Data and Model-Driven Decision Support for Environmental Management of a Chromium Plume at Los Alamos National Laboratory (LANL)

- 13264

Velimir V. Vesselinov ("monty")[1] vvv@lanl.gov, Danny Katzman[2], David Broxton[1], Kay Birdsell[1], Steven Reneau[1], David Vaniman[3], Pat Longmire[3], June Fabryka-Martin[3], Jeff Heikoop[3], Mei Ding[3], Don Hickmott[3], Elaine Jacobs[3], Tim Goering[2], Dylan Harp[1], Phoolendra Mishra[1]

[1] Computational Earth Sciences, Earth and Environmental Sciences,
[2] Environmental Programs,
[3] Earth Systems Observations, Earth and Environmental Sciences,
Los Alamos National Laboratory (LANL), Los Alamos, NM

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Outline

- ✧ **Model-based Decision Support**
- ✧ **Deterministic, Probabilistic vs Non-Probabilistic Decision Methods**
- ✧ **Information Gap (info-gap) Decision Theory**
- ✧ **Decision Support for Chromium contamination site @ LANL**
  - Site conceptual model
  - Model-based decision analyses
  - Monitoring network design
  - Additional activities related to contaminant remediation

✧ **MADS: Model Analyses & Decision Support**
Open source computational framework
http://mads.lanl.gov

✧ **Decision Support in ASCEM (Advanced Subsurface Computing for Environmental Management) | http://ascemdoe.org**

Model-based Decision Support

- provides decision makers with model analysis of decision scenarios: evaluation, ranking and optimization of alternative decision scenarios
- takes into account site data and knowledge including existing uncertainties
  (uncertainties in conceptualization, model parameters, and model predictions)
- Decision metric(s): e.g. contaminant concentration or environmental risk at a point of compliance, etc.
- Decision goal(s): e.g. no exceedance of MCL's, dose limits, or risk levels at compliance points
- Decision scenarios: combinations of predefined activities to achieve the decision goal(s)

Model-based Decision Support (cont.)

- Activities:
  - data acquisition campaigns
  - field/lab experiments
  - monitoring
  - remediation
- Activities are analyzed in terms of their impact on decision making process (decision uncertainties)
- Decision uncertainties: uncertainties associated with selection of optimal decision scenarios, or performance of specific decision scenarios
- The Game: Decision maker vs. Nature

Important:

- Additional activities are selected only to reduce decision uncertainties
- Additional activities are not selected to reduce model or parameter uncertainties (unconstrained problem).

Decision Methods

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Decision Methods

- **Deterministic methods ("traditional" performance assessment): a single model simulation representing worst-case or expected ("best" estimated) system behavior**
- **Probabilistic methods (Bayesian techniques, GoldSim): analyses based on a series of model simulations capturing expected probabilistic uncertainties (Monte Carlo, Markov Chain Monte Carlo, Null Space Monte Carlo, etc.)**
- **Non-probabilistic methods: analyses based on a series of model simulations representing unknown uncertainties (Minimax/Maximin Theory, Information Gap Decision Theory, etc.)**

Non-Probabilistic Decision Methods

- Lack of knowledge or information precludes decision analyses requiring probabilistic distributions (e.g. Bayesian approaches)
  - probability distributions cannot be defined (!)
  - uniform distributions frequently applied instead (causing biased decision analyses)
- Severe uncertainties can have important impact in the decision analyses
  - heavy tails: non-Gaussian distributions will infinite variances
  - black swans: low probability events in distribution tails with significant decision impacts
  - dragon kings: unexpected high probability events in the distribution tails
- Non-probabilistic decision methods can be applied to effectively incorporate lack of knowledge and severe uncertainties in decision making process
- Non-Probabilistic and Probabilistic methods can be coupled
  (e.g. unknown probability distribution parameters can be a subject of non-probabilistic analysis, e.g. info-gap)

Information Gap Decision Theory

- Non-probabilistic methodology for comparison of alternative decision scenarios
- Decision uncertainty is bounded by robustness and opportuneness functions
- Robustness function (immunity to failure)
- Opportuneness function (immunity to windfall)

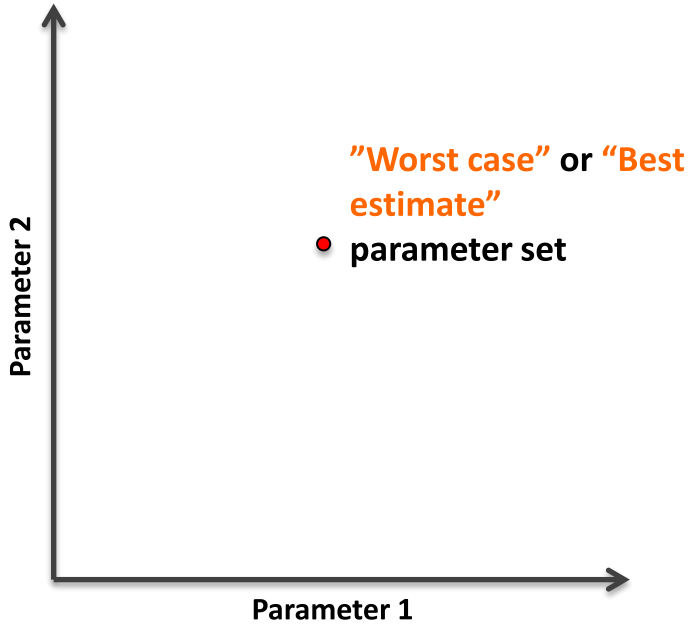
- Information Gap Decision Theory @ http://mads.lanl.gov

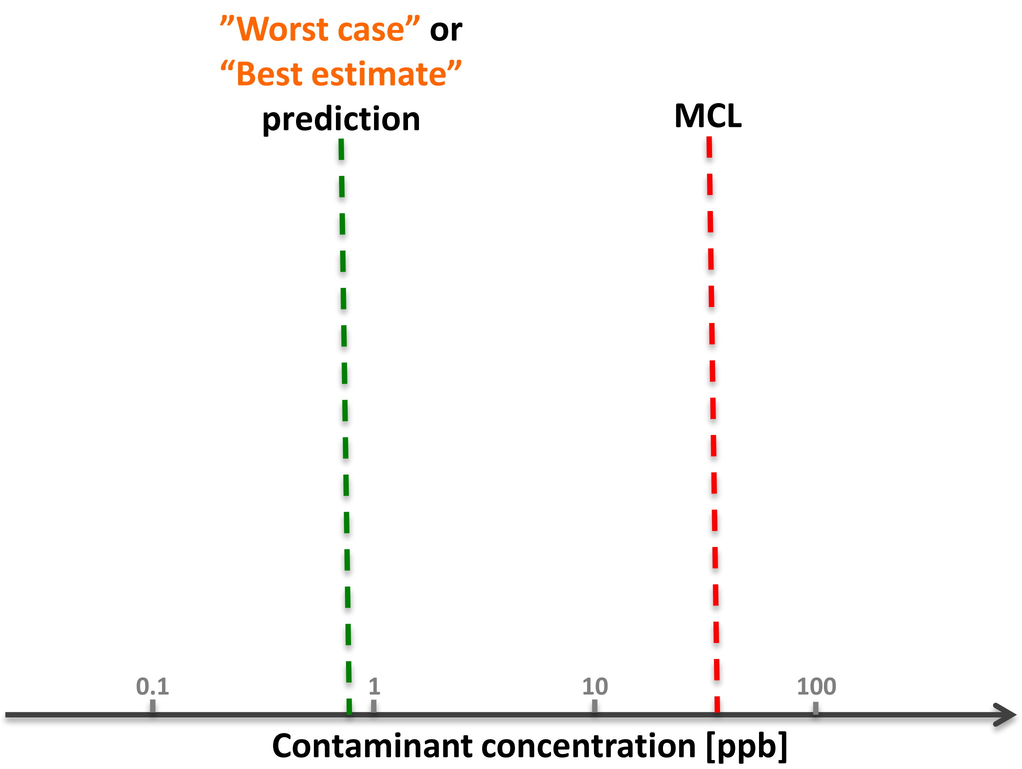
Ben-Haim (2006). *Info-gap decision theory: decisions under severe uncertainty*. Academic Press.

Example analyses:

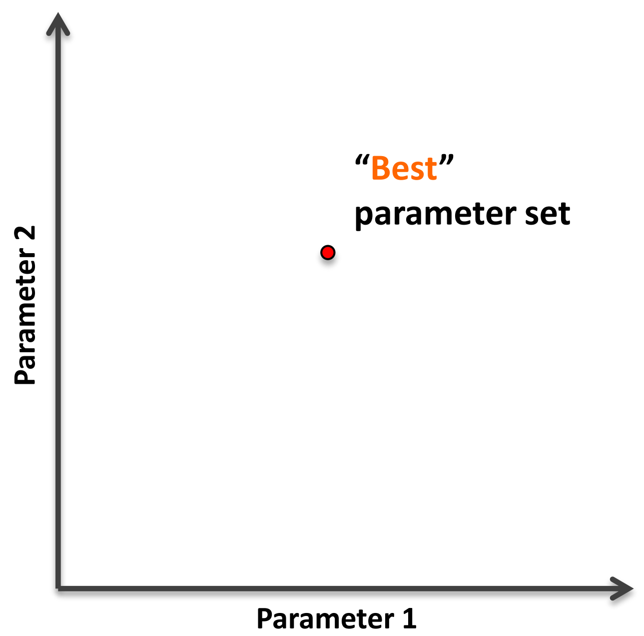
- Deterministic
- Probabilistic (Bayesian)
- Non-probabilistic (Info-Gap)

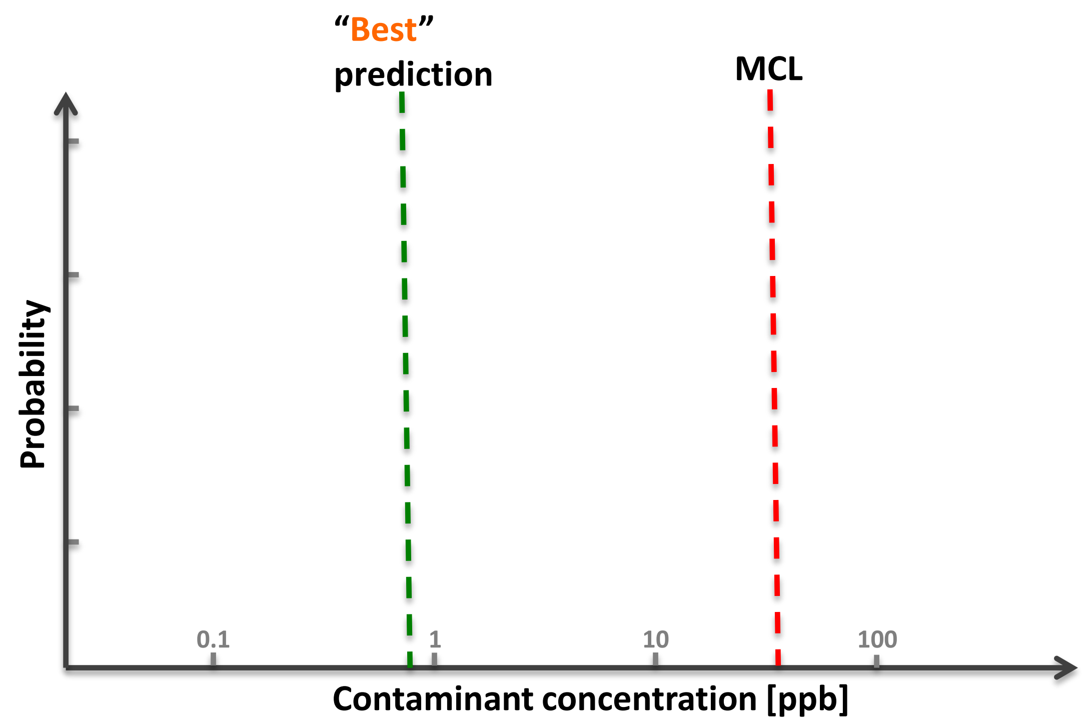
Deterministic analysis





Bayesian (probabilistic) analysis





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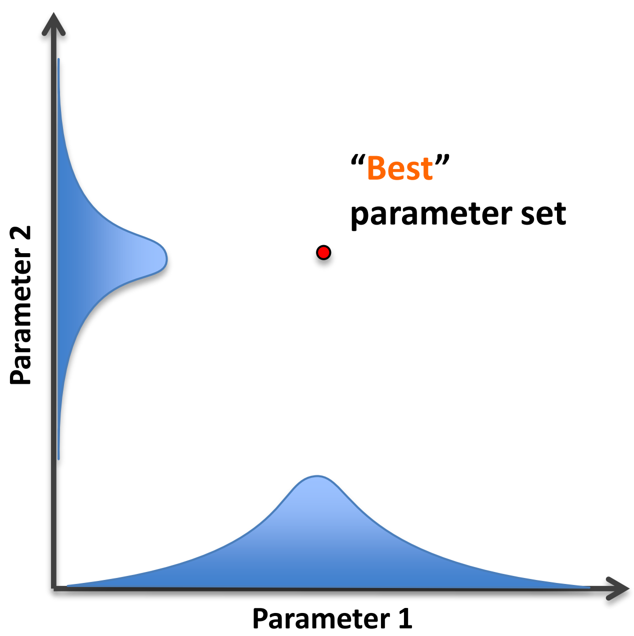

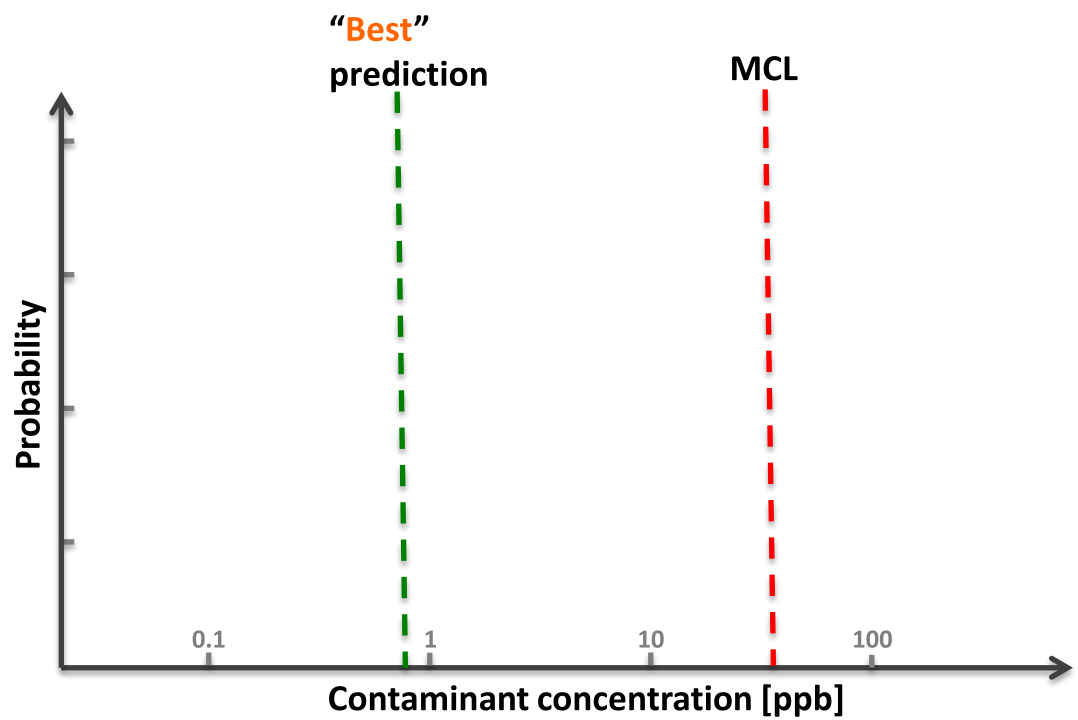

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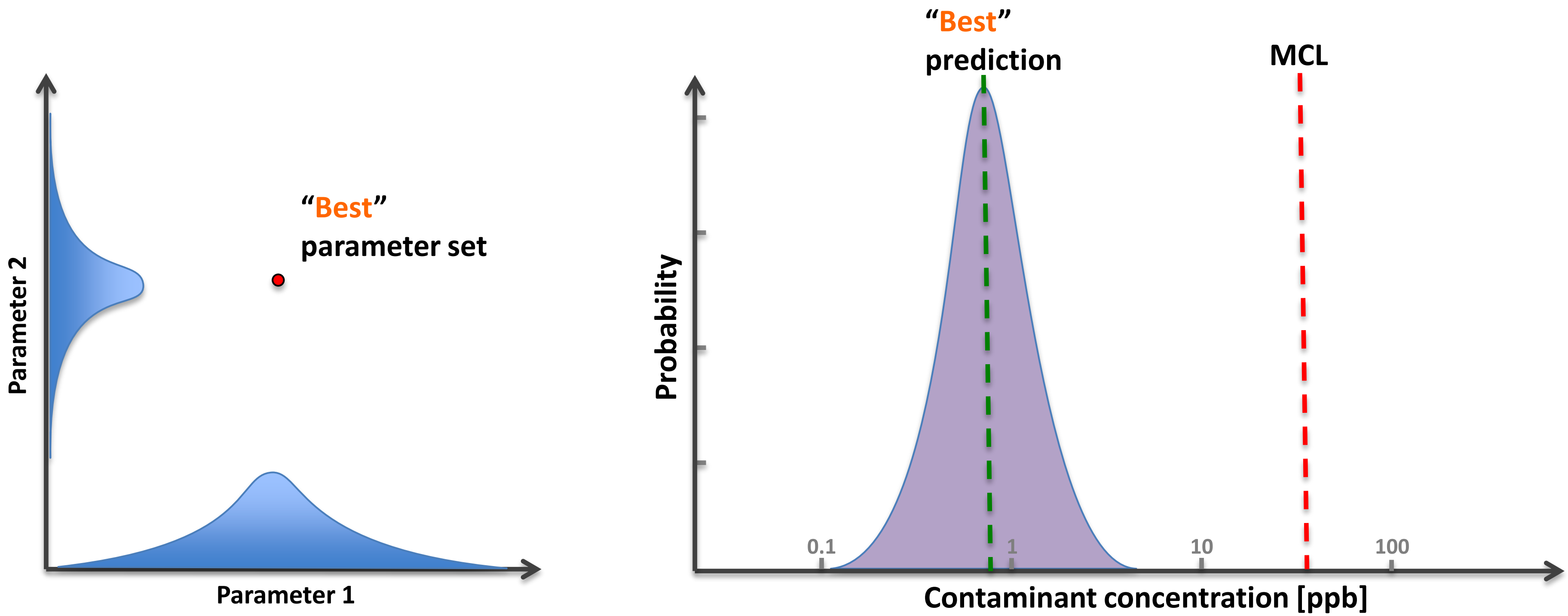

