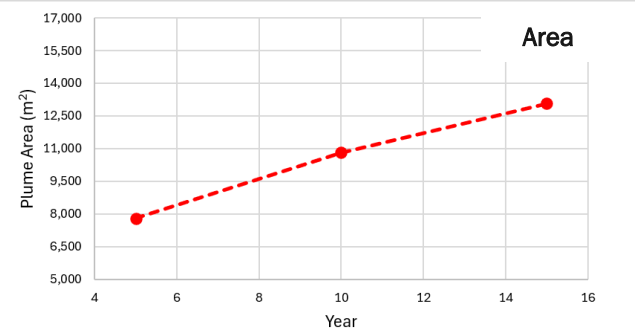


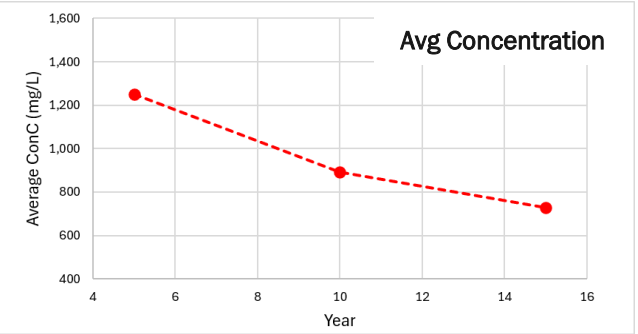


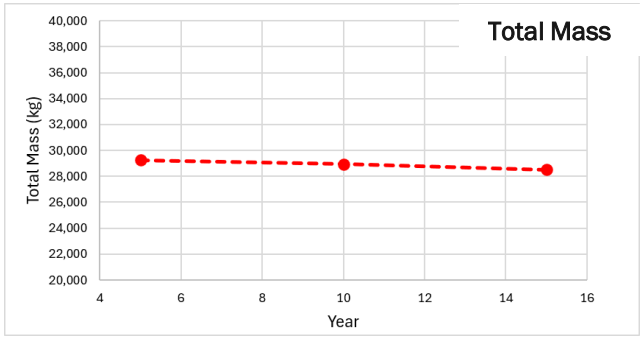
RICKER METHOD - OVERVIEW

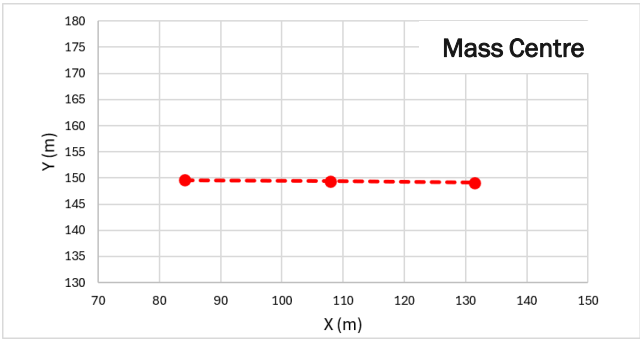
- Ricker (2008) provided a framework for plume stability analysis
  - Trend of plume areas
  - Trend of average concentration
  - Trend of total mass
  - Changes in mass center
- Considerations
  - Calculation methods can be updated using GIS tools (updated by Ricker recently)
  - Results could be affected by sampling network and methods to generate heat maps
  - Mass center shift may be different than plume migration directions
- A numerical experiment
  - A simple numerical model to simulate plume migration (Chloride and no infiltration)
  - Data from a 5-m grid are used to test Ricker Methods
  - Results are as expected





