DIGITAL TWINS FOR CONTAMINATED SITES

CONCEPTS, OPPORTUNITIES AND CHALLENGES

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OUTLINE

1. Digital data and digital twins
2. “Paper-based” use of digital data
3. Misconceptions of “press-button” solutions
4. An example using numerical model to refine CSM and develop long-term monitoring strategies

Acknowledgment: This presentation incorporates concepts inspired by discussions with Dr. Qunli Dai

CONCEPTS OF DIGITAL TWIN

- Digital Twin
  - “A digital twin is a dynamic virtual representation of a physical object, process, or system, linked to real-time data from sensors and other sources, allowing for simulation, analysis, and prediction of the physical entity's behavior across its entire lifecycle.” - ParsonsGPT
- Key components of a digital twin
  - Physical Asset or System: The real-world entity being modeled
  - Data Integration: Real-time data collected from sensors and devices
  - Simulation and Analytics: Tools to analyze and predict outcomes
  - Feedback Loop: Insights from the digital twin can be applied to improve the physical system

- A traffic monitoring and control system as an example
  - Physical Asset or System: The physical system in this case is the road network, vehicles, traffic signals, and other infrastructure.
  - Data Integration: Sensors, cameras, GPS devices, and IoT-enabled traffic signals collect real-time data on vehicle movement, congestion, weather conditions, and accidents
  - Simulation and Analytics: The digital twin uses this data to create a virtual model of the traffic system. Advanced algorithms and simulations can predict traffic patterns, identify bottlenecks, and test the impact of changes (e.g., adjusting signal timings or rerouting traffic)
  - Feedback Loop: Insights from the digital twin can be used to make real-time adjustments to traffic signals, provide drivers with alternate routes, or plan long-term infrastructure improvements
  - Application examples:
    - A city could use a digital twin of its traffic system to simulate the impact of closing a major road for construction and determine the best detour routes
    - It could also predict how traffic will behave during peak hours or special events and adjust traffic control measures accordingly

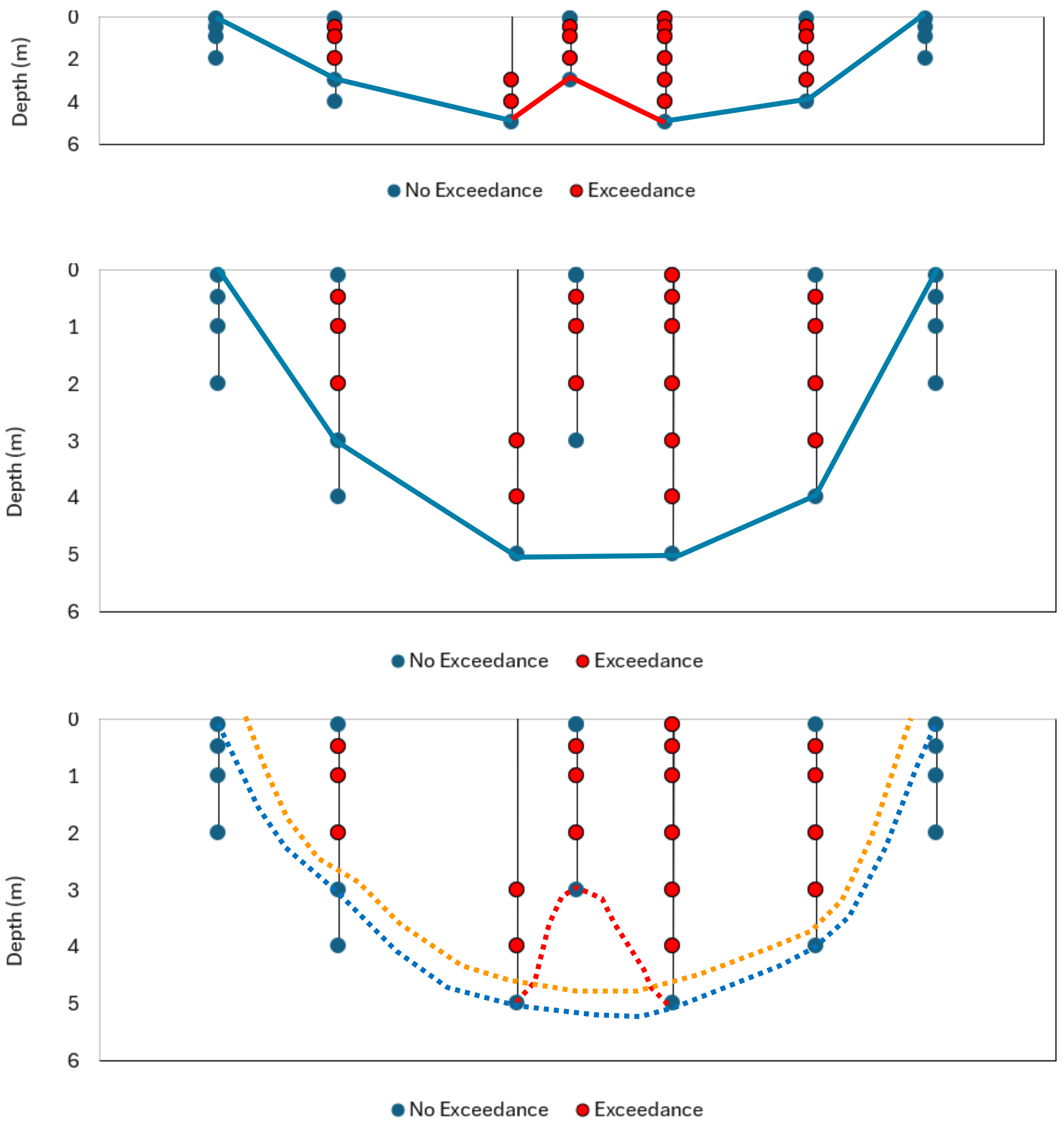
DIGITAL TWINS FOR CONTAMINATED SITES

- Digital Data
  - Data stored in a digital format, ranging from less structured formats (e.g., Excel spreadsheets) to highly organized systems such as Geographic Information Systems (GIS) and environmental databases
- Digital Twins for contaminated sites
  - A virtual replica (or digital model) of physical features of a contaminated site
  - A virtual replica of site investigation process
- Advantages of borrowing Digital Twin concepts and technologies
  - Maximized use of data stored in digital formats
  - Help to refine conceptual site models (CSMs), particularly during advanced stages of site management, by incorporating supplemental data collected. Improve consistency and transparency of CSMs
  - Allow for the simulation of "what-if" scenarios and optimize physical activities such as drilling, sampling, or testing
  - Take advantage of data integration to support informed decision-making
  - Serve as a powerful tool for visualizing and sharing complex site data, fostering clearer communication among stakeholders

DATA AND MODEL

An example to illustrate “data” and “model”

- Estimation of volume of soil excavation requires a dataset showing exceedances and no exceedance at different locations and depths
- Also need a model (or models) to determine extent of impact
  - e.g., typical “defined by closest clean samples”
  - e.g., “professional judgment” may be used to group two or more boreholes as representing a single location
- Digital models to interpret between data points
  - e.g., different interpolation methods to estimate depths of impact or cut-off between data points
- Points to note
  - Different models can lead to different outcomes
  - Digital models require spell-out of the logic and rules during interpretation and improve transparency and reproducibility