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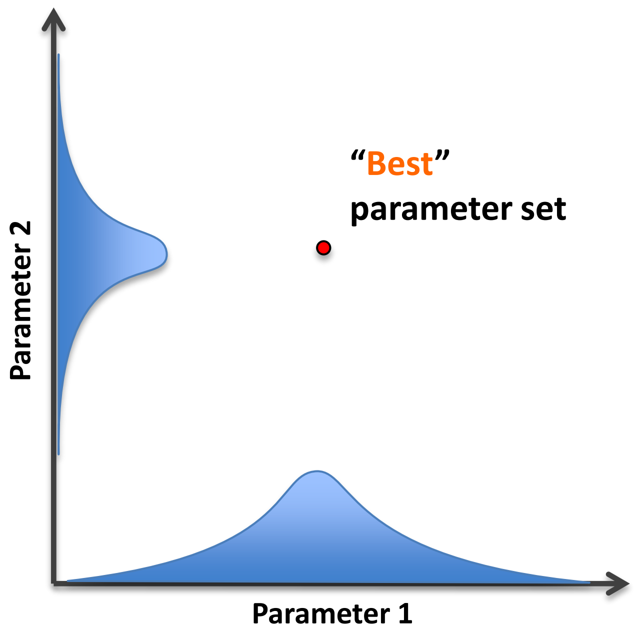
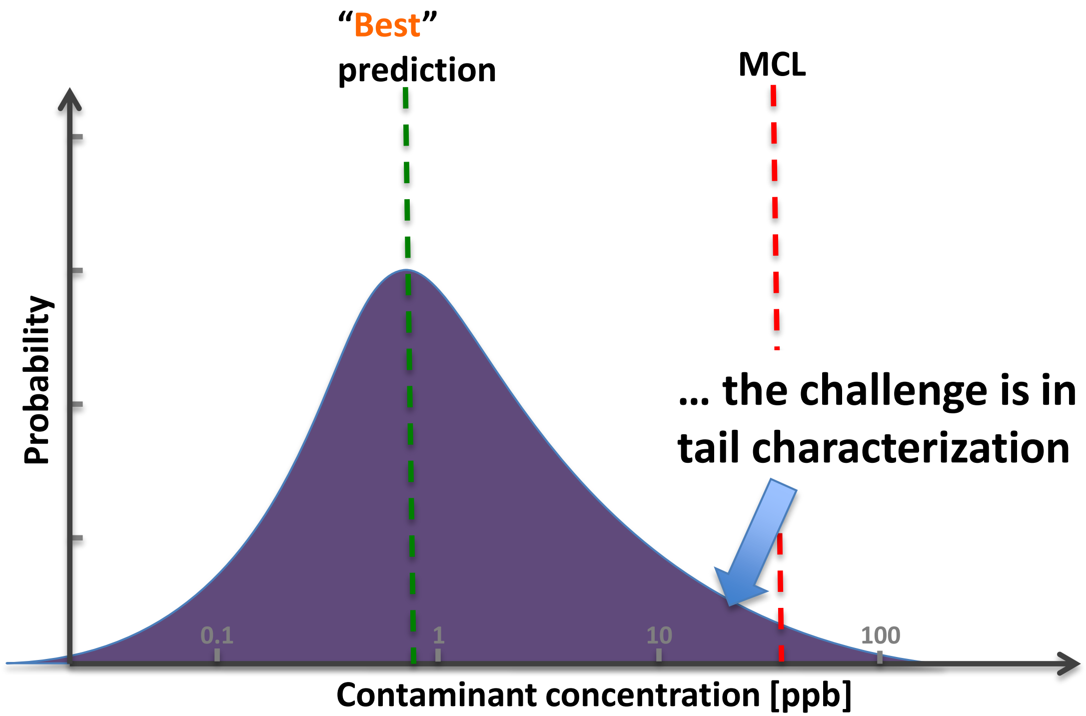
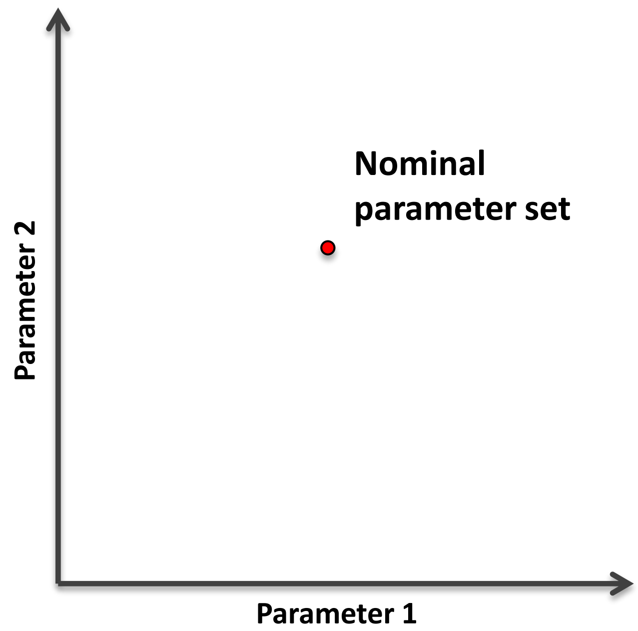
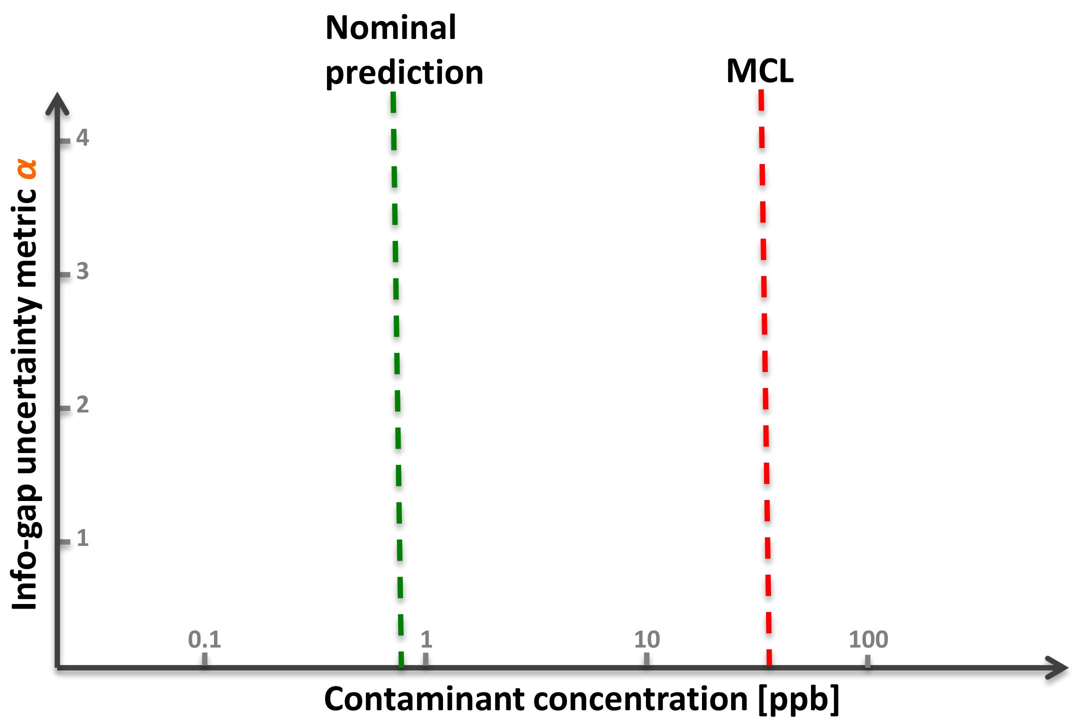




Info-Gap (non-probabilistic) analysis





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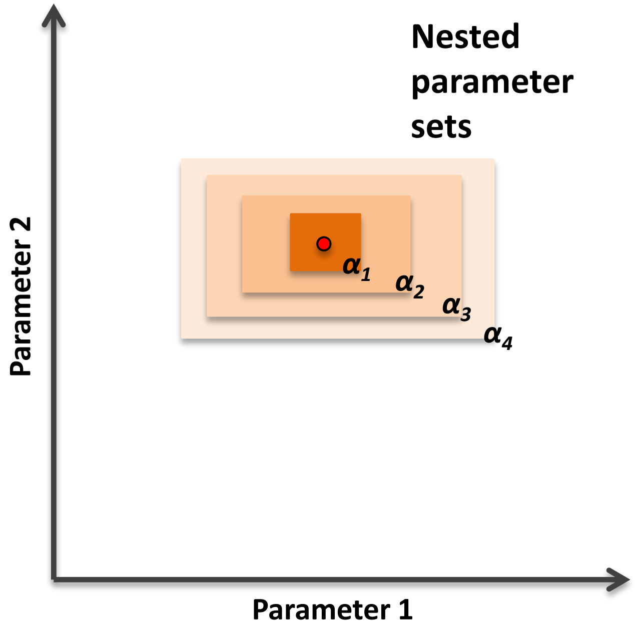

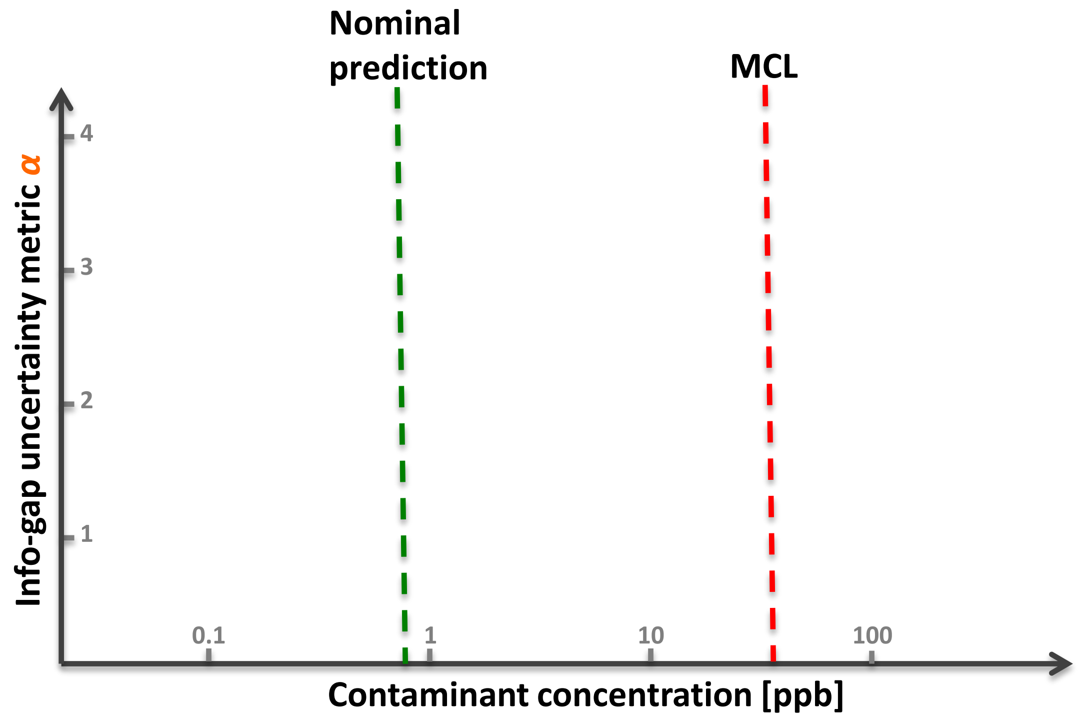

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$\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 \ldots < \alpha_\infty$

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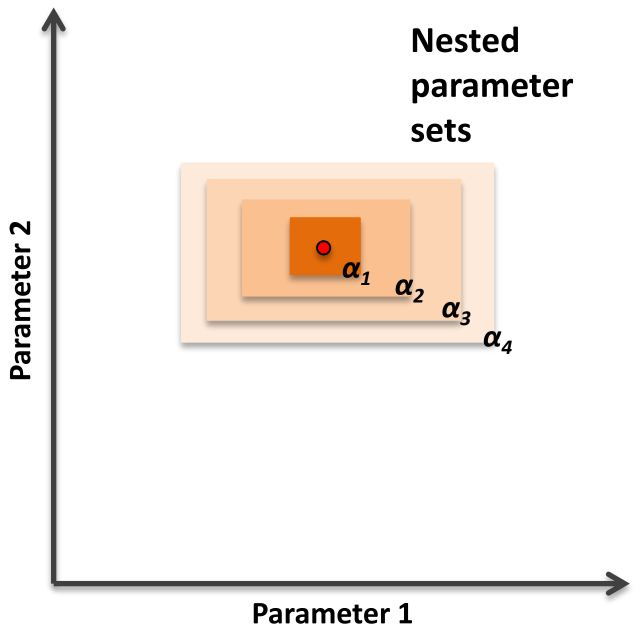

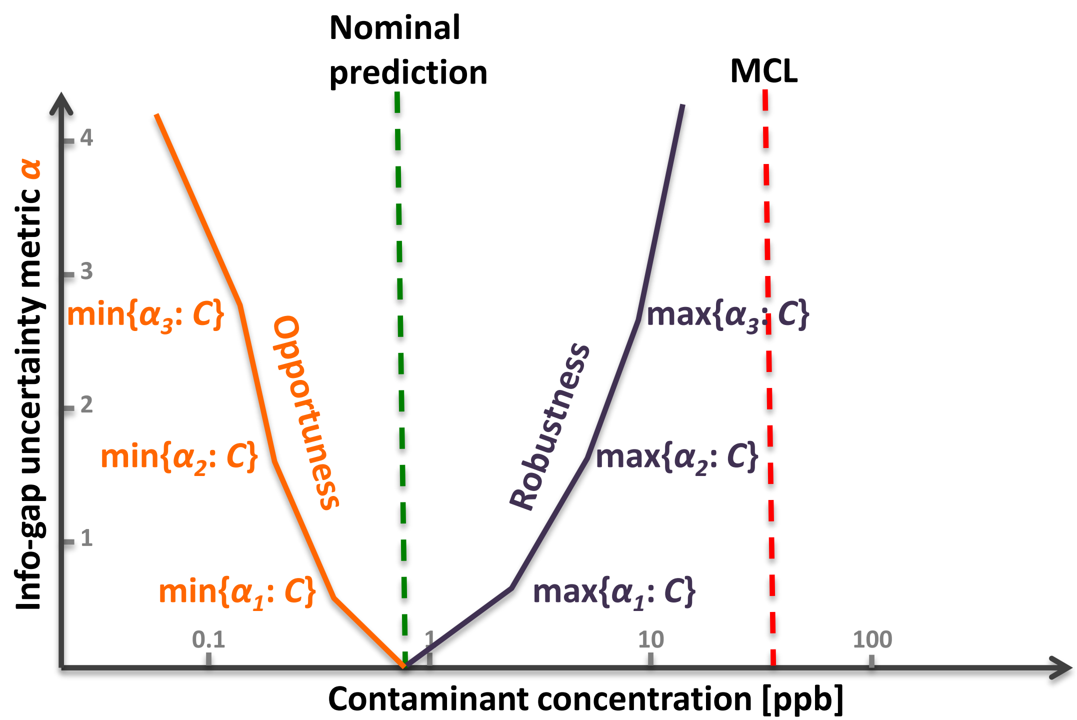

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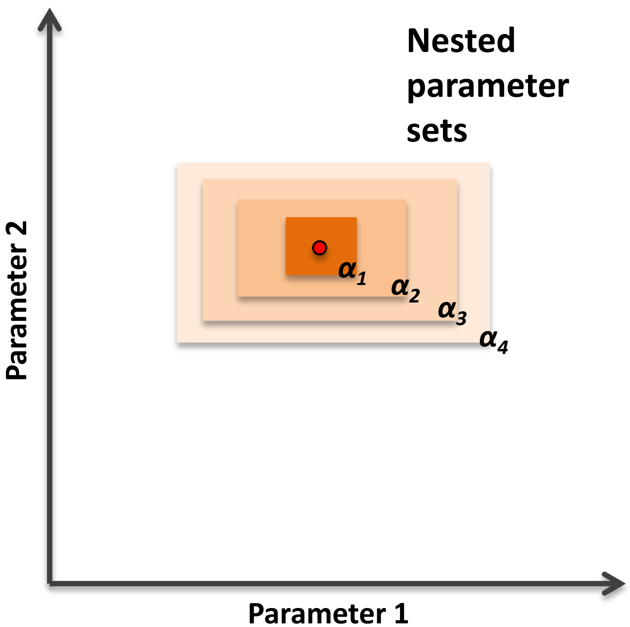