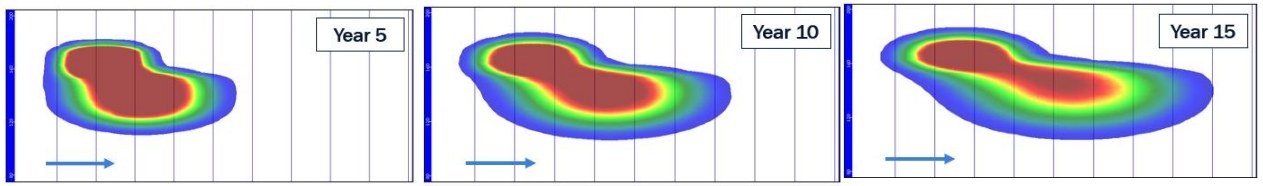


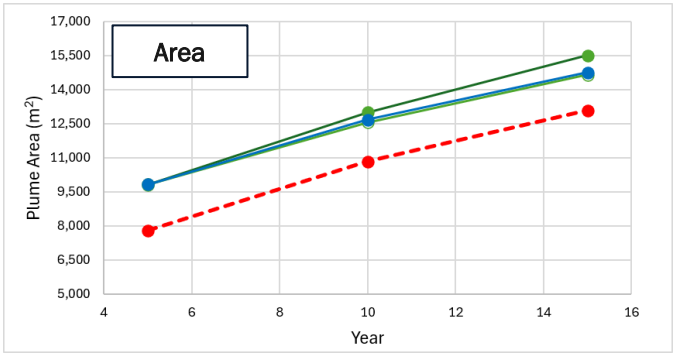


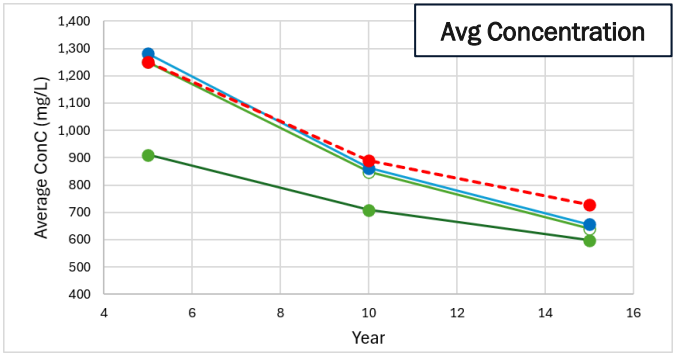


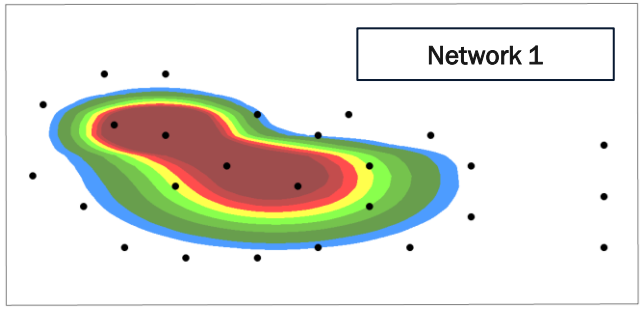
RICKER METHOD – NETWORK AND INTERPOLATION

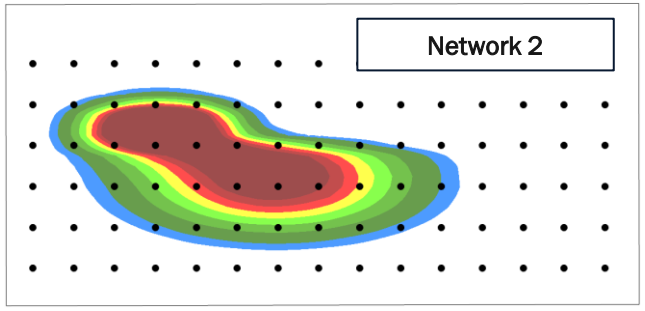
- Results are affected by the sampling network as well as interpolation methods
  - May provide qualitative assessment of plume changes
  - But may not be sufficient for quantitative assessment of remedial measures or natural attenuation