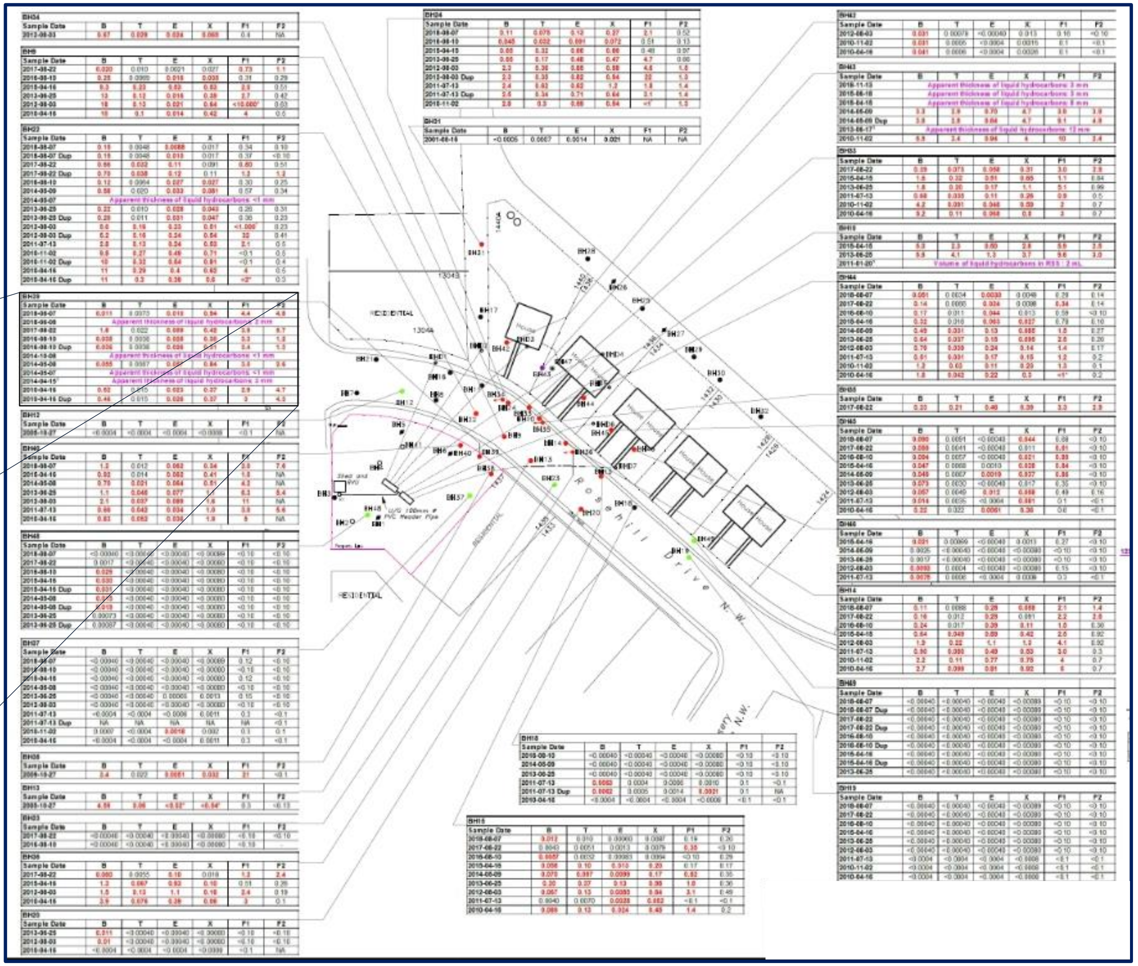


“PAPER-BASED” USE OF DIGITAL DATA

Pop-up drawings as an example

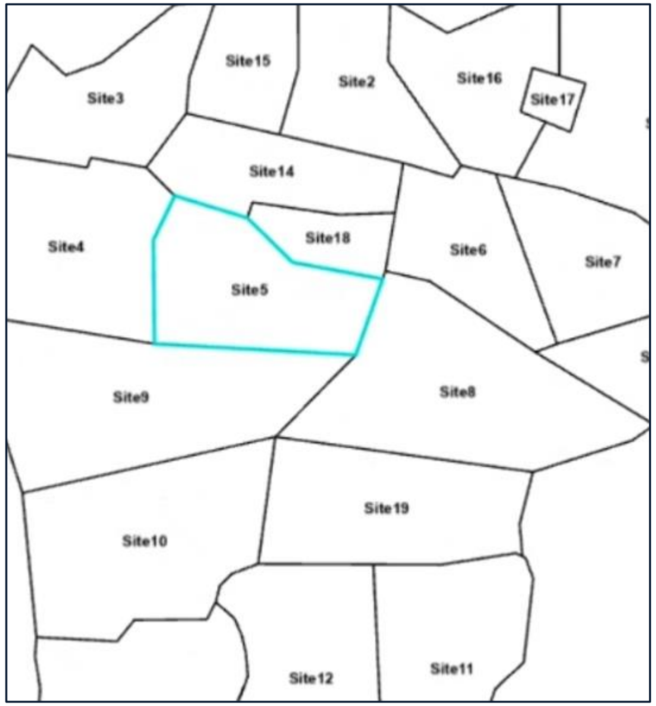
- A very popular presentation of data at contaminated sites
  - Enables readers to review detailed data (e.g., depth-specific and time-specific) presented in tables, alongside a site plan that highlights locations exceeding thresholds

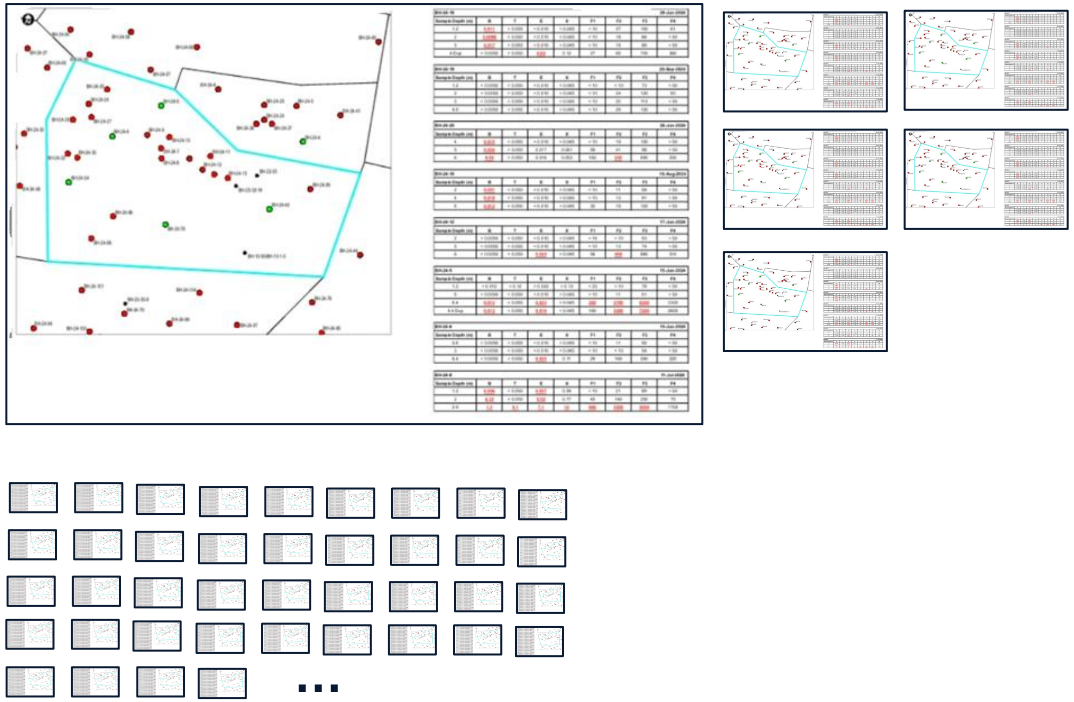
BH39						
Sample Date	B	T	E	X	F1	F2
2018-08-07	0.011	0.0073	0.010	0.94	4.4	4.8
2018-06-08	Apparent thickness of liquid hydrocarbons: 2 mm					
2017-08-22	1.8	0.022	0.059	0.42	3.9	5.7
2016-08-10	0.035	0.0038	0.025	0.30	3.3	1.2
2016-08-10 Dup	0.036	0.0038	0.026	0.31	3.4	1.3
2014-10-08	Apparent thickness of liquid hydrocarbons: <1 mm					
2014-05-08	0.055	0.0087	0.057	0.84	3.0	2.6
2014-05-07	Apparent thickness of liquid hydrocarbons: <1 mm					
2014-04-15[1]	Apparent thickness of liquid hydrocarbons: 3 mm					
2010-04-16	0.52	0.015	0.023	0.37	2.9	4.7
2010-04-16 Dup	0.46	0.015	0.026	0.37	3	4.3