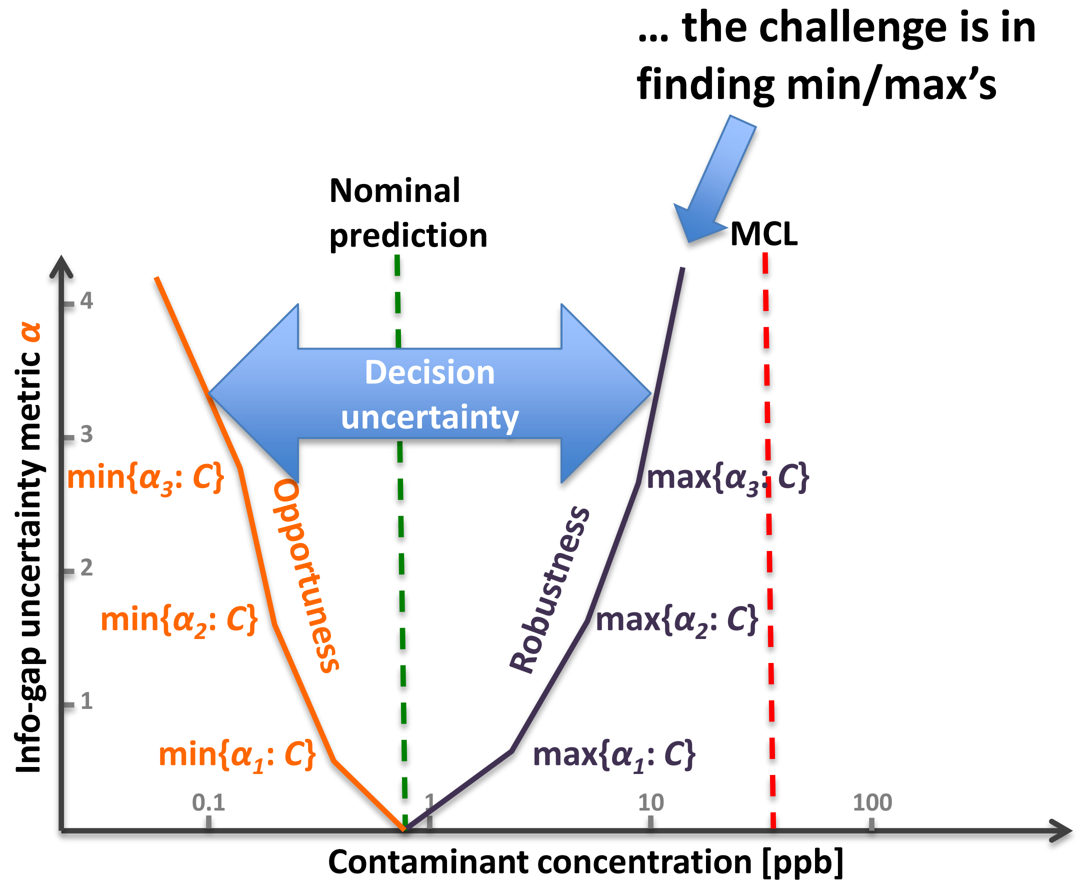

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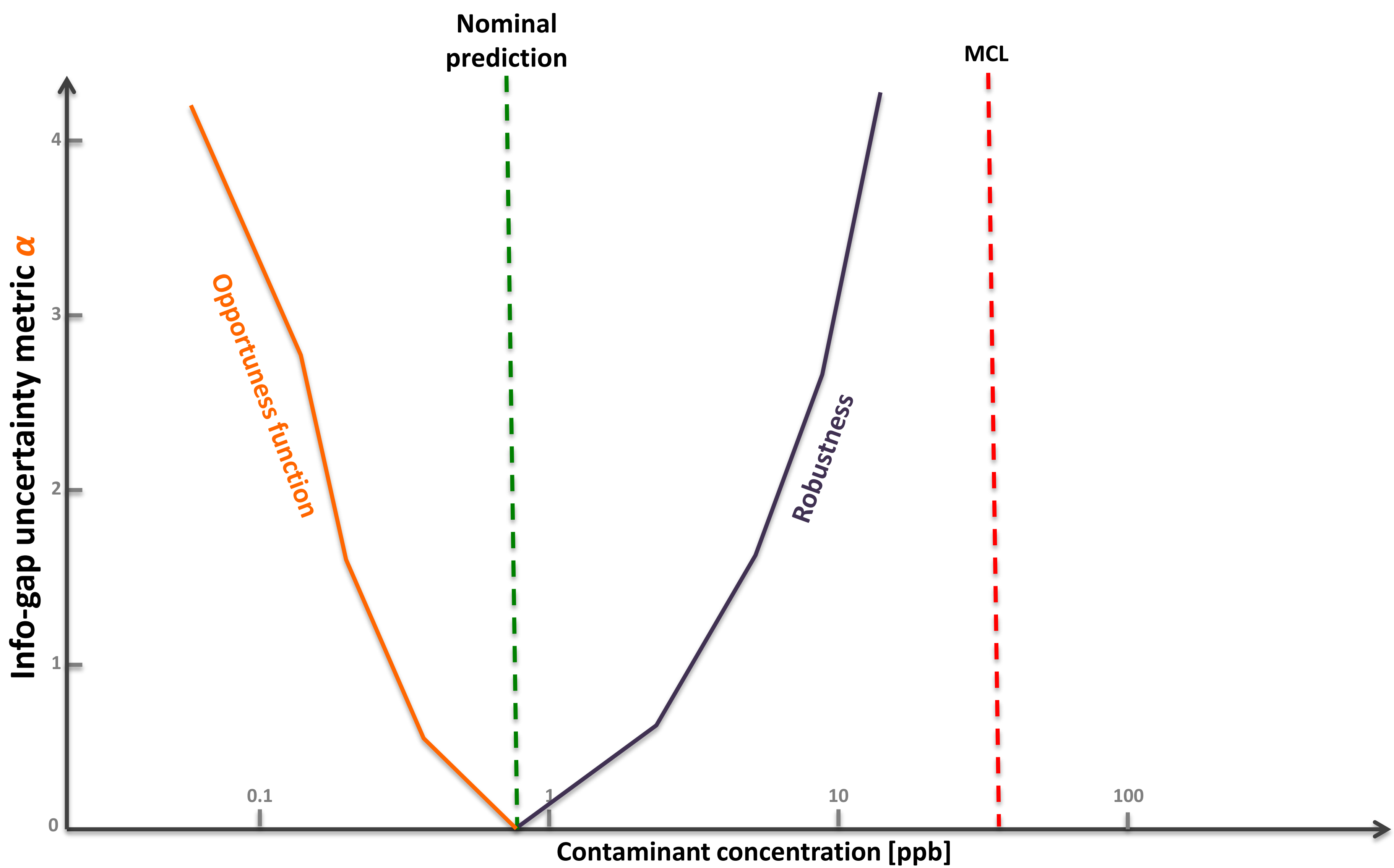
Info-Gap Analysis: Decision selection based on robustness



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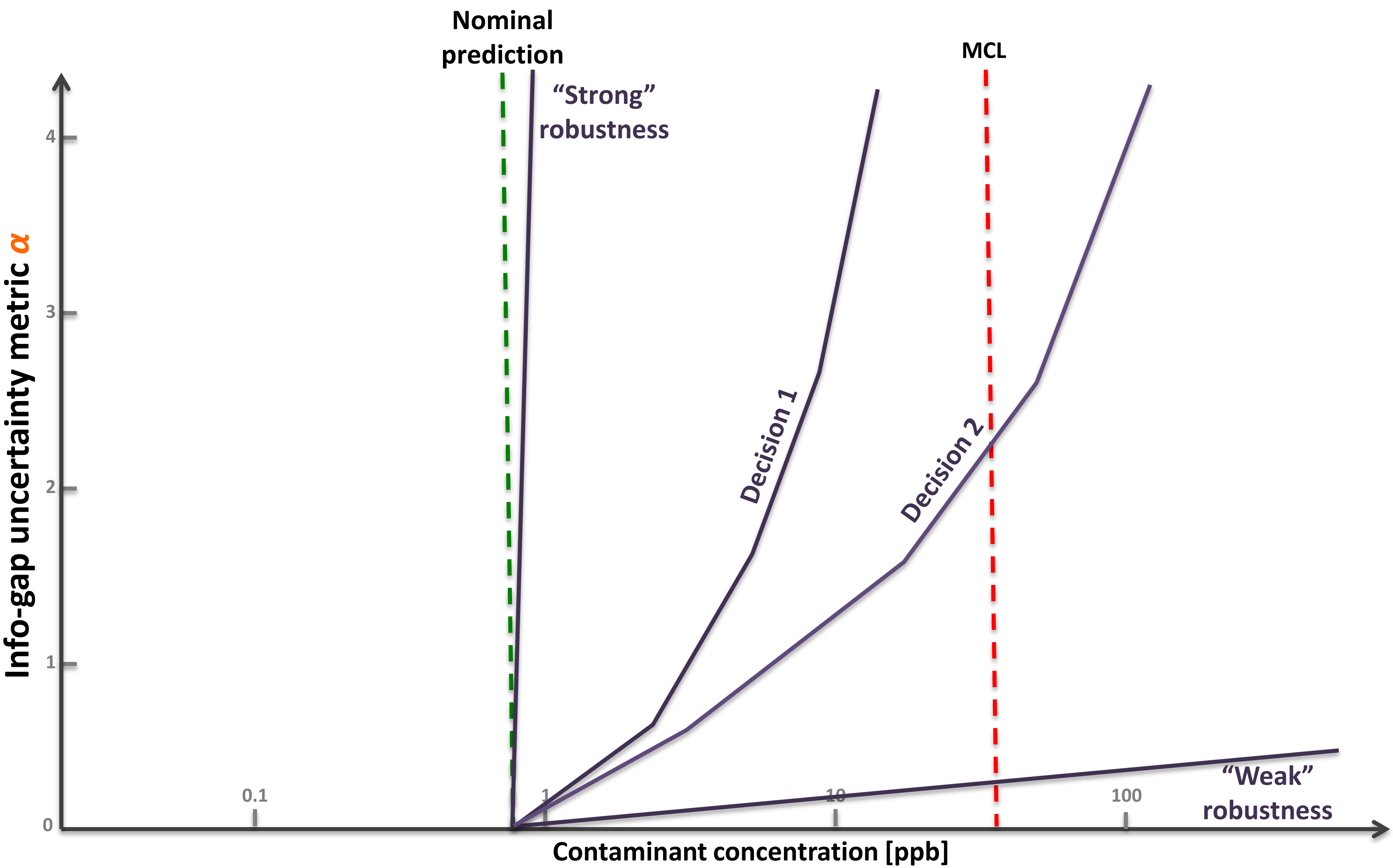

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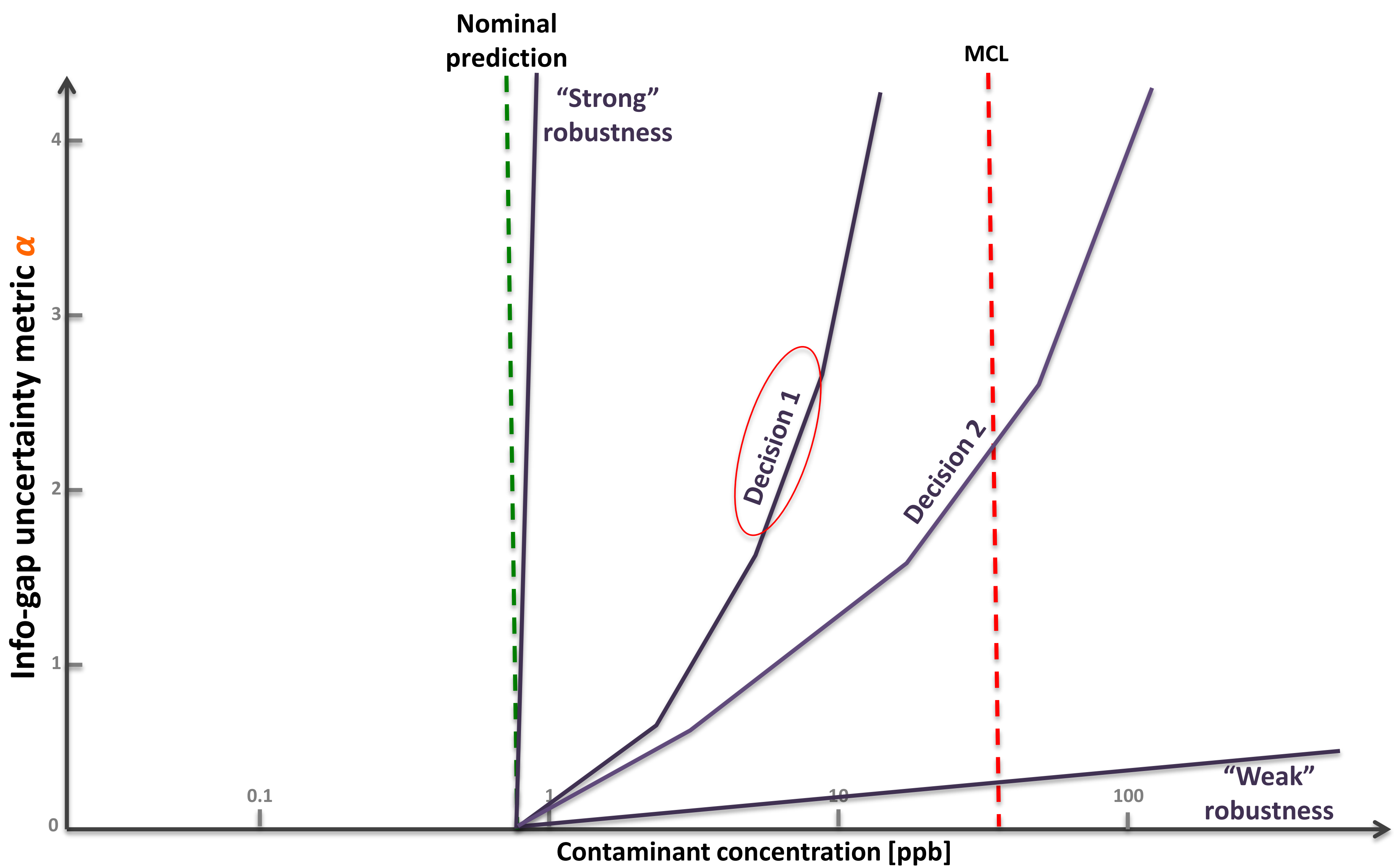
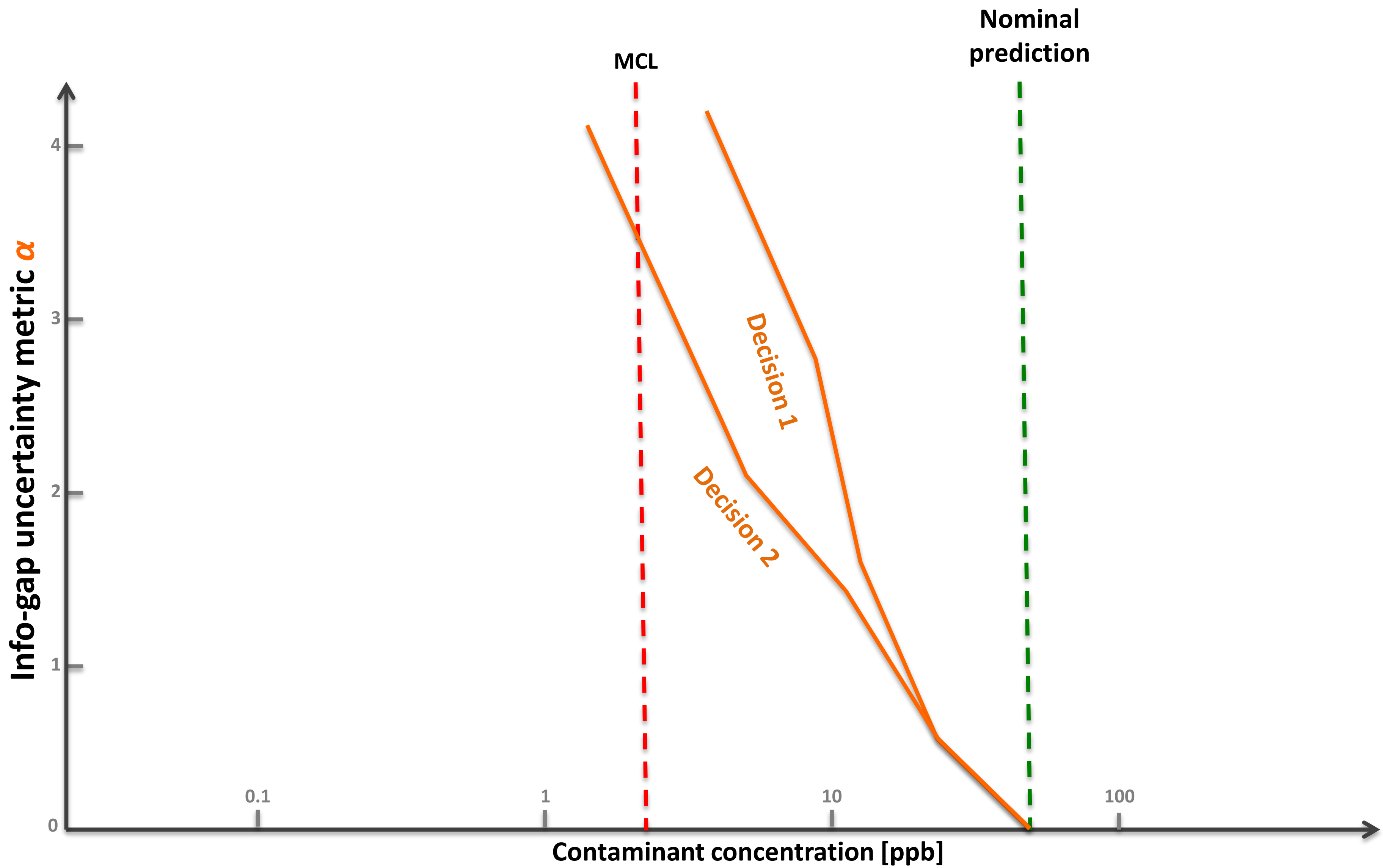