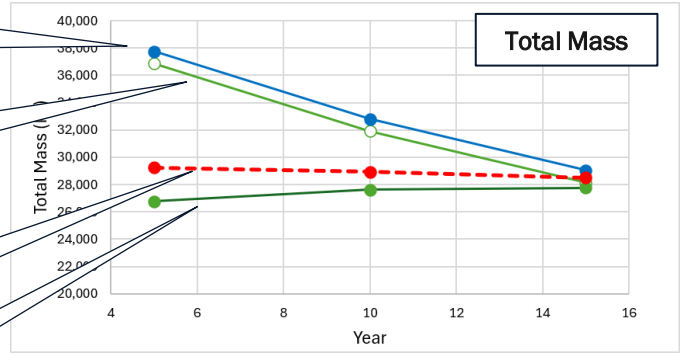


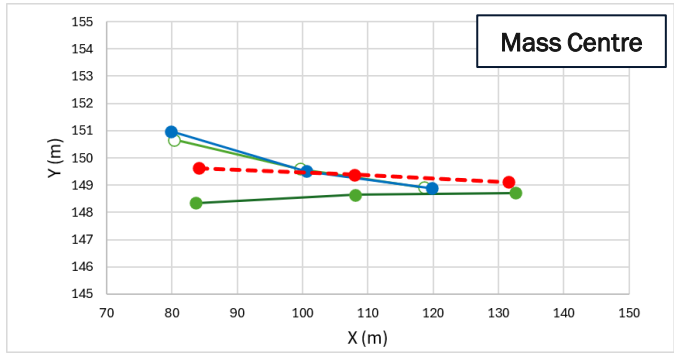
-23.1 % in 10 years

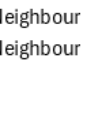
-23.6 % in 10 years

-2.5 % in 10 years

+3.8 % in 10 years

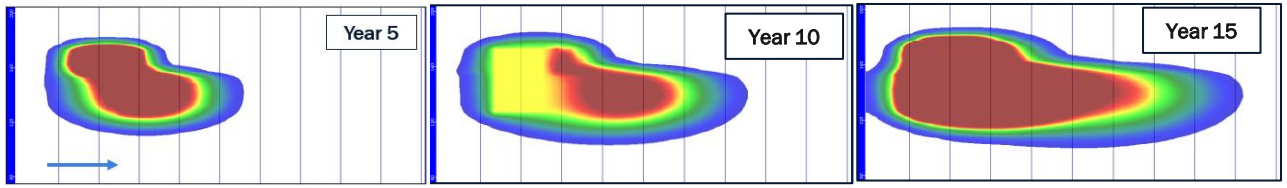


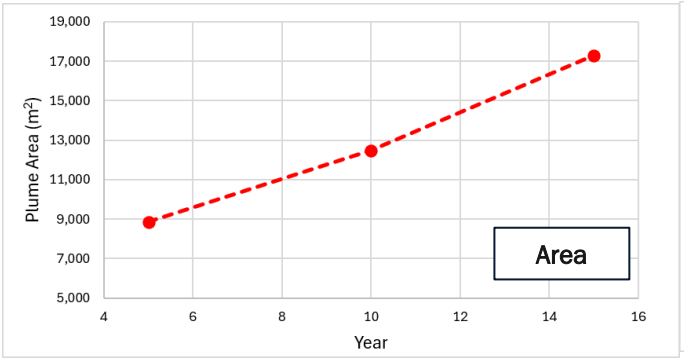


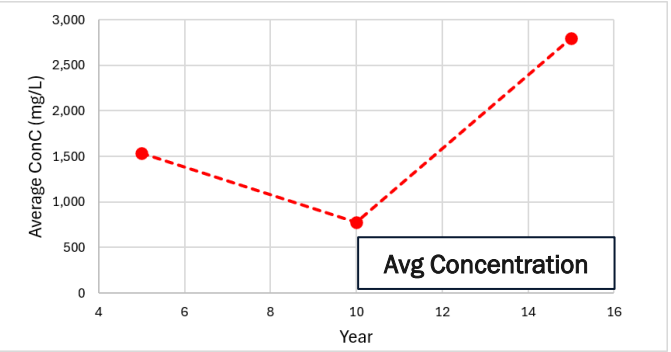


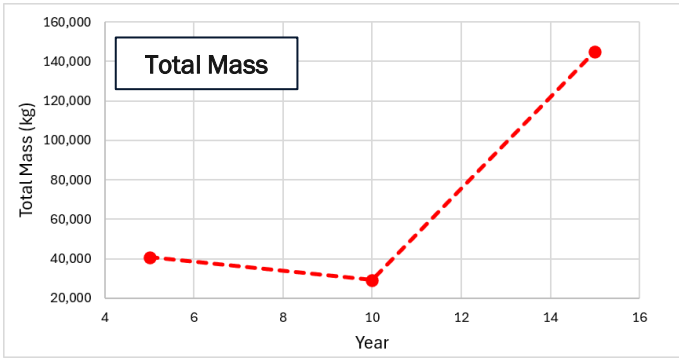
RICKER METHOD – CHANGING SOURCE CONCENTRATIONS