“PAPER-BASED” USE OF DIGITAL DATA

- Challenges at large and complex sites
  - Producing a large number of drawings is a challenge and difficult to automate
  - Multiple pages of pop-up drawings can diminish the effectiveness of visualization, reducing the ability to interpret data clearly

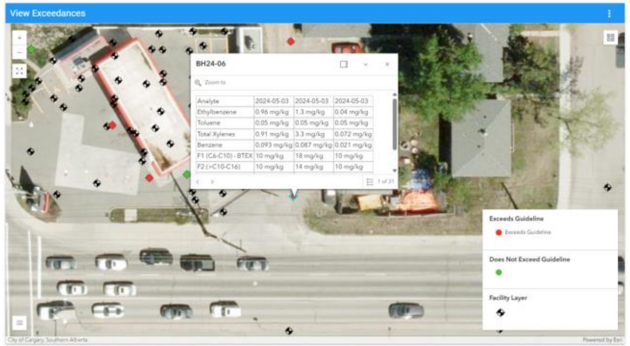


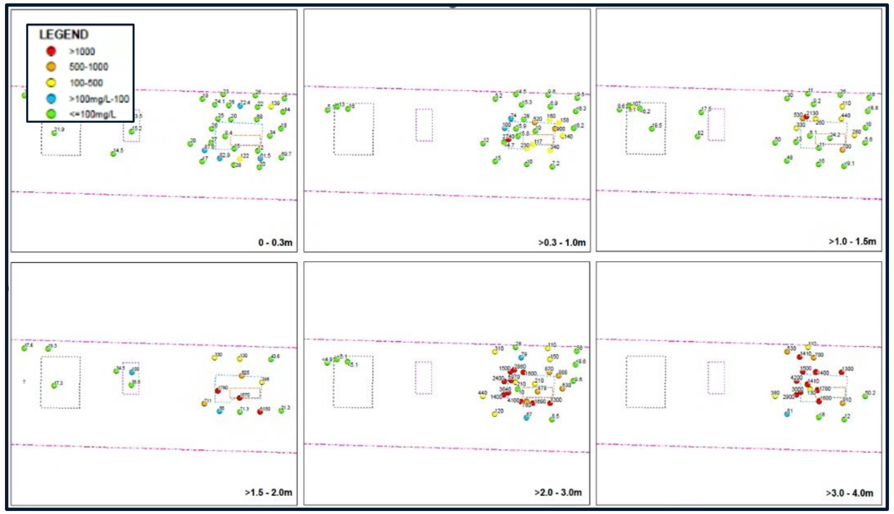


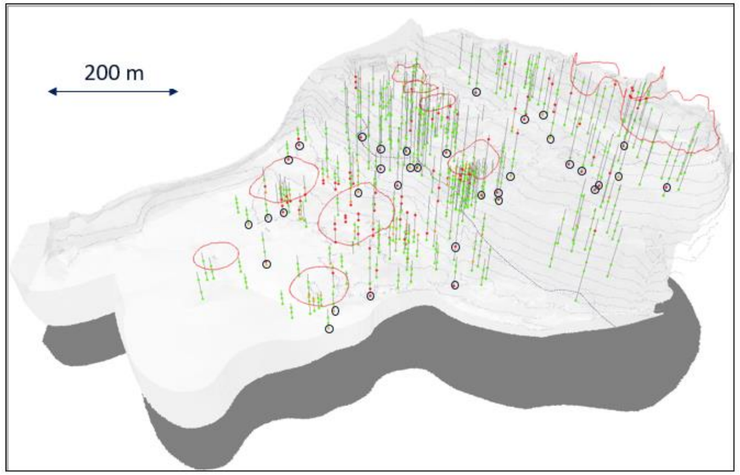
An APEC with 24 boreholes need > 20 drawings for soil data (4 for PHC, 8 for PAHs, 4 for general and 8 for metals). A total of > 300 drawings for the site with 20 APECs

ALTERNATIVE METHODS FOR PRESENTING DIGITAL DATA

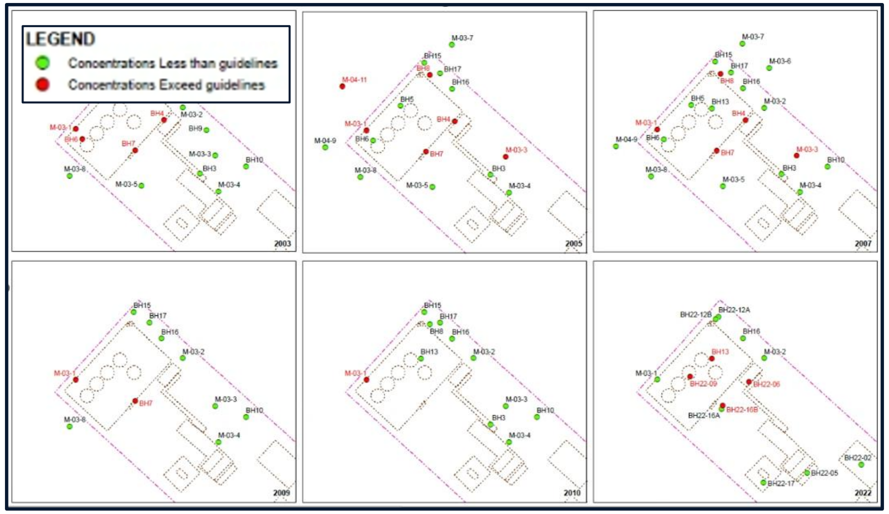
- Numerous alternative methods are available to present digital data, enhancing both visualization and interpretation
  - Stacked depth-specific exceedance maps
  - Stacked time-specific exceedance maps
  - Interactive online pop-up presentations
  - 3D visualizations and models
  - etc.