Info-Gap Analysis: Decision selection based on opportuness



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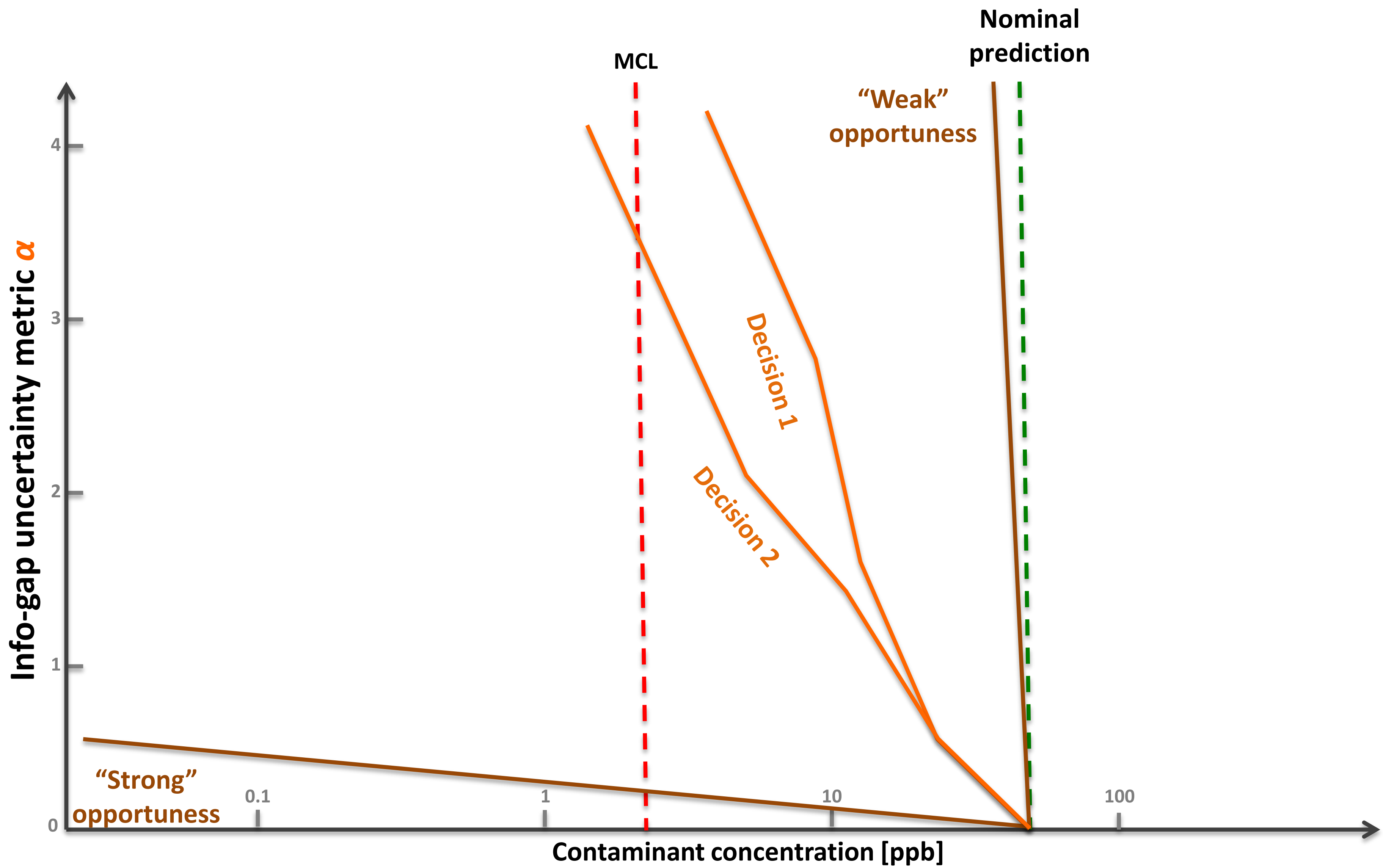

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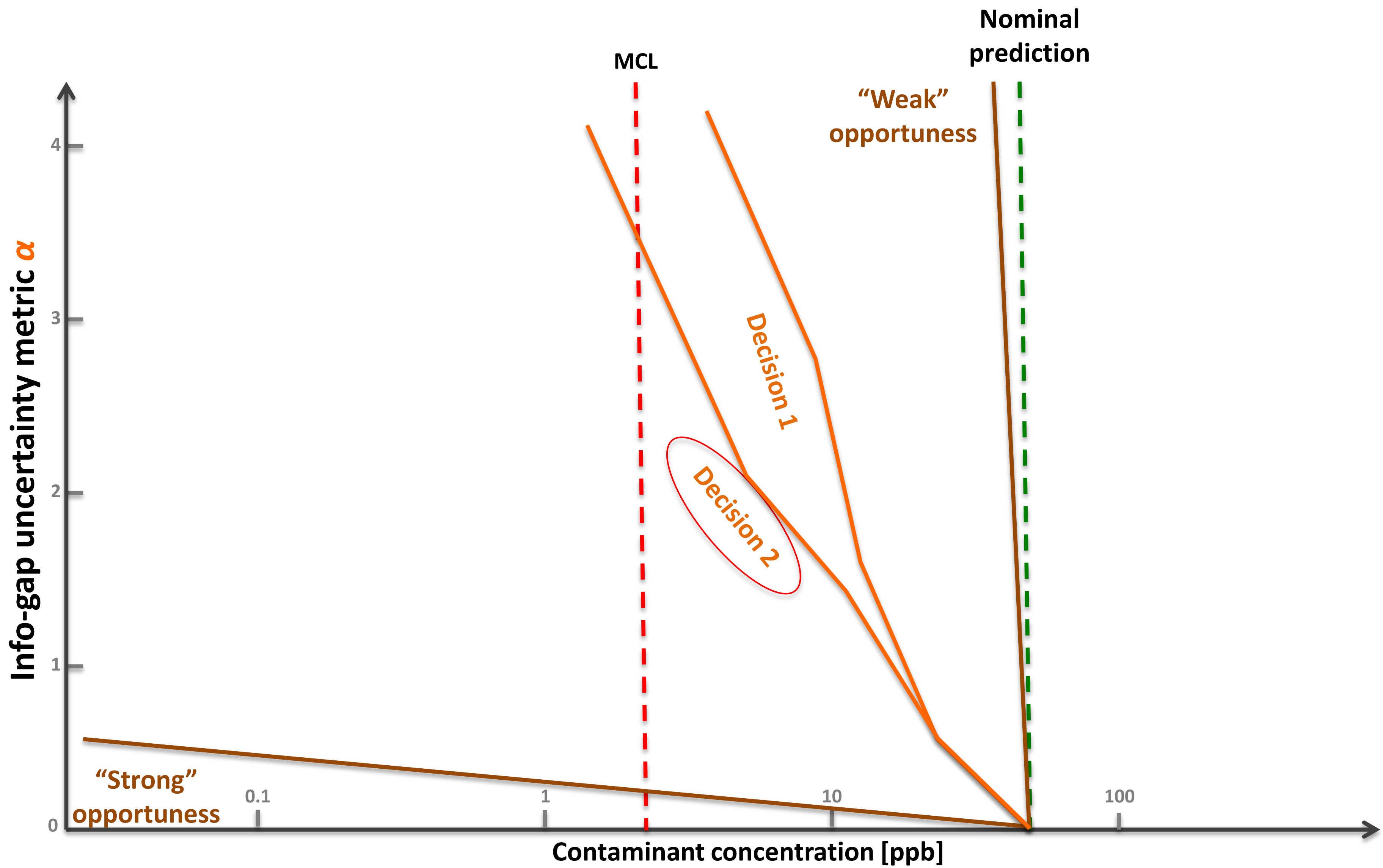
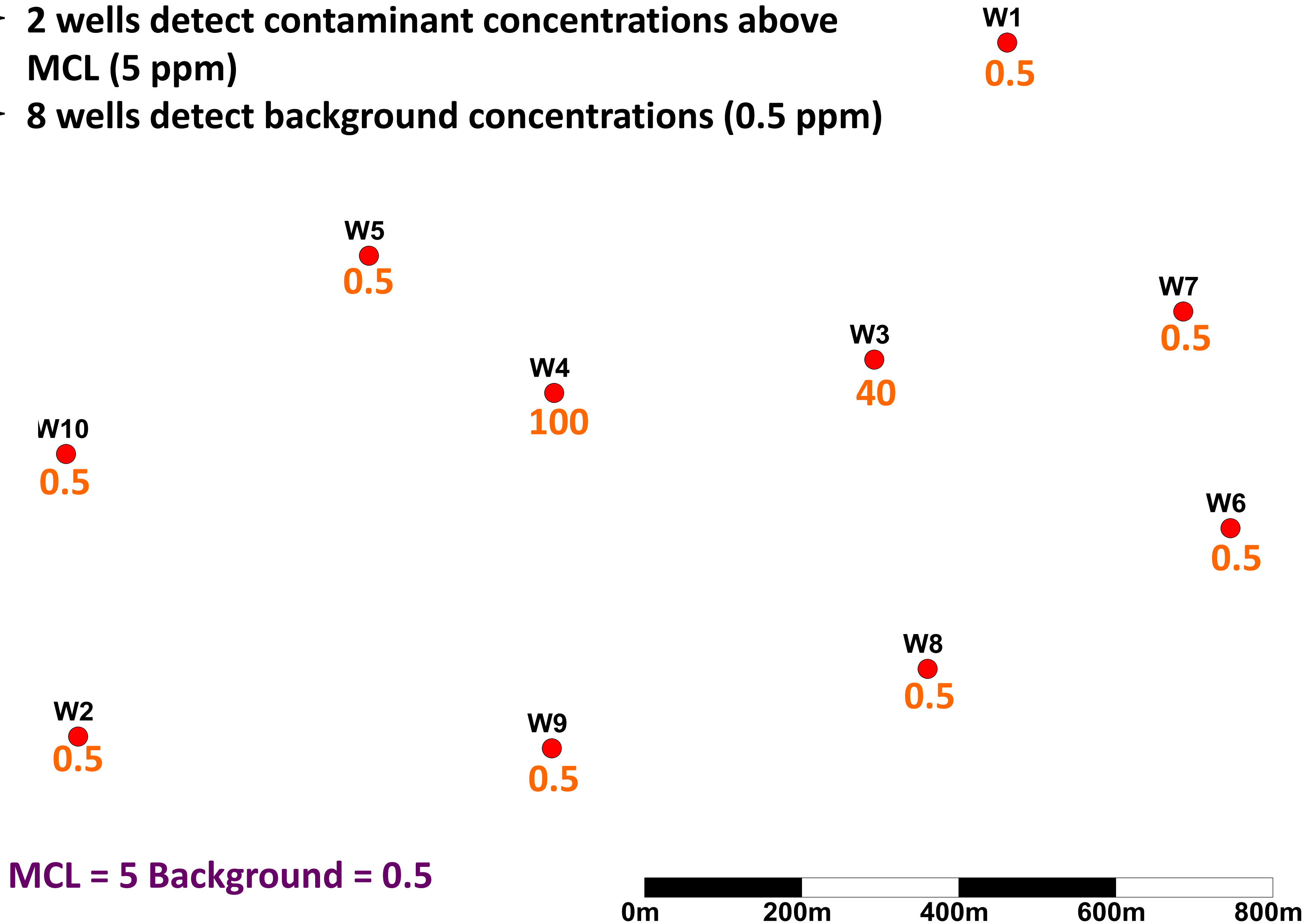


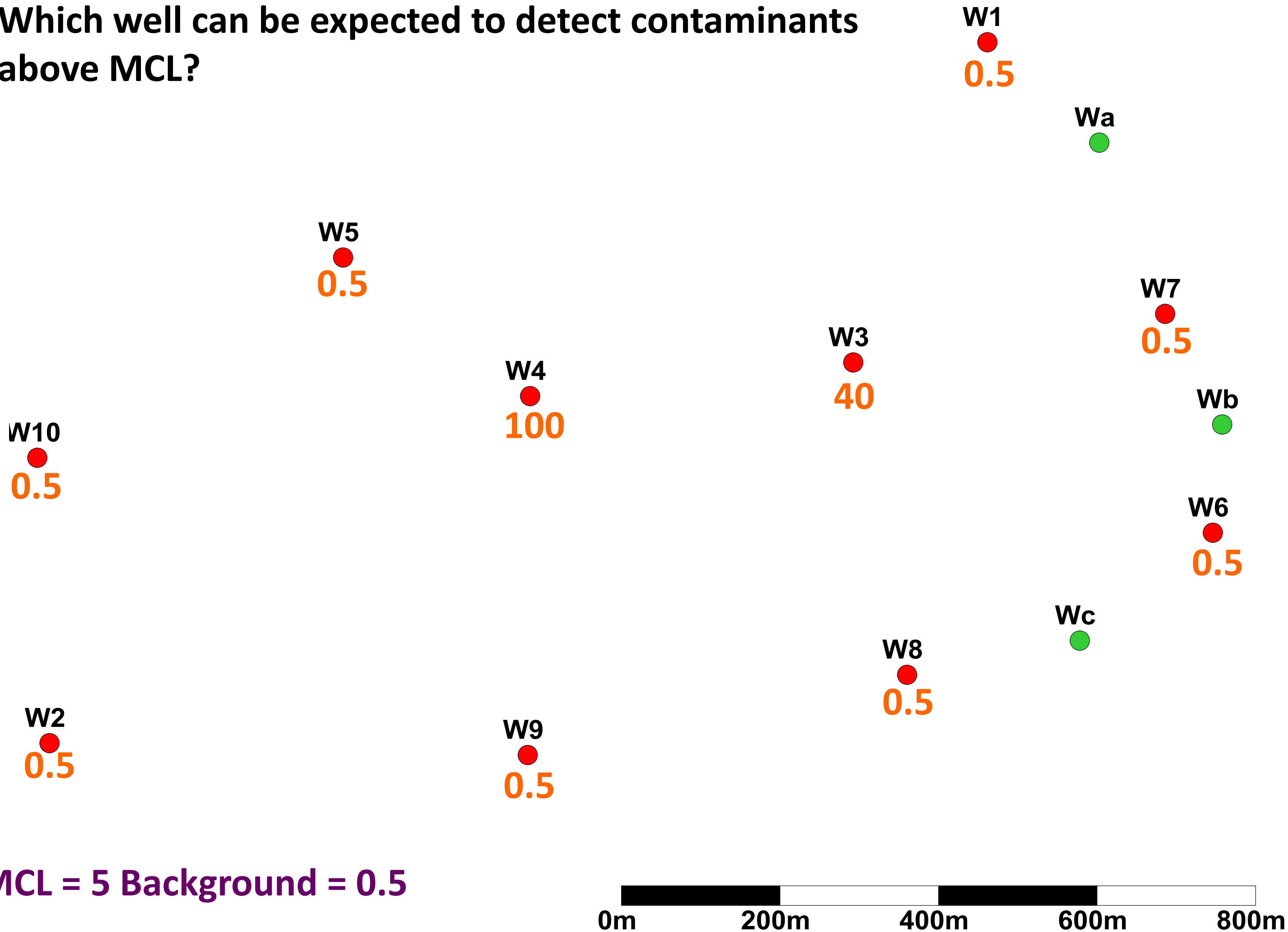
Info-Gap Analysis: Synthetic Network Design

- 10 monitoring wells in an aquifer
- 2 wells detect contaminant concentrations above MCL (5 ppm)
- 8 wells detect background concentrations (0.5 ppm)



Info-Gap Analysis: Synthetic Network Design

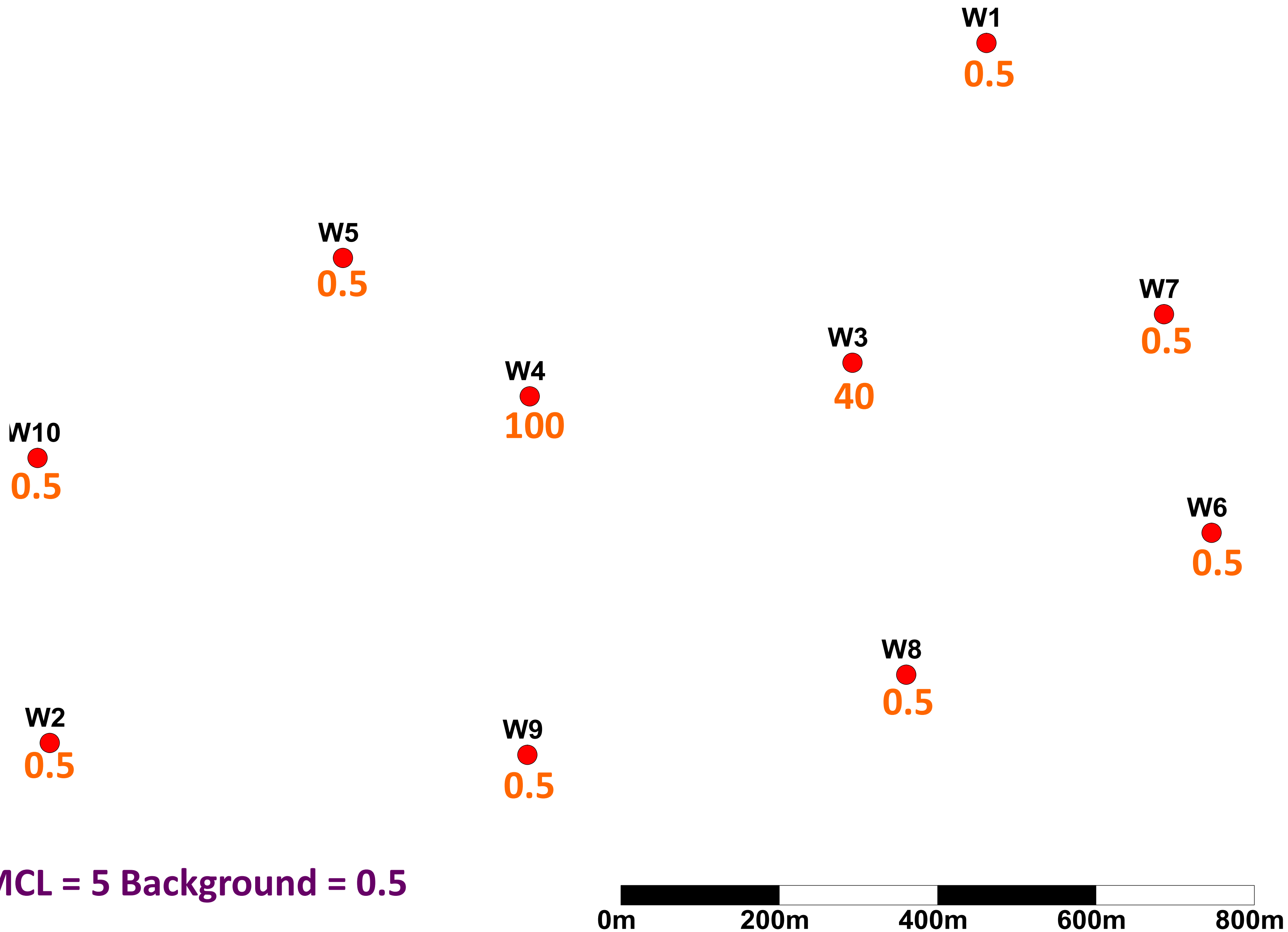
- 3 new proposed monitoring well locations (green dots)
- Which well can be expected to detect contaminants above MCL?