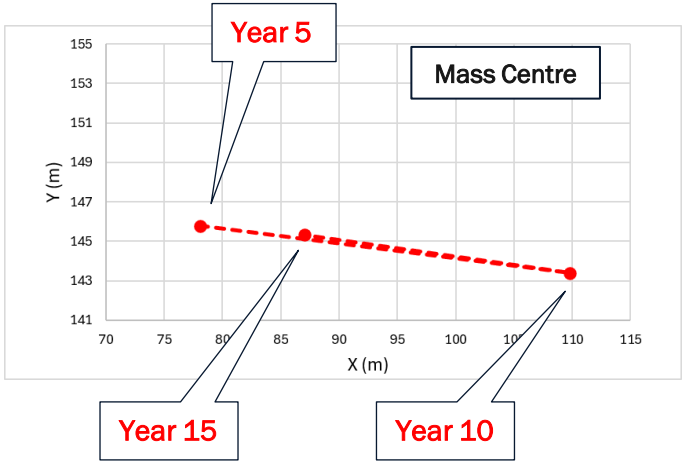
- In some cases, the direction of mass center changes may not align with the direction of plume expansion
- A numerical experiment
  - Similar to the previous one but assumes a decrease in concentration in source areas due to remedial actions (such as chemical injection), followed by increase in concentration due to an additional spill
  - As expected, the average concentration and total mass show decreasing then increasing trends, but the plume area continues to expand and migrate toward the receptor
  - In this scenario, the mass centre moves forward in the direction of groundwater flow before “moving backwards” due to the additional spill
  - Use caution interpreting the results when the Ricker Method is used for a plume with multiple sources and changing source concentrations