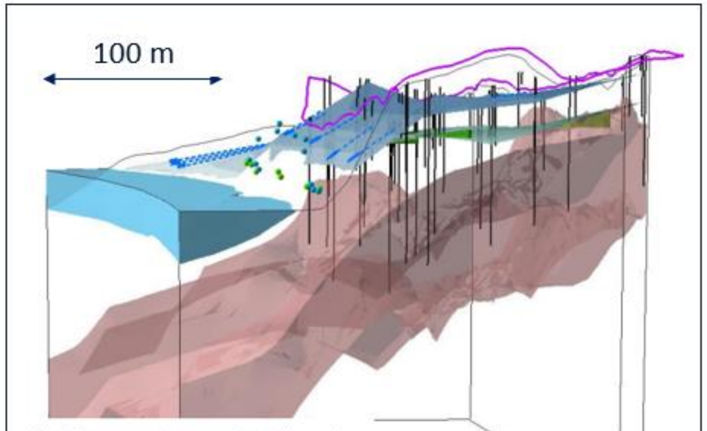






PHC F3 Exceedances (showing deep impacts likely caused by natural PHC seepages)



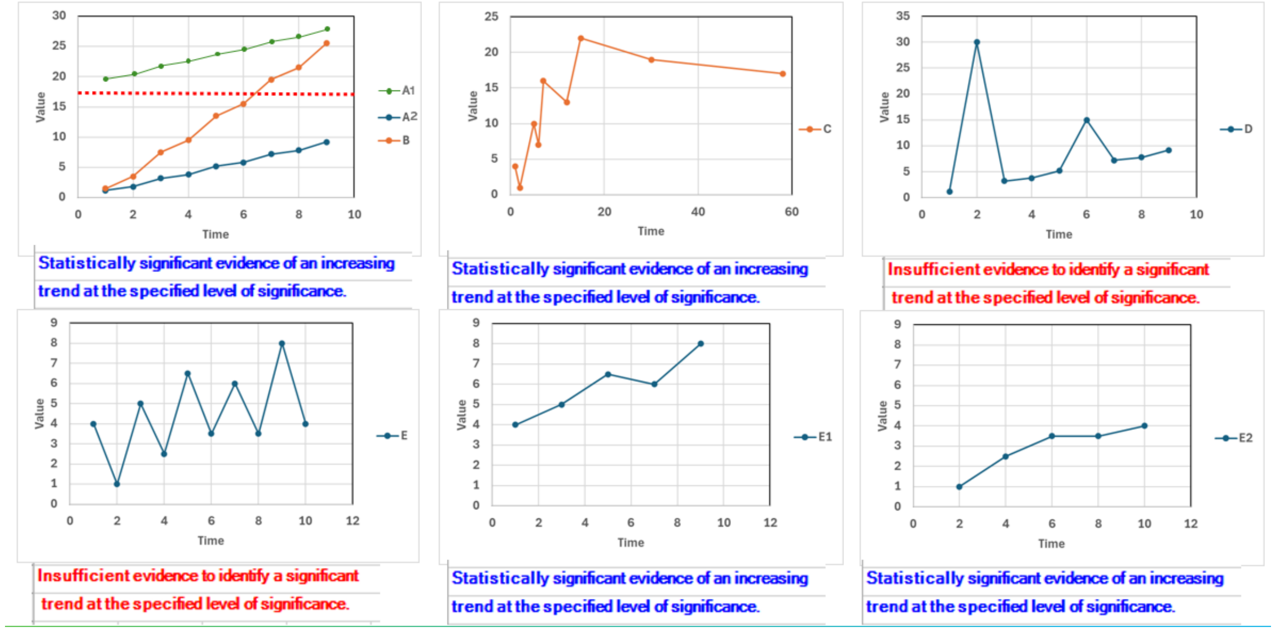


Shallow vs Deep GW levels

MISCONCEPTIONS ABOUT "PRESS-BUTTON" SOLUTIONS

Mann-Kendall analysis as an example

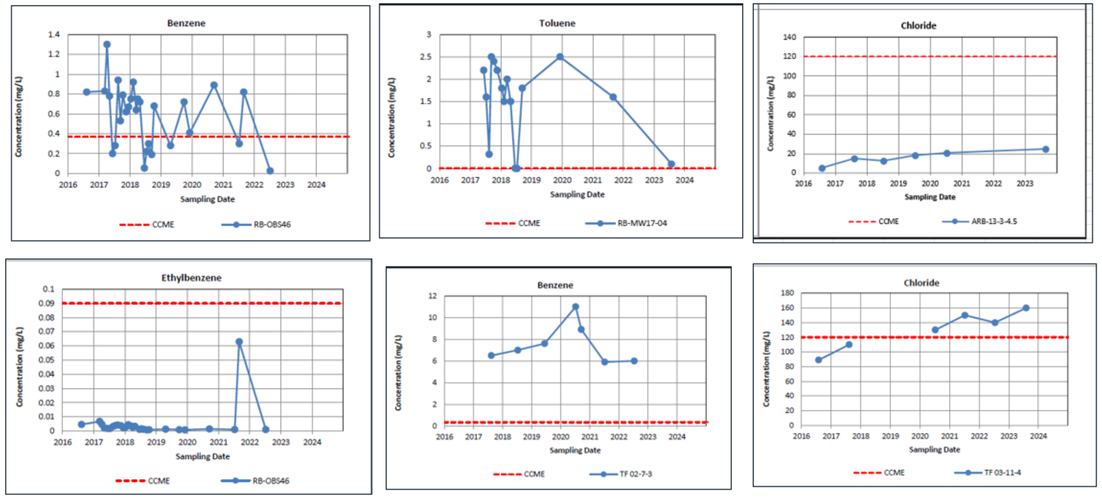
- MK is a widely used method for performing trend analysis. "Press-button" tools are available to process large batches of datasets and deliver conclusions to project managers
- However, users often overlook the assumptions and limitations of the method, which can impact the interpretation of the results.
    - It is a non-parametric method with limited interpretation power
    - The original MK can only detect a "monotonic" trend (increase, decrease, or no trend) and does not account for seasonal variations or multi-year fluctuations.
    - Results can be heavily influenced by outliers. Statistical procedures exist to detect and remove outliers but are not commonly applied
    - MK identifies the presence of a trend but does not provide information on the magnitude of changes or the changes relevant to data values



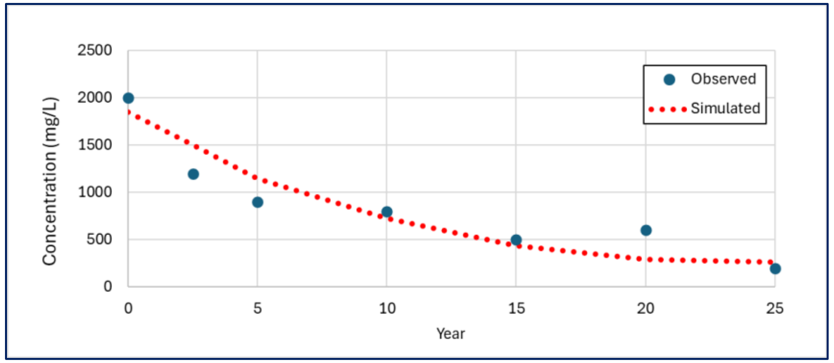
Hypothetical datasets demonstrating MK limitations

MISCONCEPTIONS ABOUT “PRESS-BUTTON” SOLUTIONS

- Users of the “press-button” MK tools need full understanding of fundamentals, assumptions and limitation of the method
- MK analysis should be used in conjunction with other statistical approaches to address its limitations
  - Commercial statistical packages typically offer additional trend analysis tools, such as covariance analysis, outlier removal procedures, and parametric curve fitting, to provide a more comprehensive assessment.
  - Visual inspection of data is important to verify MK results and ensure accurate interpretation based on professional knowledge of site conditions
  - Dynamic models, such as groundwater flow and transport models, can reproduce and predict data trends, providing insights beyond statistical methods alone. MK analysis may be used as a screening tool if needed before modeling, but not after, which was asked for in some real cases