MCL = 5 Background = 0.5

Info-Gap Analysis: Synthetic Network Design

✧ **Where is the contaminant source?**



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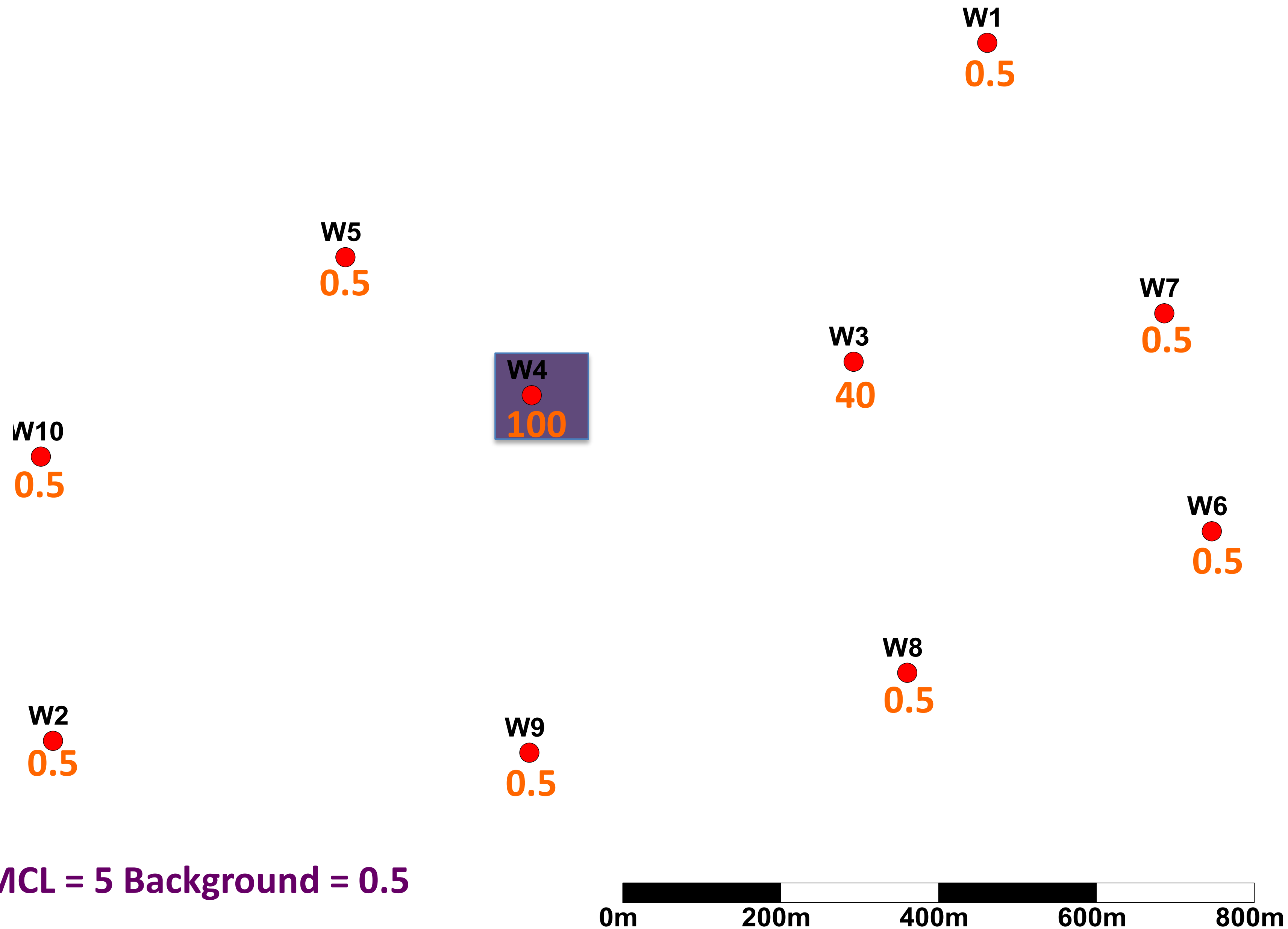

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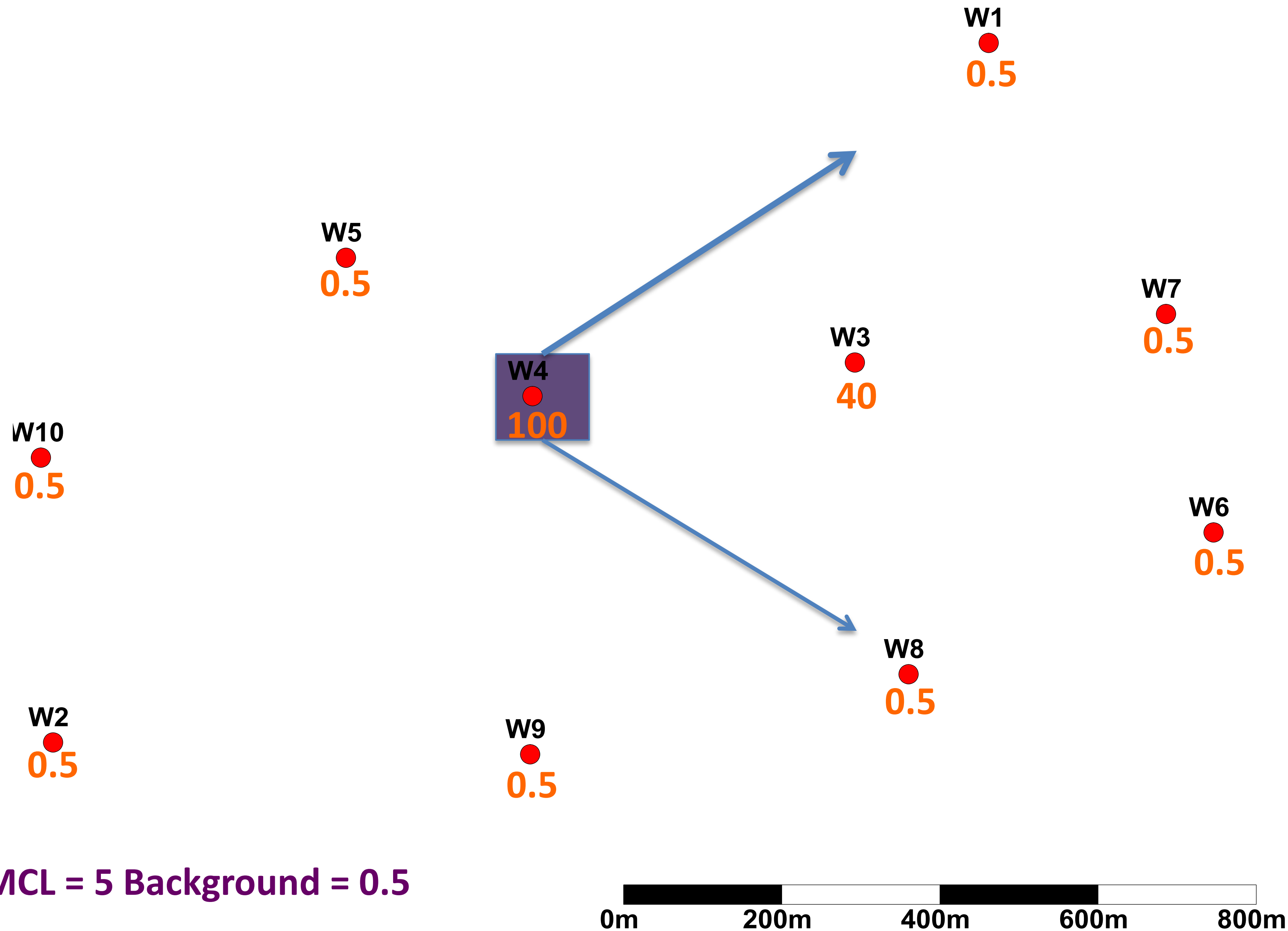

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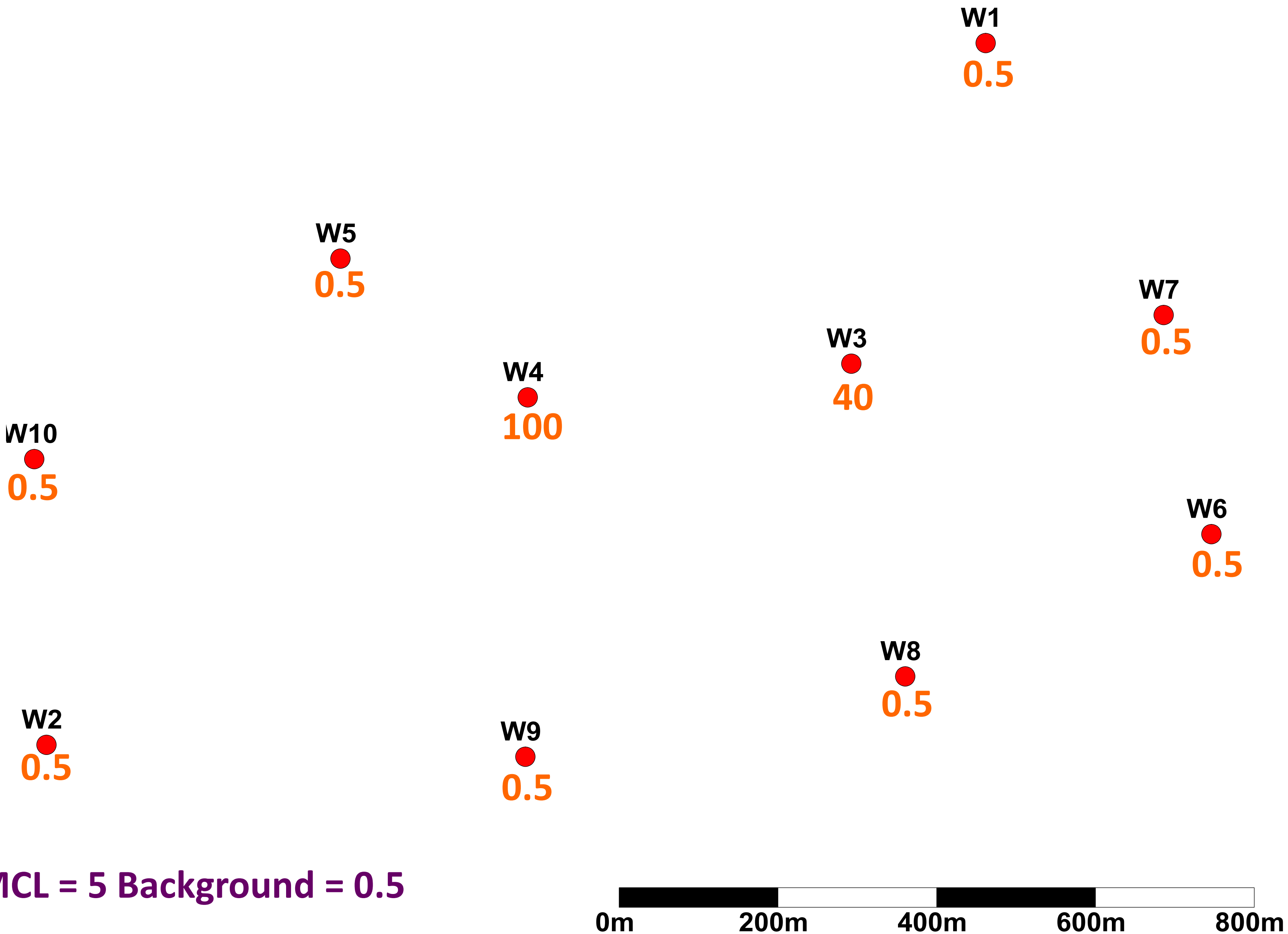

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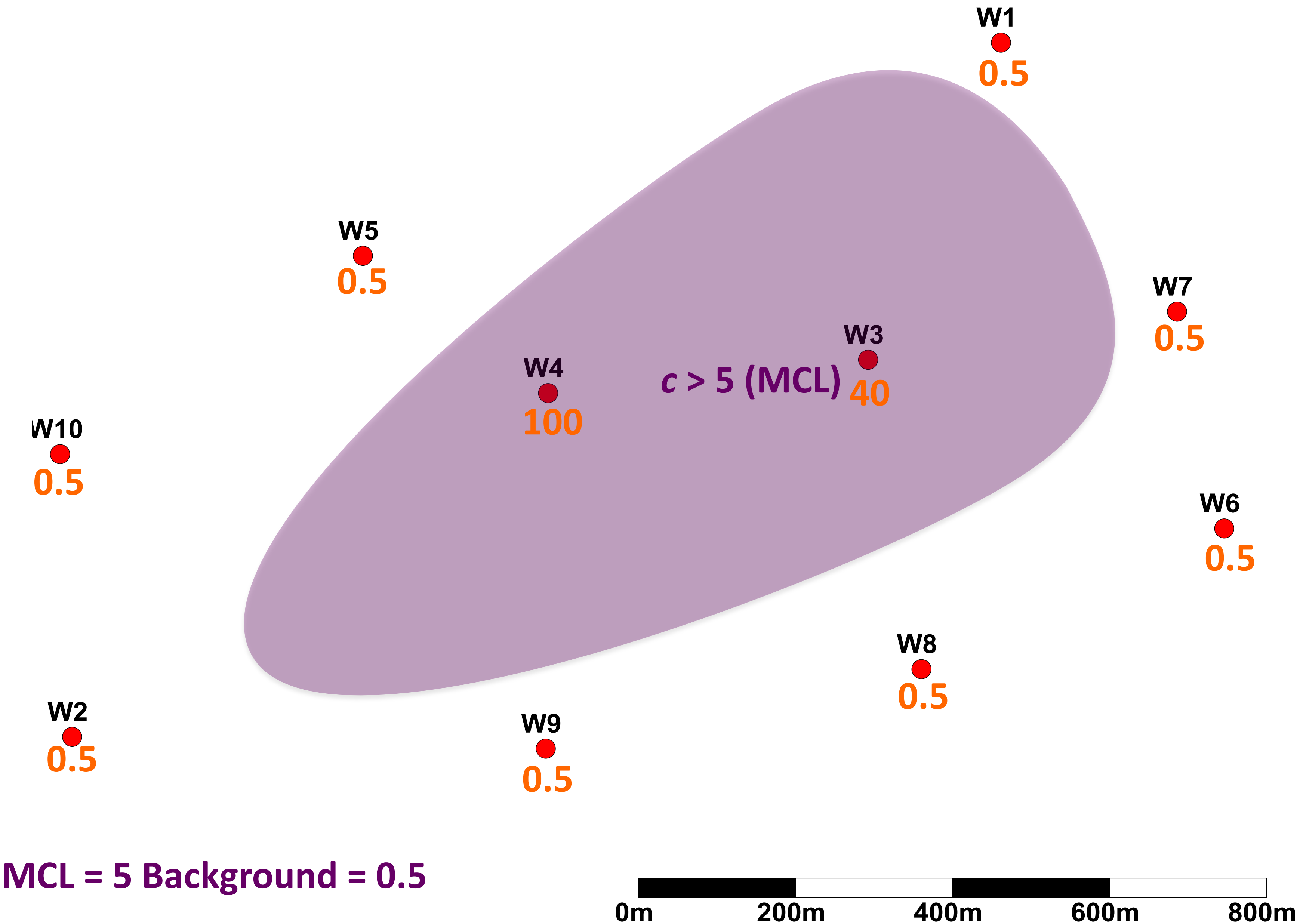
✧ **Multiple plausible plume configurations …**