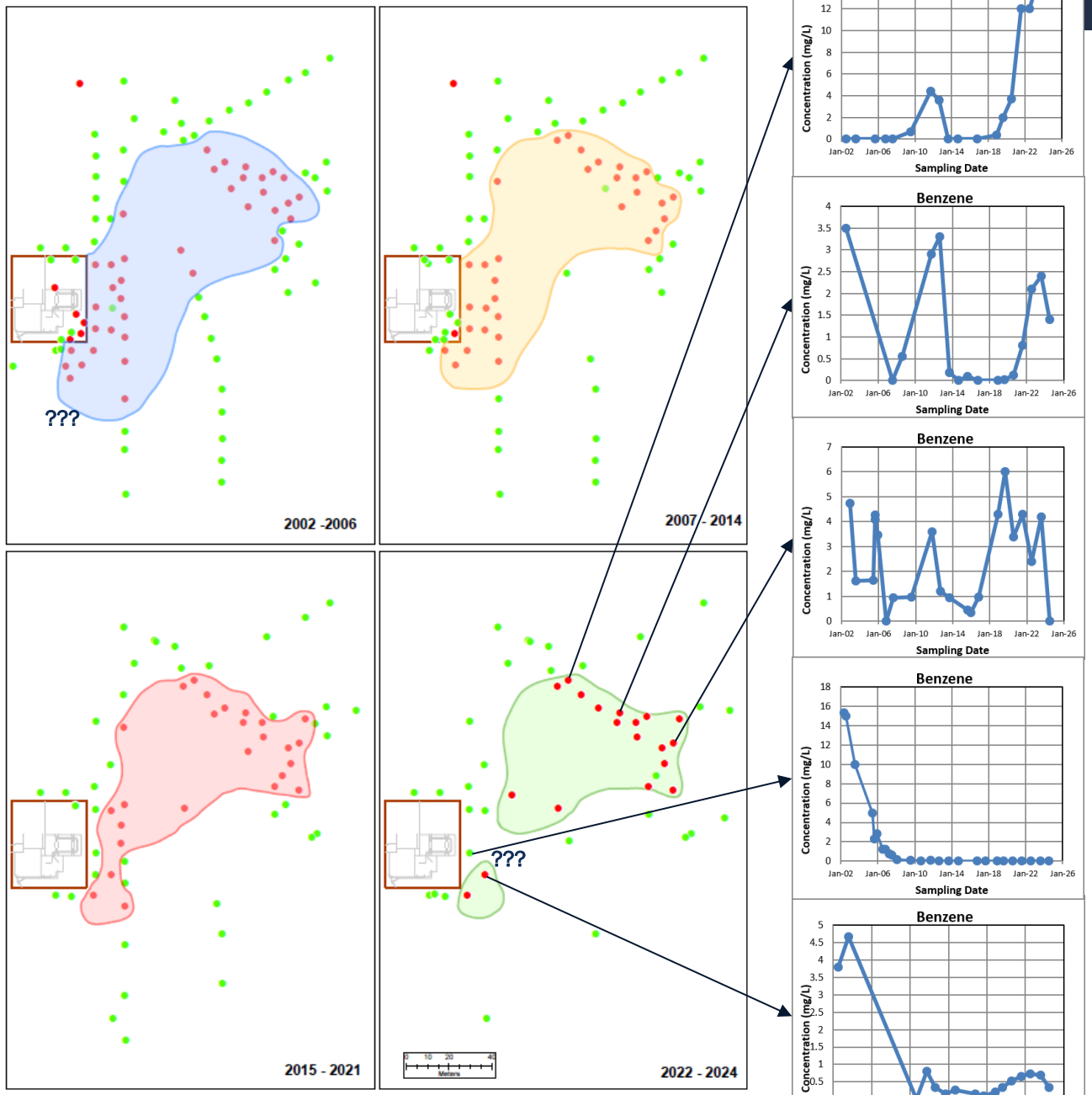






RICKER METHOD – CONSIDERATIONS AT A SITE

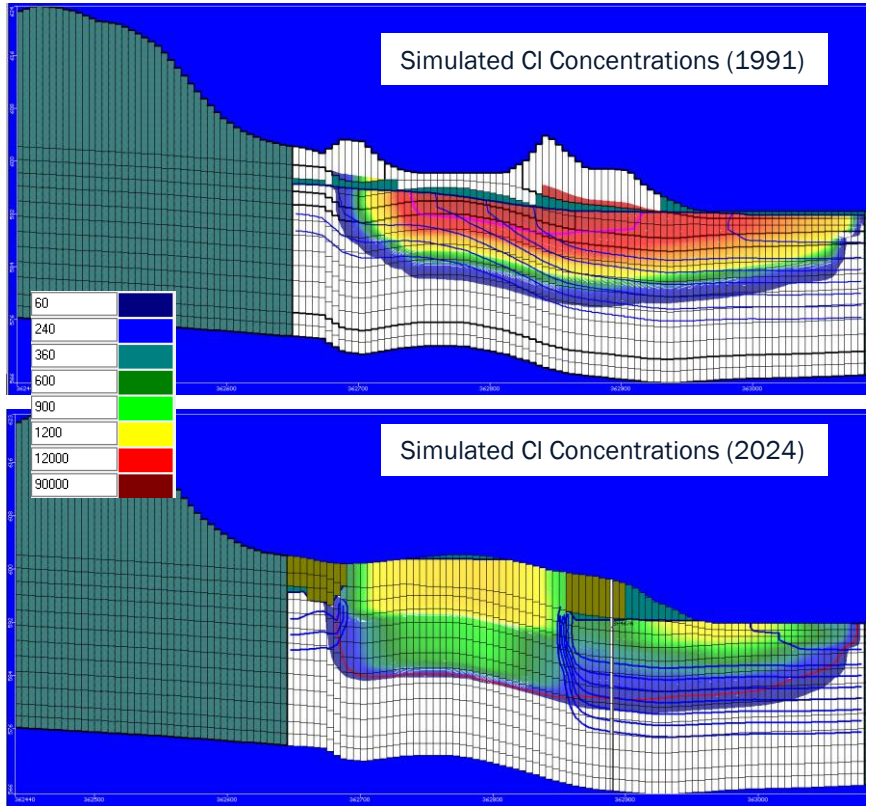
- Over the past decade, the extent of PHC impacts has generally been stable or decreasing, although apparent plume shape may be influenced by data from a few key wells
- PHC concentrations in the source area have decreased following source removal and remedial actions
- Monitoring wells at the leading edge of the plume show variable PHC concentrations, including periods of apparent increases, raising concerns about increased inhalation risk
- Applying the Ricker Method will provide a statistical review of overall plume changes, but additional assessment is needed to explain concentration changes at the leading edge
  - Concentration increases appear to correlate with significant decreases in groundwater levels
  - Groundwater modelling will help explain these changes, which are not attributable to altered migration from the source areas