Concentration versus time charts from a site



Observed and Simulated Concentrations

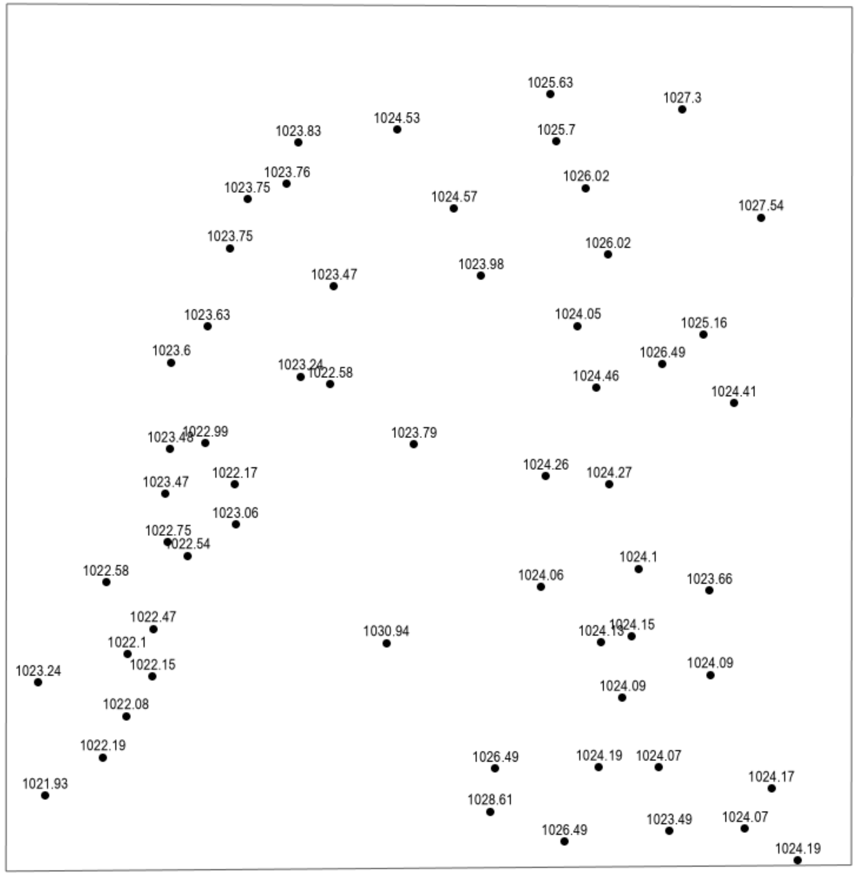
	2022	2023	2024	2025
MW08				
MW15				

	not sampled
	below 50% guidelines
	exceed 50% guidelines
	exceed guidelines
	exceed 10 x guidelines

MISCONCEPTIONS OF “PRESS-BUTTON” SOLUTIONS

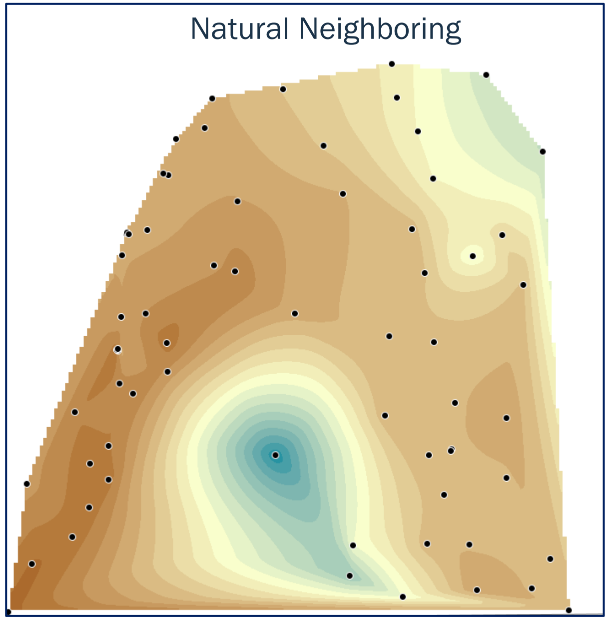
Groundwater contour maps as an example

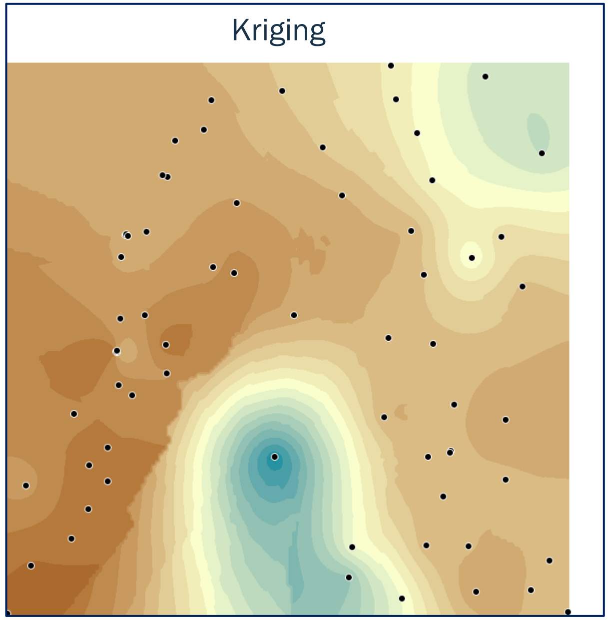
- With the groundwater elevation data in digital formats, many “press-button” tools are available to create groundwater contour maps (using GIS or Surfer)
- However, different contour maps can be created depending on the tools used. Most contour maps do not actually follow hydrogeological principles and reflect site-specific conditions
- An example is provided based on real data from a site
  - Test different contour generation methods
  - Create a contour map based on hydrogeological conditions