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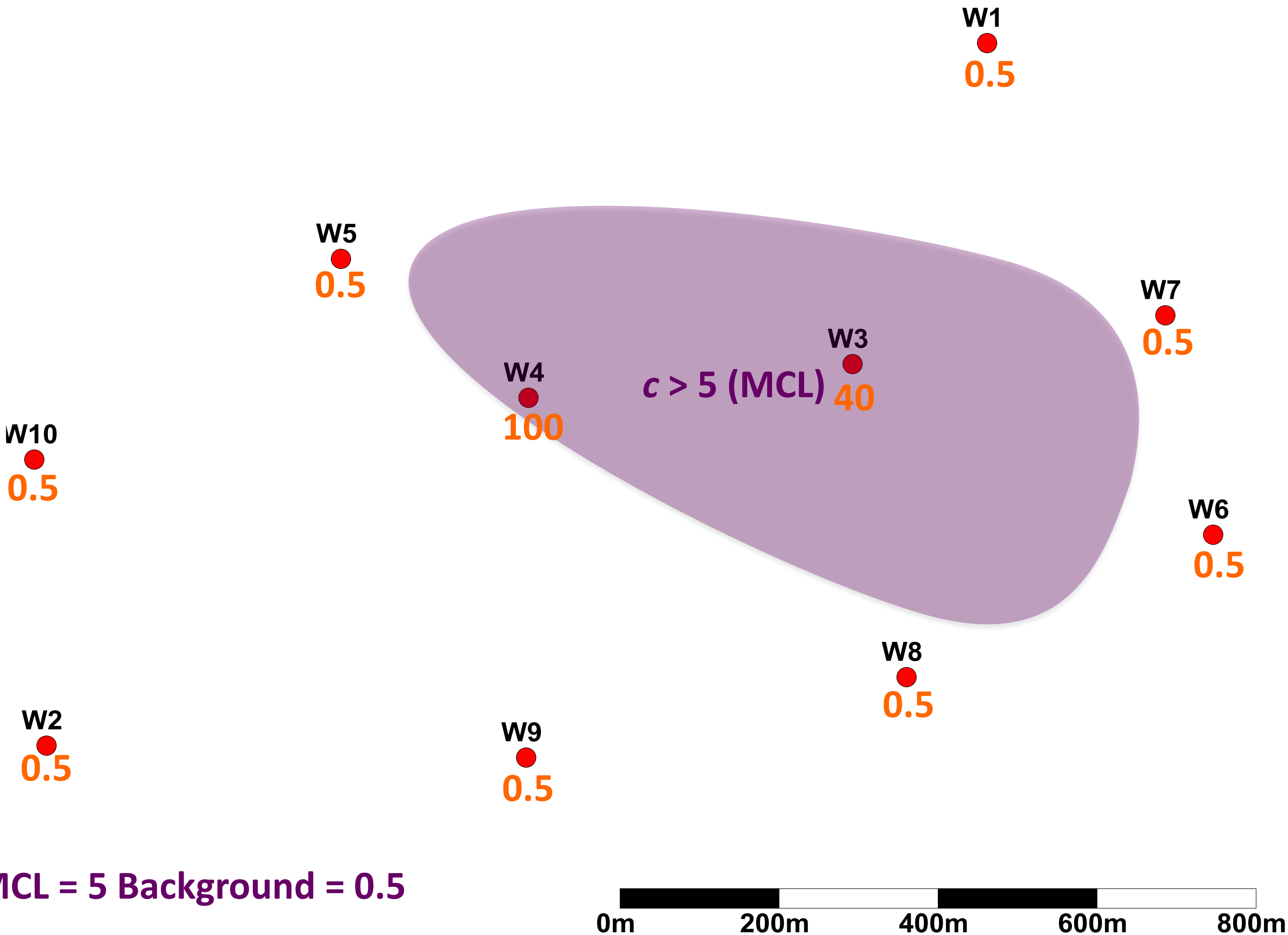

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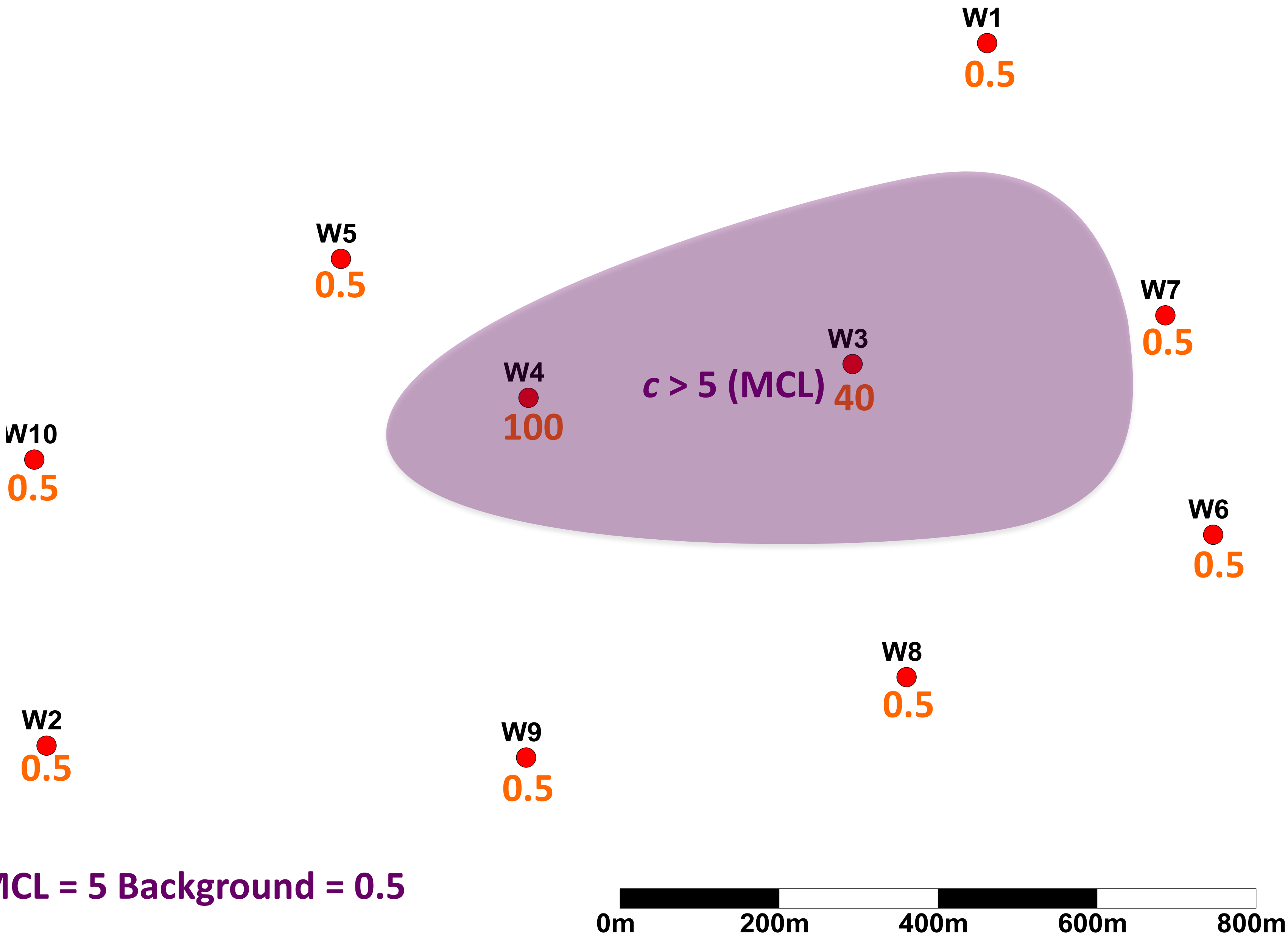

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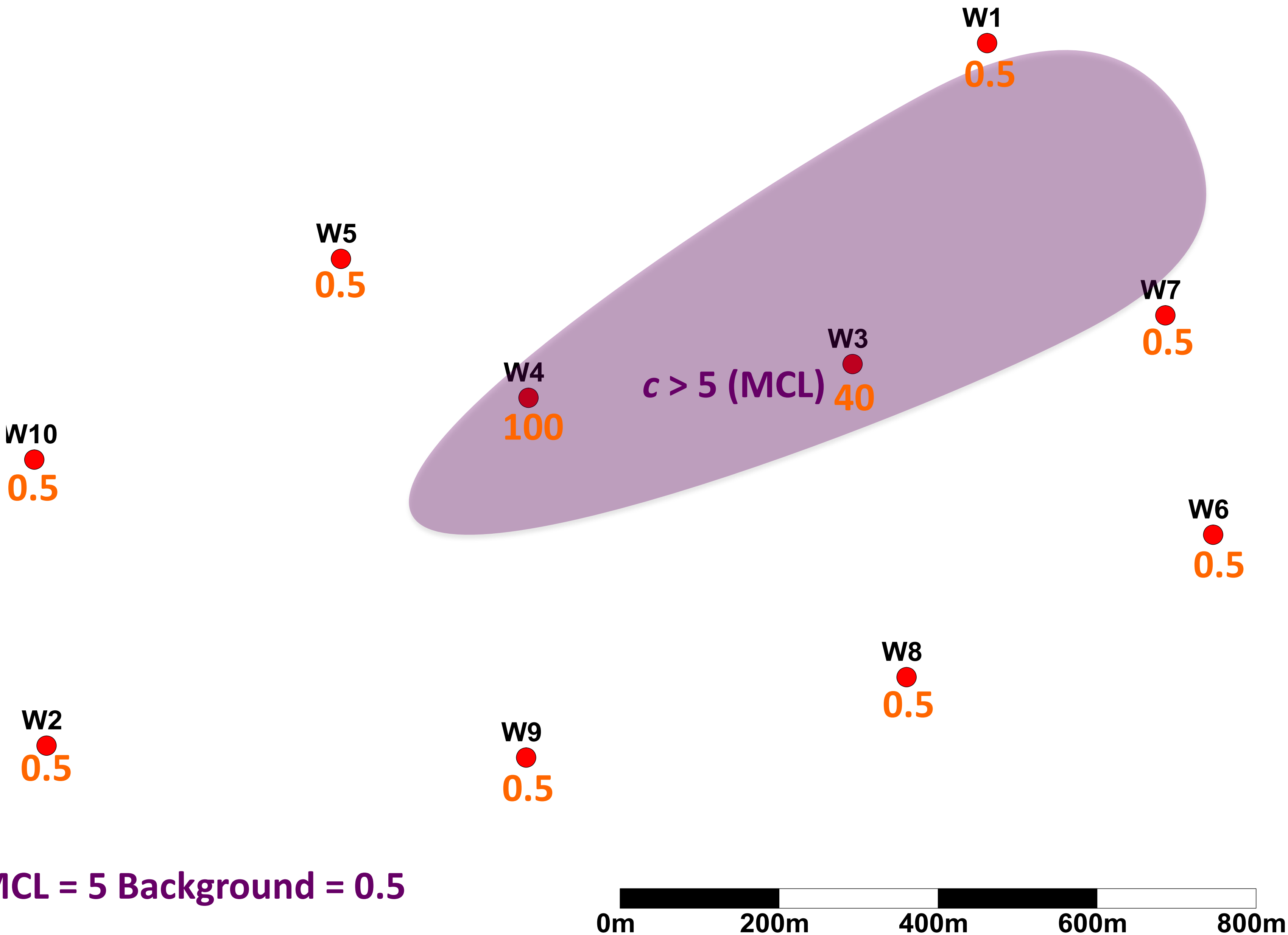

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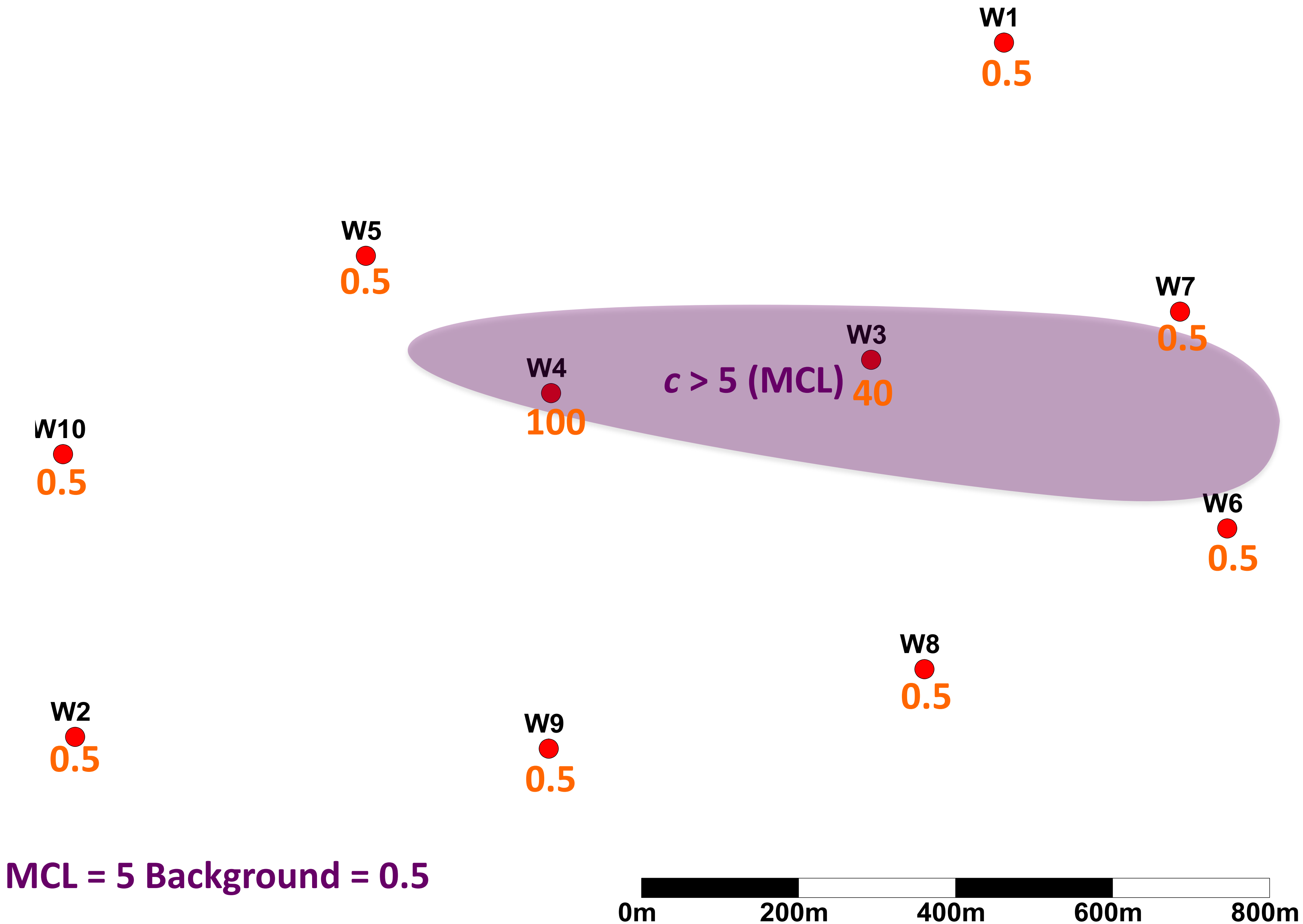

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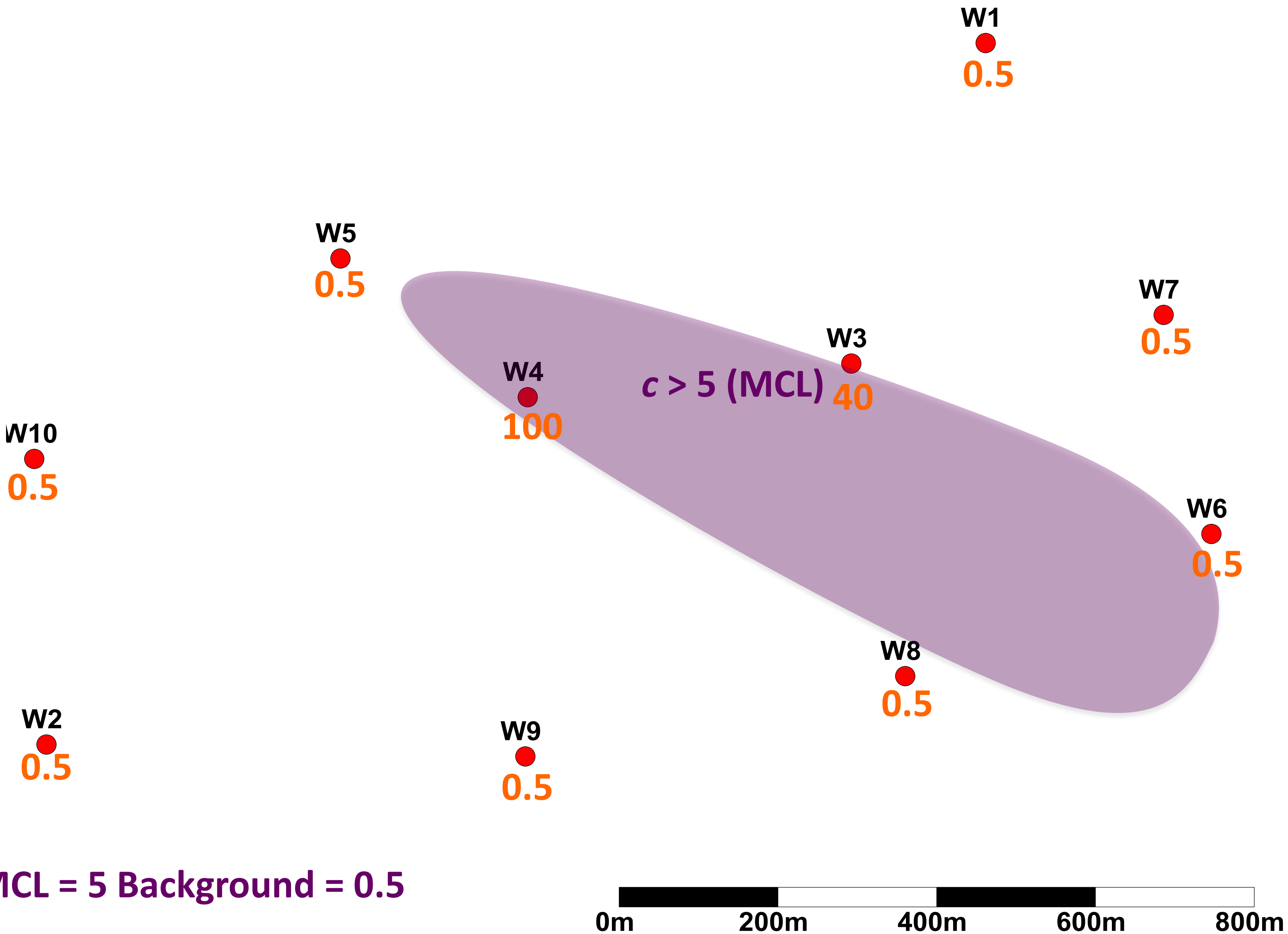