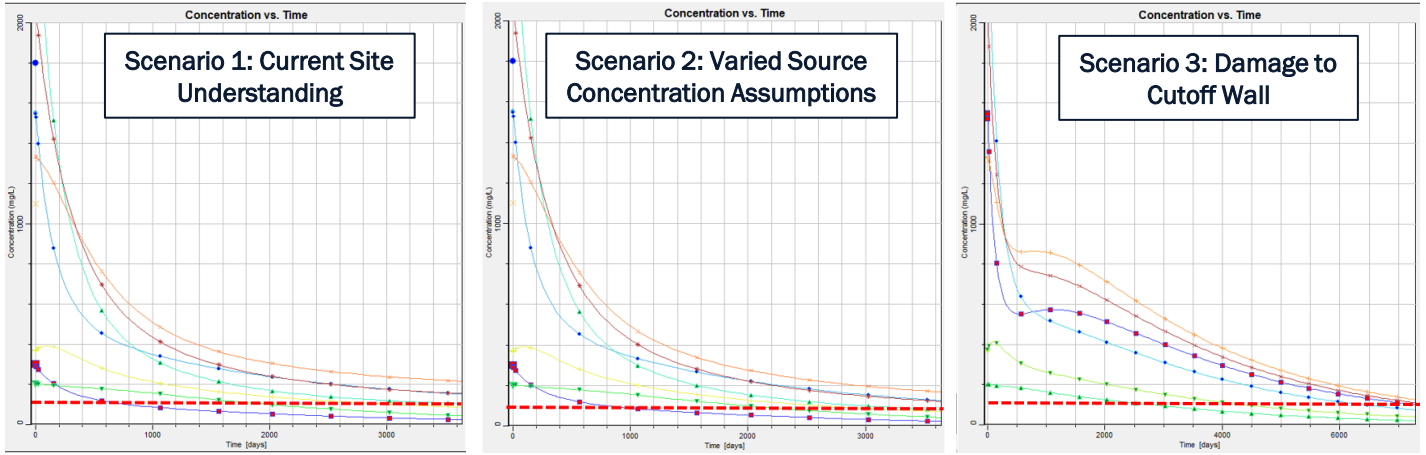


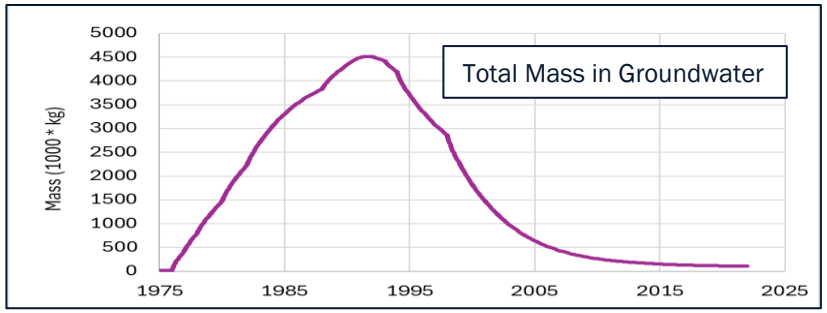
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MODELLING METHOD

- Groundwater modelling can be used for plume analysis
  - Case study shows historical chloride migration to a river
- Key advantages of groundwater modelling
  - Explains the observed changed in concentration
  - Predict future concentration changes based on different scenarios
- Practical considerations
  - Cost and time
  - Uncertainties caused by adding different components to the model