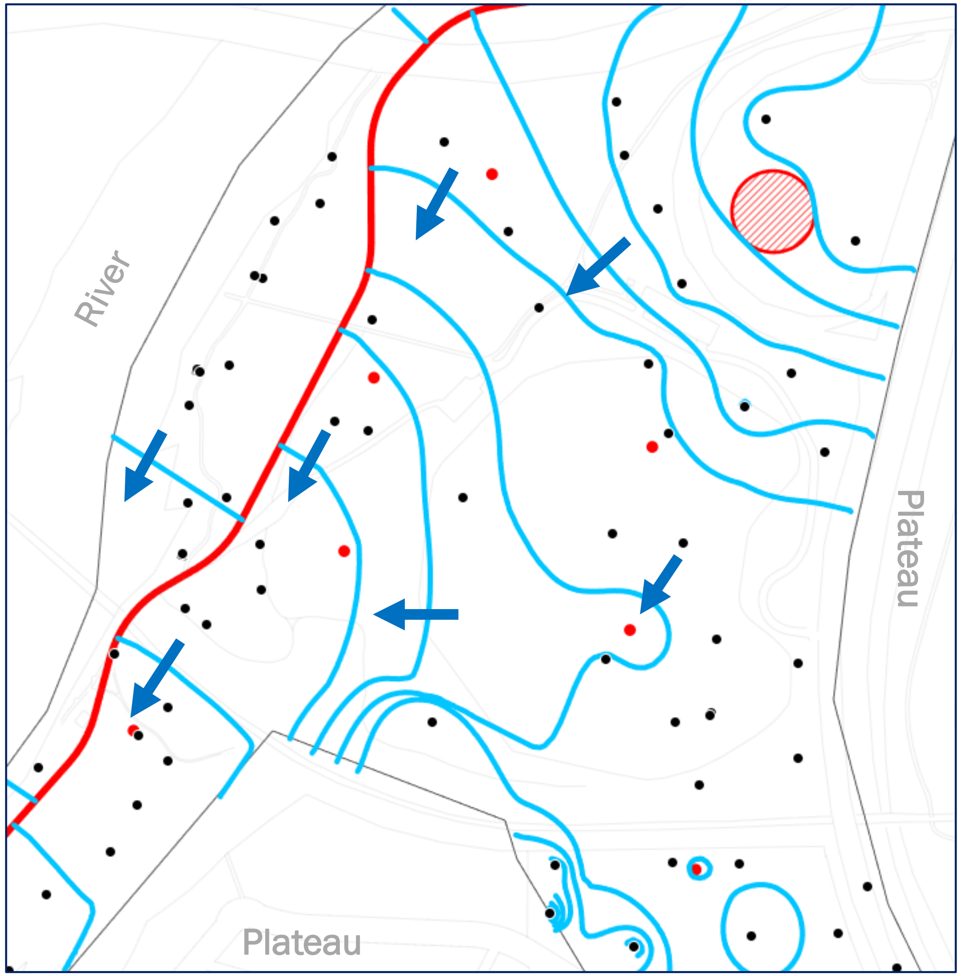


Groundwater elevation data from a site

MISCONCEPTIONS OF "PRESS-BUTTON" SOLUTIONS





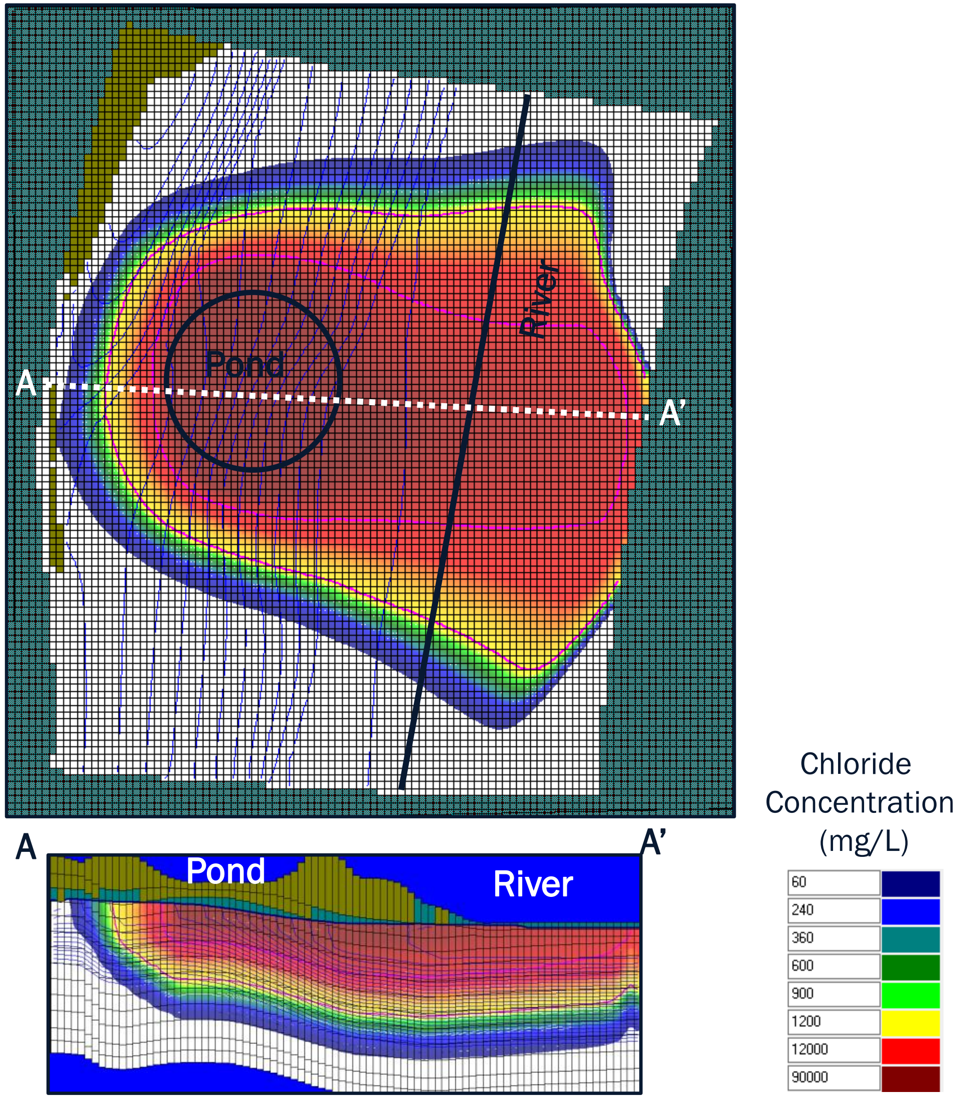


- Final contour map is based on site-specific hydrogeological conditions (discharge points, extraction wells, injection gallery, underground slurry wall, etc.)
- Manually modified based on computer-generated contours, experience of professional hydrogeologist and preliminary groundwater modelling results

GROUNDWATER MODEL TO REFINE CSM

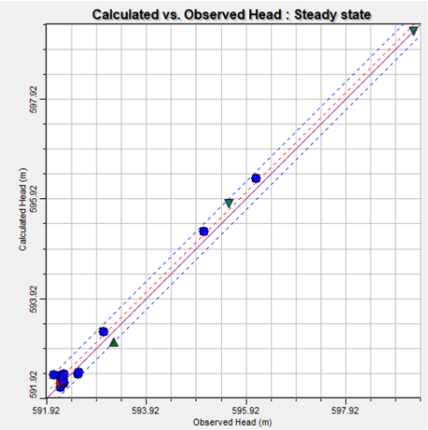
As An Example of Dynamic Models

- Groundwater flow and contaminant transport model created at a site
  - to refine site conceptual model (CSM)
  - to develop long-term monitoring strategies
- Preliminary CSM
  - Groundwater has been impacted by leakage from a historic brine pond, resulting in chloride concentrations in groundwater and riverbed porewater samples exceeding FAL guidelines
  - Groundwater risk management measures have included extraction for ~30 years and installation of a cutoff wall ~5 years ago to seal the pond
  - Chloride concentrations have shown a significant decline over the past 50 years, both before and after implementation of these risk management measures.
  - Consideration is being given to terminating groundwater extraction, which requires a long-term monitoring plan to support the decision.
  - It is necessary to determine whether the existing monitoring network and sampling frequency are sufficient for effective post-extraction monitoring

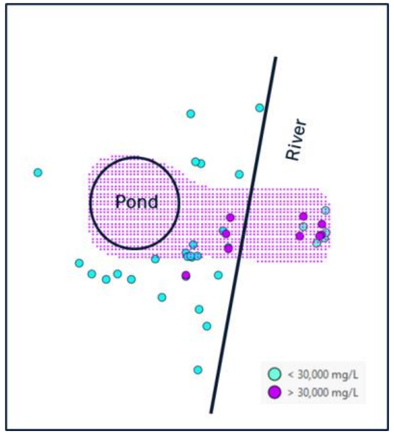


GROUNDWATER MODEL TO REFINE CSM

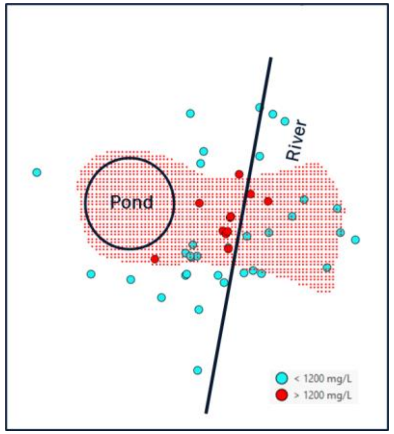
- Objectives of CSM refinement
  - Explain the presence of a vertical hydraulic gradient and its influence on chloride migration
  - Assess reasons for persistent chloride exceedances despite long-term concentration declines and the implementation of risk management measures
  - Evaluate the necessity of installing deep monitoring wells in bedrock
  - Determine future monitoring frequency
- Groundwater models were developed to represent the flow system and reconstruct the contamination history
  - Models achieved reasonable calibration of groundwater levels
  - Chloride concentrations in groundwater and riverbed porewater over the past ~50 years were approximately matched to observed data. This level of agreement is expected due to uncertainties in characterization of site details
  - Despite these uncertainties, achieving an approximate match is considered necessary and valuable for refining the conceptual site model (CSM)