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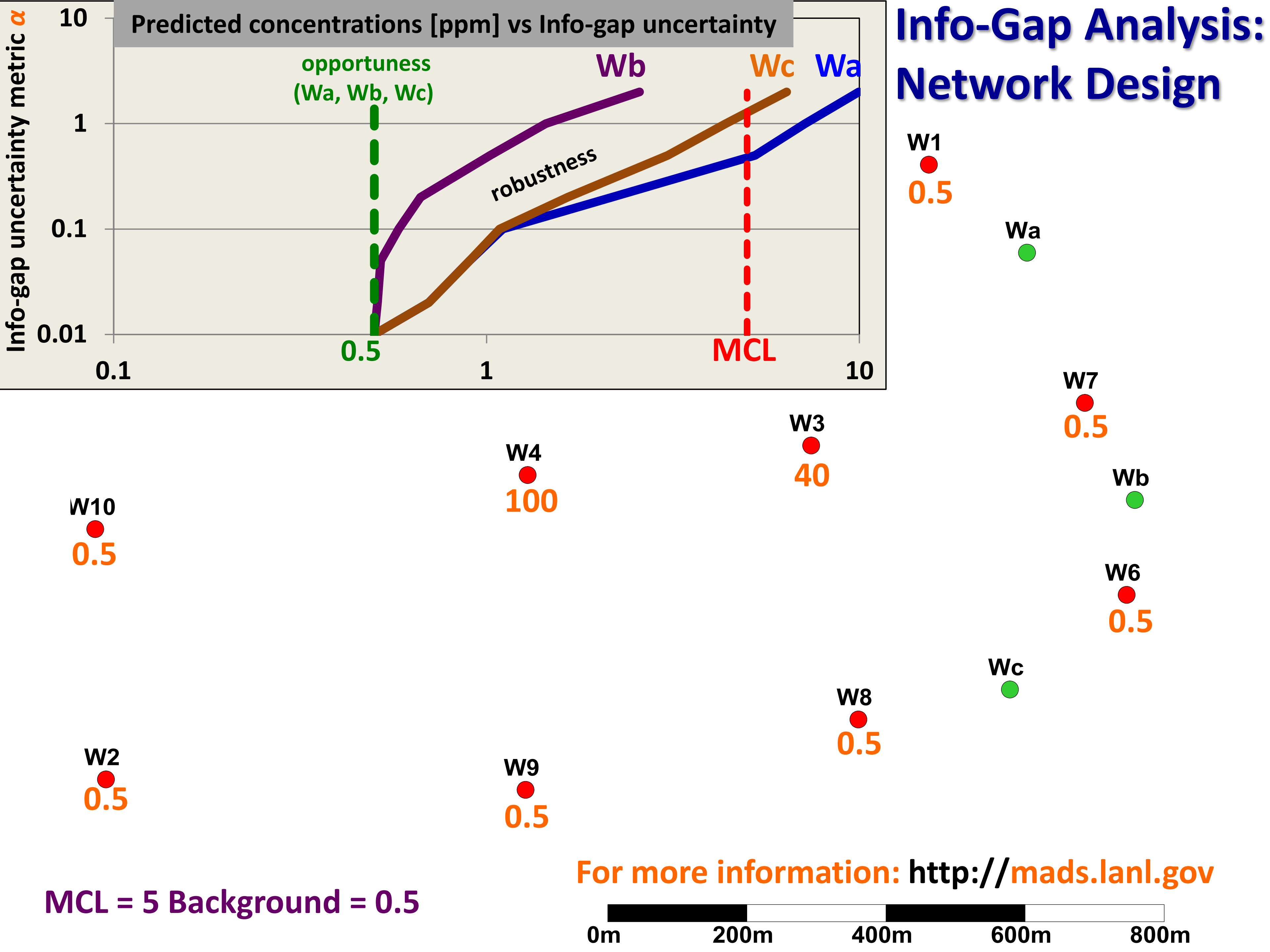
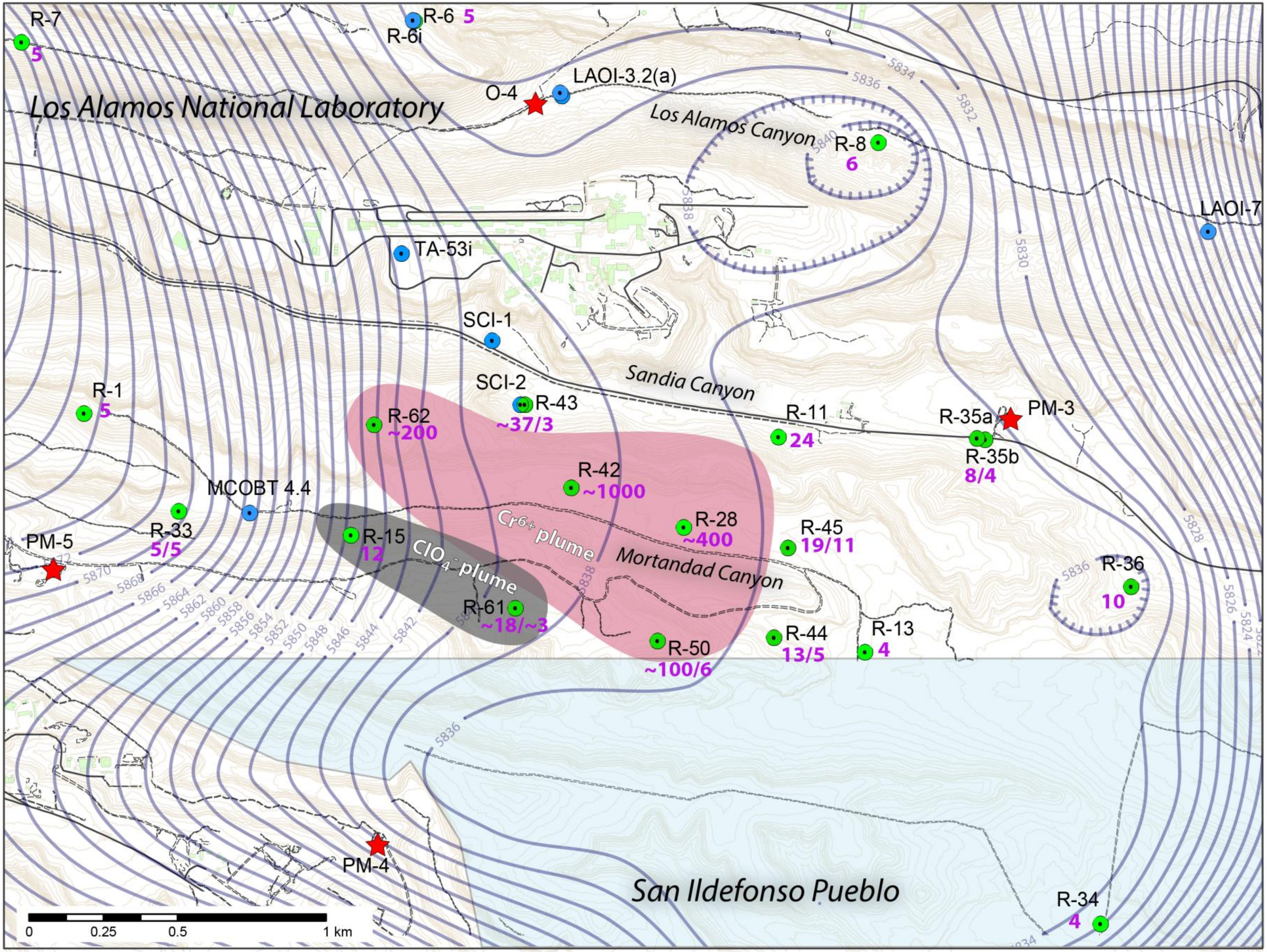


Info-Gap Analysis:
Network Design
Predicted concentrations [ppm] vs Info-gap uncertainty
Info-gap uncertainty metric α
10
1
0.1
0.01
0.1
1
10
opportuness
(Wa, Wb, Wc)
0.5
Wb
Wc
Wa
robustness
MCL
W1
0.5
Wa
W7
0.5
W3
40
W4
100
Wb
W10
0.5
W6
0.5
Wc
W8
0.5
W2
0.5
W9
0.5
For more information: http://mads.lanl.gov
MCL = 5 Background = 0.5
0m
200m
400m
600m
800m

Chromium plume in the regional aquifer at LANL



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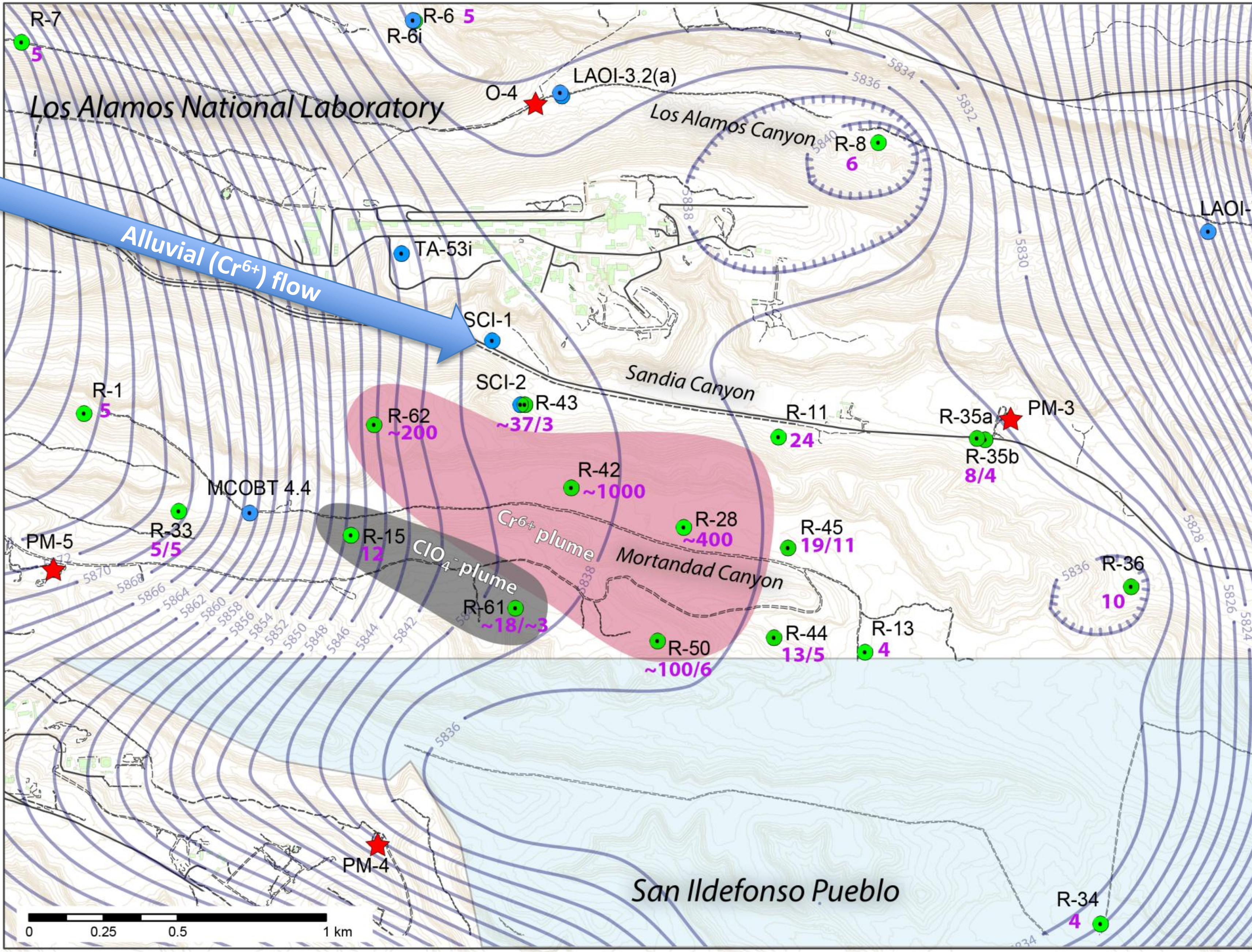

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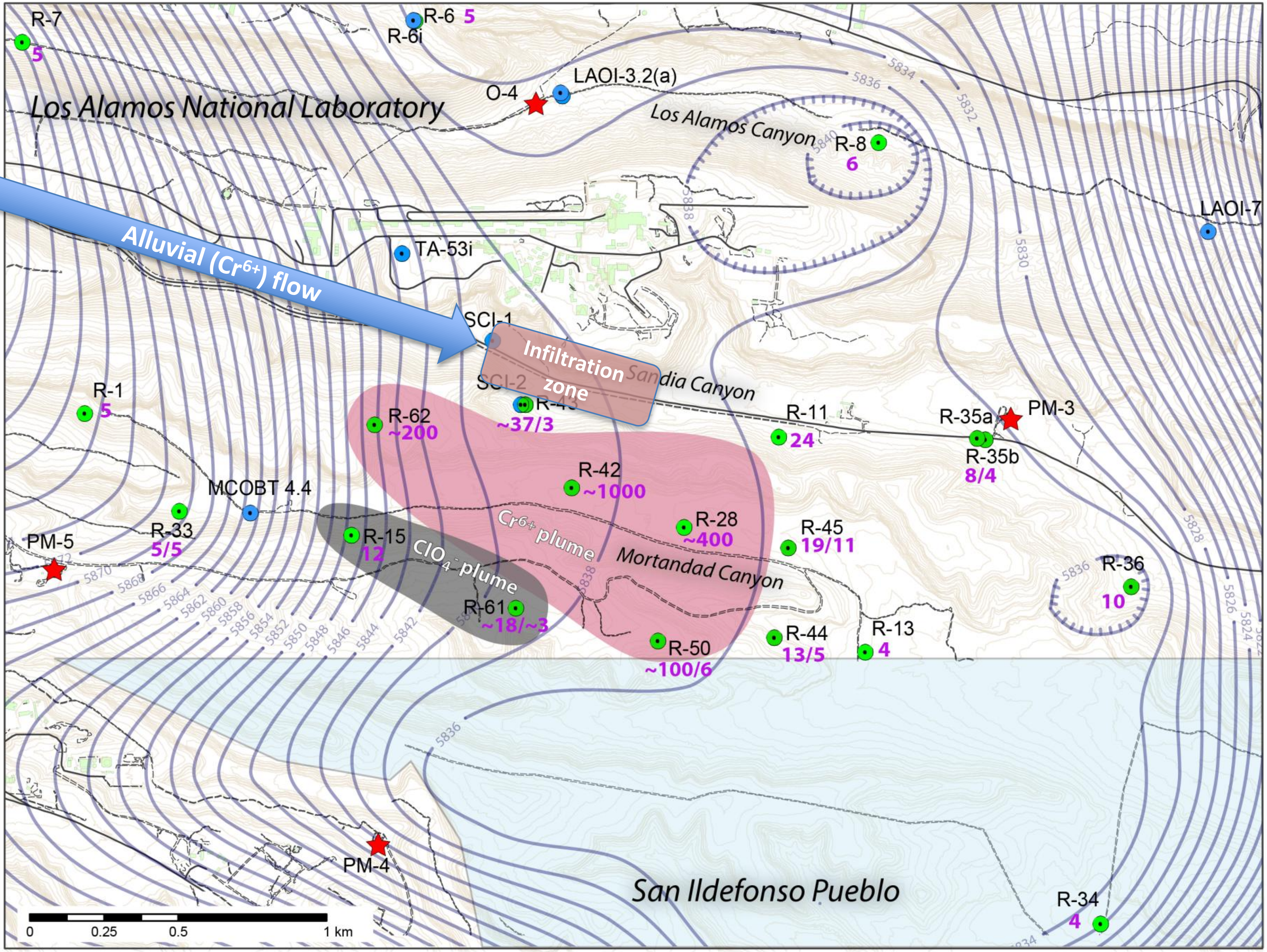