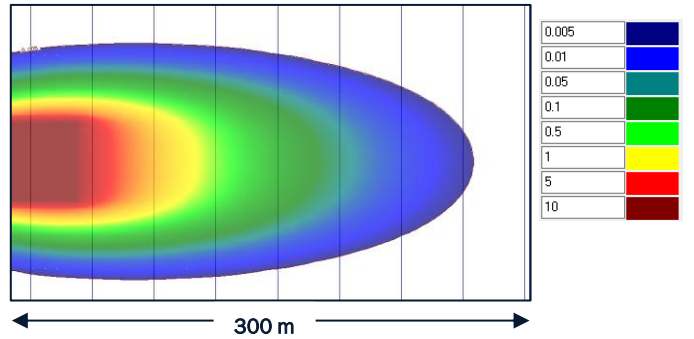


MODELLING METHOD

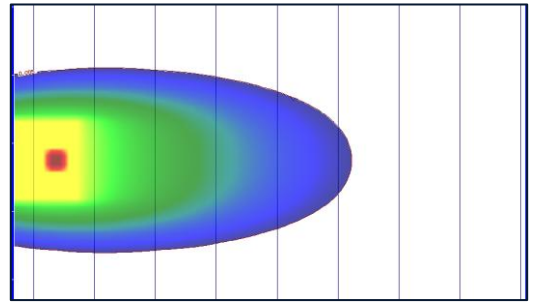
- Use of simple analytical models
  - BIOSCREEN or Alberta DF4
- A numerical experiment
  1) Replication of Alberta DF4 calculation for benzene in numerical model
  2) Consider concentration distribution rather than a uniform concentration based on the maximum concentration
  3) Add infiltration
  4) Consider no continuous source

- Conclusion
  - Alberta DF4 provides a conservative prediction of plume migration based on Tier 2 assumptions (such as constant and uniform source concentration and no infiltration)
  - A numerical version of the DF4 calculation could be used to incorporate more site-specific conditions while retaining the major Tier 2 assumptions

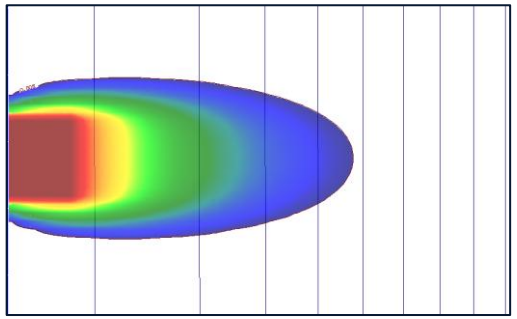
1) Alberta DF4 for Benzene (100 year)