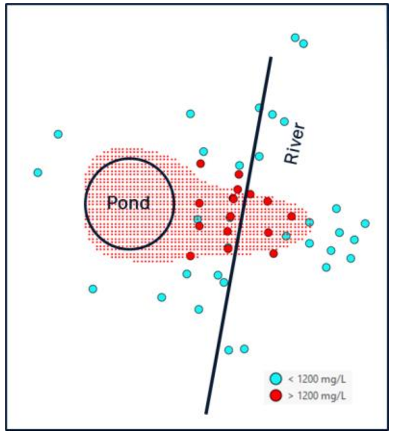
Calibration of GW Levels



Observed and Simulated Cl Concentrations (1997)



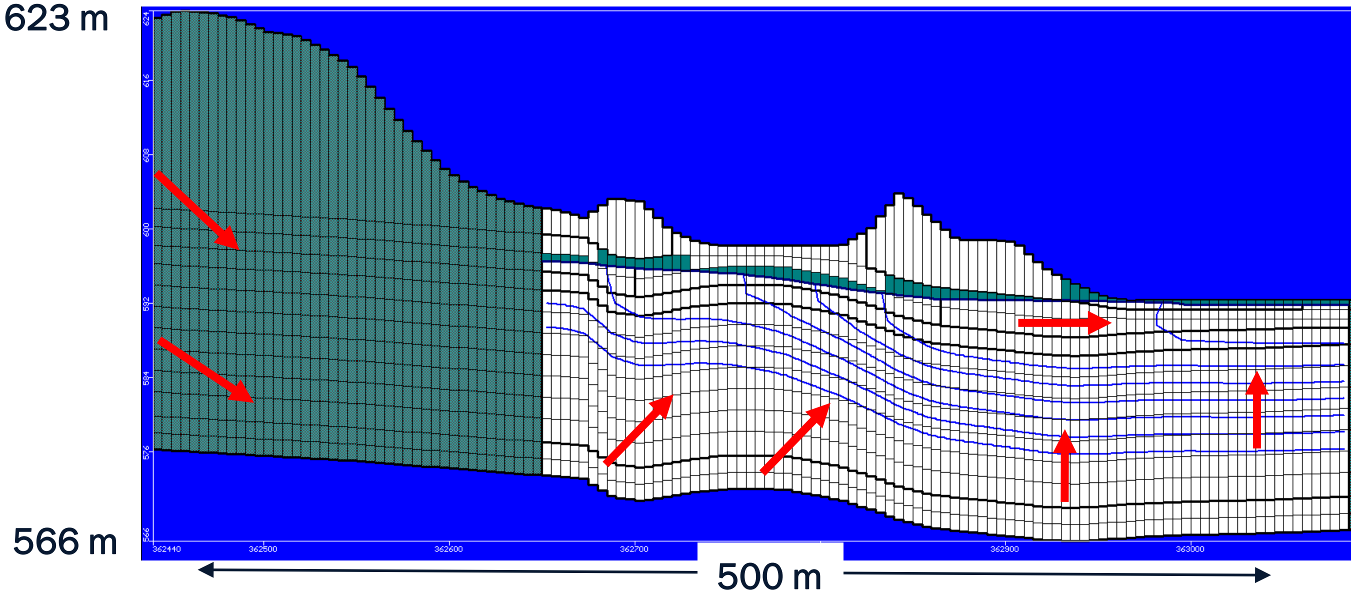
Observed and Simulated Cl Concentrations (2013)



Observed and Simulated Cl Concentrations (2020)

GROUNDWATER MODEL TO REFINE CSM

- The models provide valuable insights into groundwater flow and contaminant migration
    - The observed upward hydraulic gradient is likely due to the regional groundwater flow system, with groundwater discharging to the river both laterally and vertically. This may explain the exceedances detected in riverbed porewater samples.

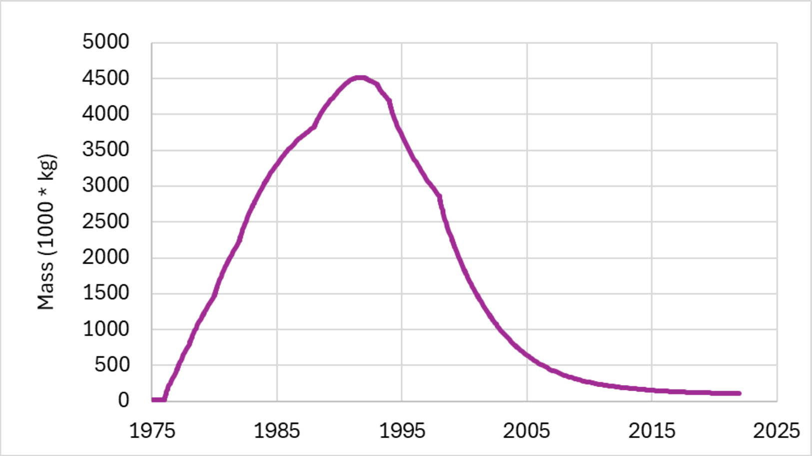


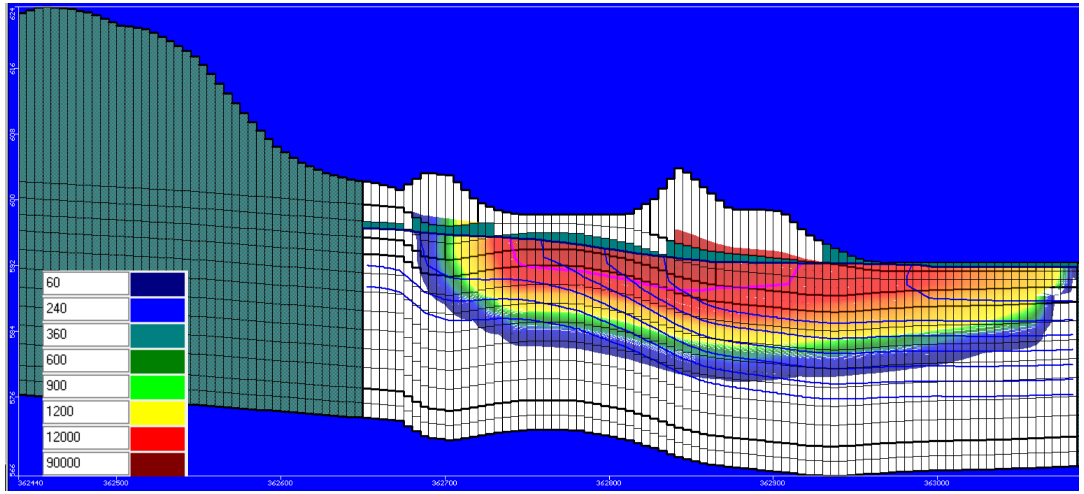
Simulated groundwater contours and interpreted flow directions