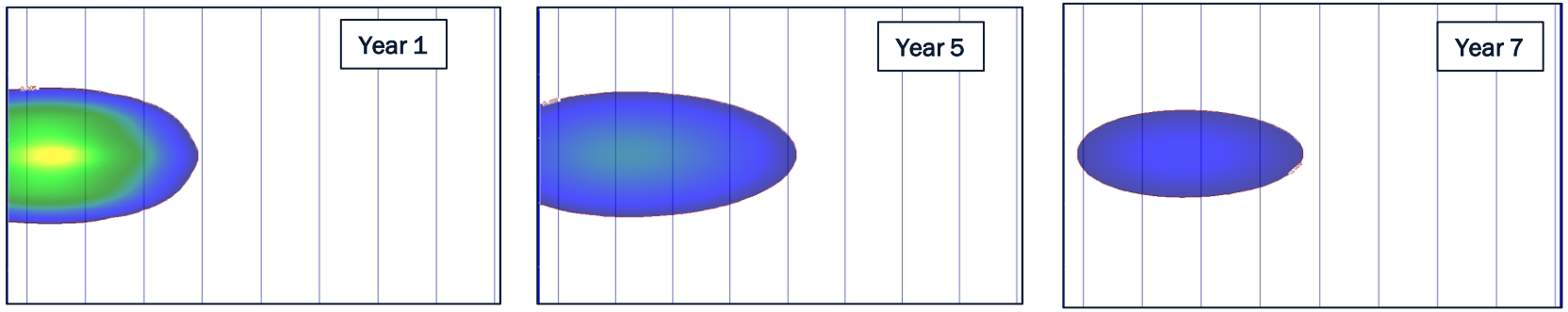
2) Use site-specific concentrations



3) Add infiltration



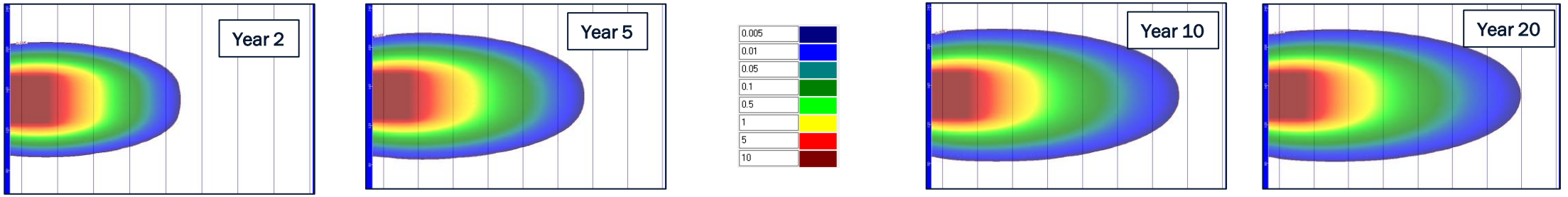
4) Assume no continuous source



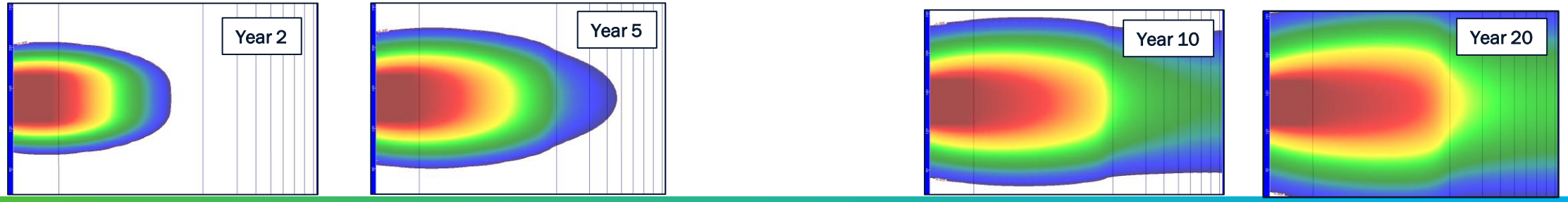
MODELLING METHOD

- Simple analytical models such as BIOSCREEN or Alberta DF4 may be suitable for screening-level estimates or guideline calculations
  - However, their ability to assess plume migration at real sites for remedial performance evaluation or natural attenuation assessment can be limited
  - One limitation is that they do not represent actual causes of concentration changes
- Models based on different assumptions may reproduce similar plume migration for a short period of time but have different long-term predictions
  - Two numerical models have been tested
    - The Alberta DF4 model with benzene (1-year half-life and no infiltration)
    - A numerical model to consider infiltration for a chemical that does not undergo biodegradation (such as chloride)

With biodegradation but no rainfall infiltration



With infiltration but not biodegradation



TAKEAWAY MESSAGES

- Many methods exist for plume stability assessment. Need to clearly define objectives and select fit-for-purpose methods
- Full-scale analysis is not always needed
  - For regulatory compliance, focus on trends at points of compliance or site boundaries
- Use caution with “press-button” tools
  - Quick tools can give incorrect or incomplete interpretations if no additional professional judgment is provided
    - Mann–Kendall trend analysis often overused without recognizing limitations, leading to misinterpretation
    - For computer-generated heat maps, their limitations are frequently ignored
- Ricker Method provides a structured framework for plume stability analysis
  - Scope of applicability must be evaluated
  - Results may be sensitive to data quantity and quality
  - Methods could be strengthened through use modern GIS and data tools
- The value of modelling methods is often underestimated
- There is a lack of detailed guidance on plume stability assessment methods

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CLOSING

Thank you!

Questions?