A GoogleEarth Profile

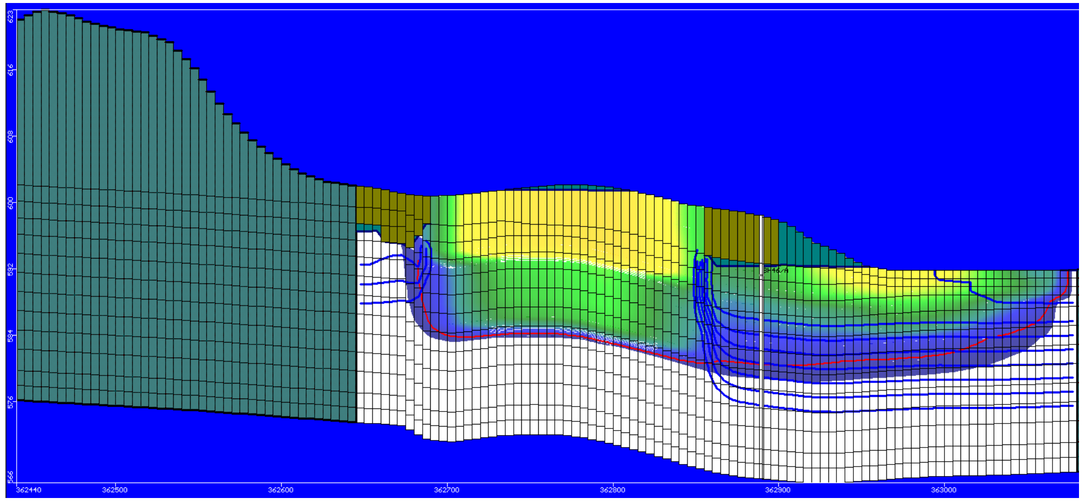
REFINED CSM

- A substantial amount of chloride may have migrated to deep bedrock, forming a pool of low but still exceeded concentrations. This could explain the persistent exceedances in groundwater, even after prolonged natural decline and groundwater extraction
- Majority (>95%) of the chloride mass from the original leakage has been “washed out”, so the overall declining concentration trend is expected to continue
- The cutoff wall has successfully contained most of the remaining chloride mass. However, continuous monitoring and assessment is required to determine when concentrations entering the river will meet guidelines





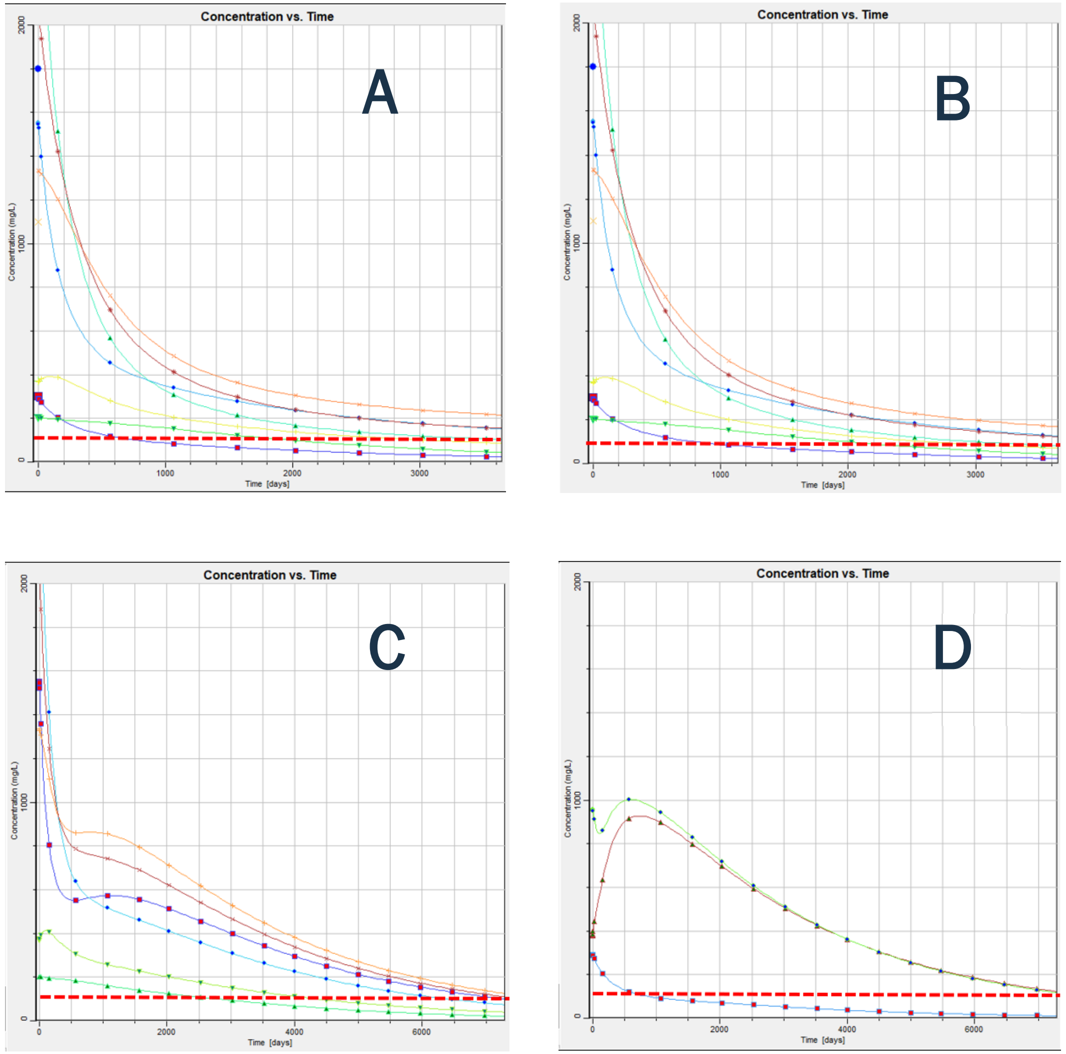
Simulated Cl Concentrations (1991)



Simulated Cl Concentrations (2024)

DEVELOPMENT OF LONG-TERM MONITORING STRATEGIES

- Existing monitoring network, including compliance points near the river, is generally sufficient for post-extraction monitoring
  - Installing deep bedrock wells is not necessary, given the expected long-term decline in concentrations.
  - One or two additional wells may be beneficial to characterize current concentrations beneath the former pond.
- Additional modelling conducted to test different scenarios
  - A: Concentrations at compliance points are expected to continue declining under current site conditions but may remain above guideline levels for an extended period (>10 years).
  - B: Varying assumptions about concentrations beneath the pond or resuming groundwater extraction have minimal impact on model predictions.
  - C: Damage to the cutoff wall could cause a short-term rebound in concentrations but would not alter the overall long-term declining trend.
  - D: Selected monitoring wells immediately downgradient of the pond can be used to detect potential wall damage.
  - An updated evaluation in five years is appropriate, based on the predicted concentration trends.



TAKEAWAY MESSAGES

- Digital data presents a goldmine of opportunities to improve data management, data presentation, and conceptual understandings for contaminated sites
  - Adopting digital twin concepts and technologies would help to maximize these opportunities
- One of the key components of a digital twin is proper use of models to represent the real world
  - “Paper-based” thinking and practices remain all too common and overlook available functions and tools offered by digital systems
  - "Press-button" tools are excellent ways to streamline workflows, but must be used with understanding of underlying assumptions and limitations of the models behind these tools
- Groundwater modelling is an excellent digital twin for contaminated sites
  - One case study is presented to show use of groundwater to refine CSM and prepare a long-term groundwater strategies
- Topics not included in this presentation
  - Digital twin concepts and technologies can enhance contaminated site planning and management processes, such as optimizing soil sampling locations and managing large groups of contaminated sites
  - Digital twins for contaminated sites have unique characteristics compared to other systems, including a general lack of sufficient data to fully characterize site conditions and longer timeframes required for data collection to slow down adjustments of field actions
  - There is currently a lack of regulatory guidance and industry-wide protocols to support and promote the application of digital twins in contaminated site management.

CLOSING

Thank you!

Questions?