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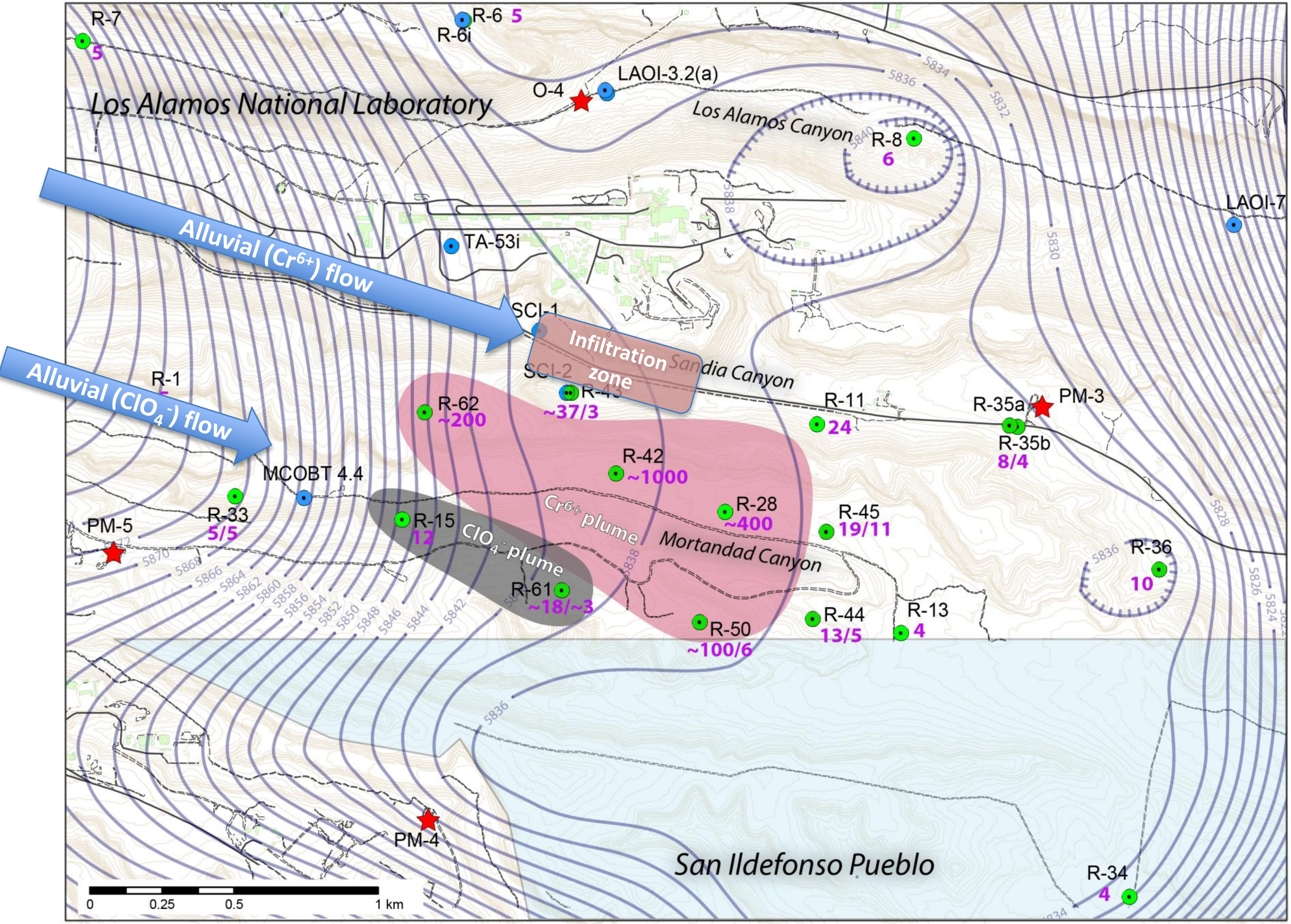

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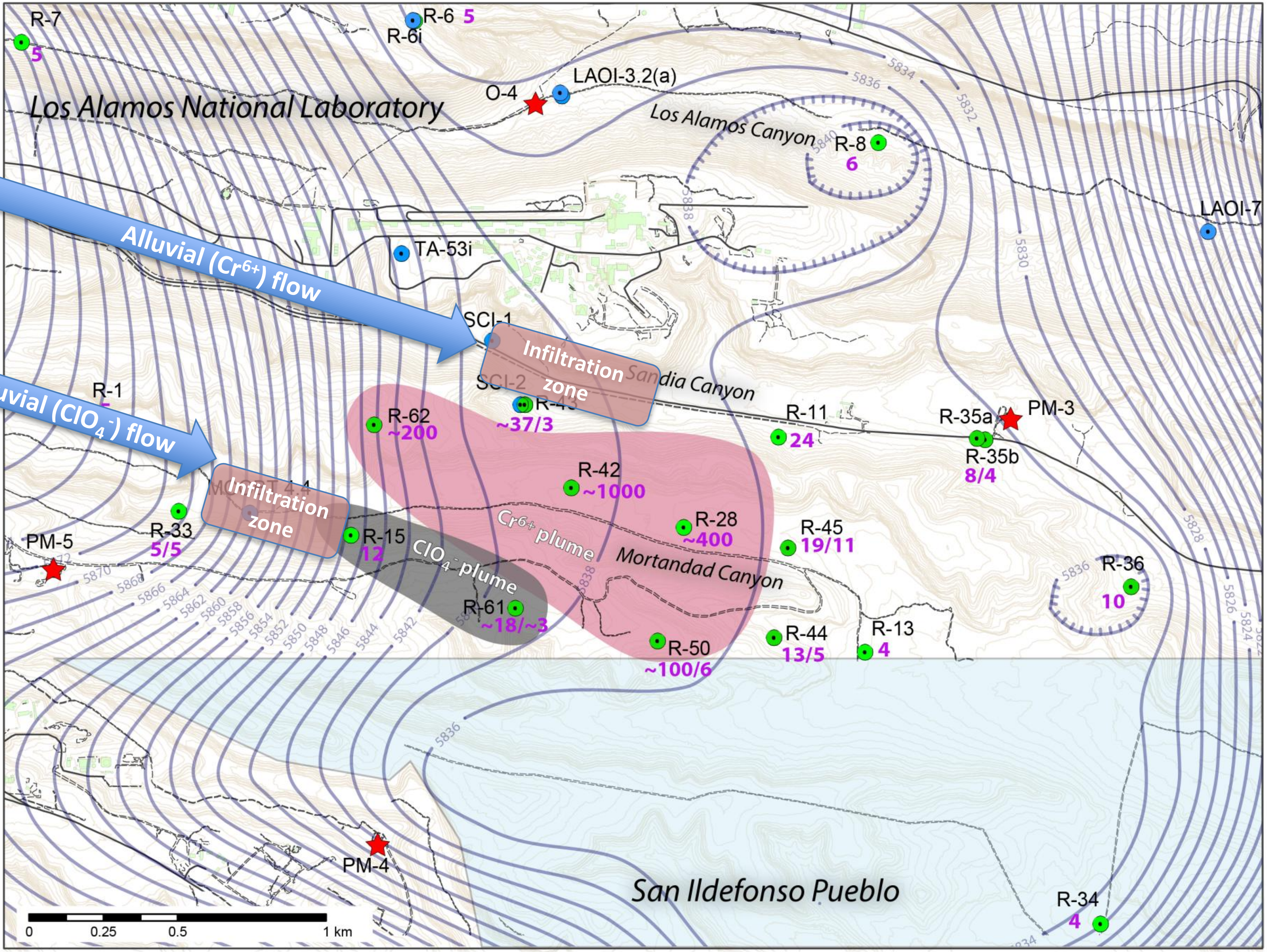

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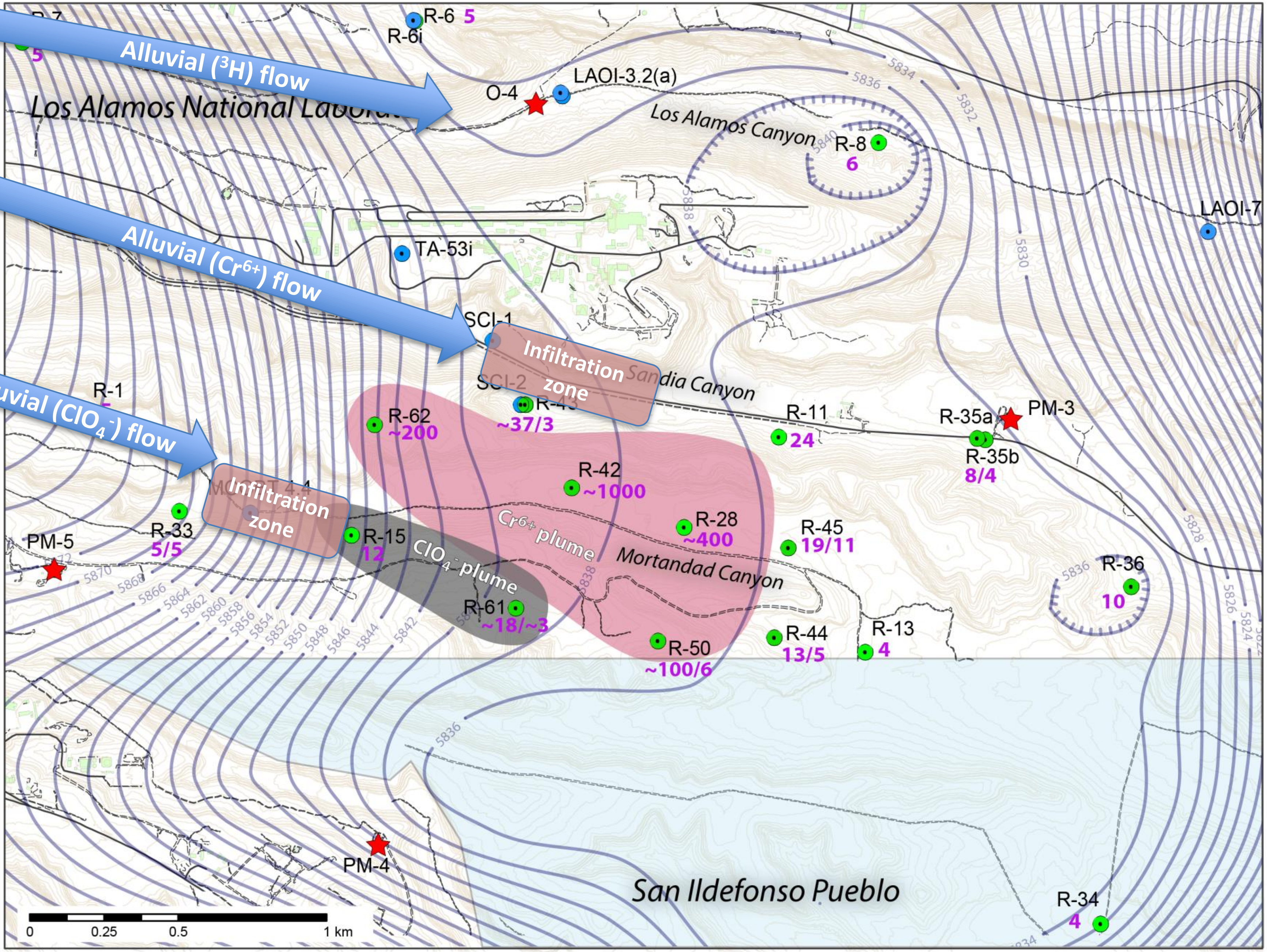

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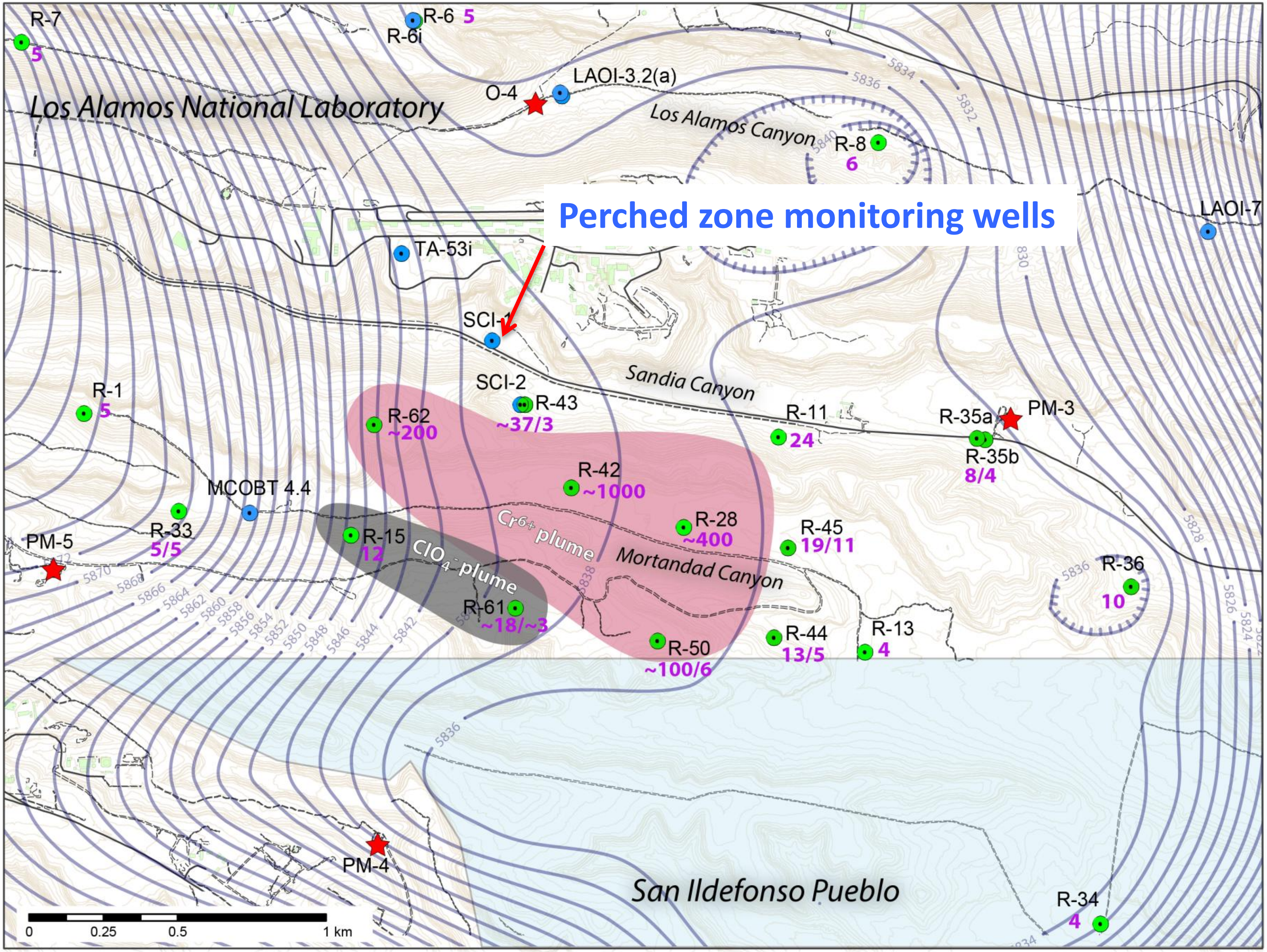

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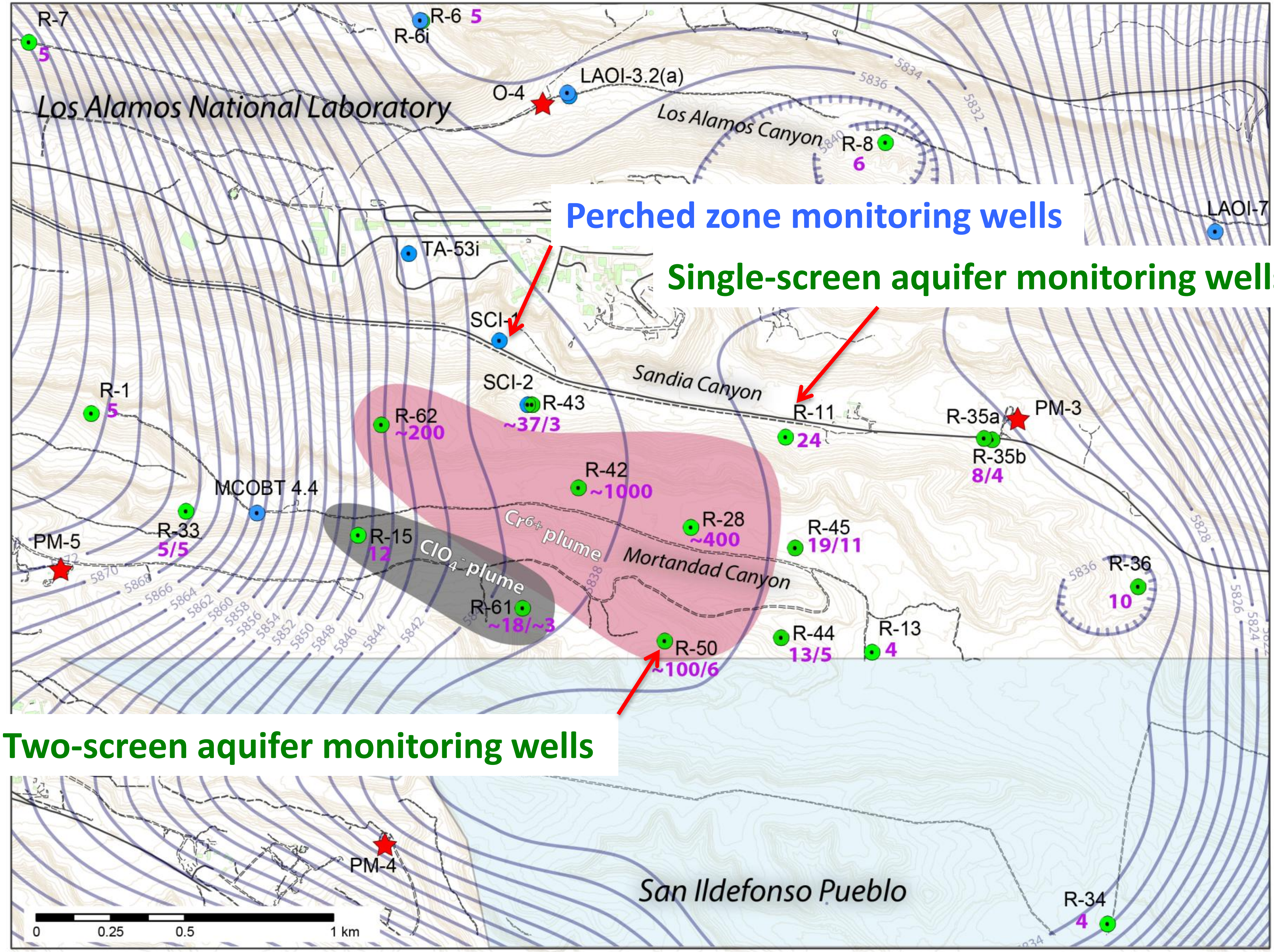

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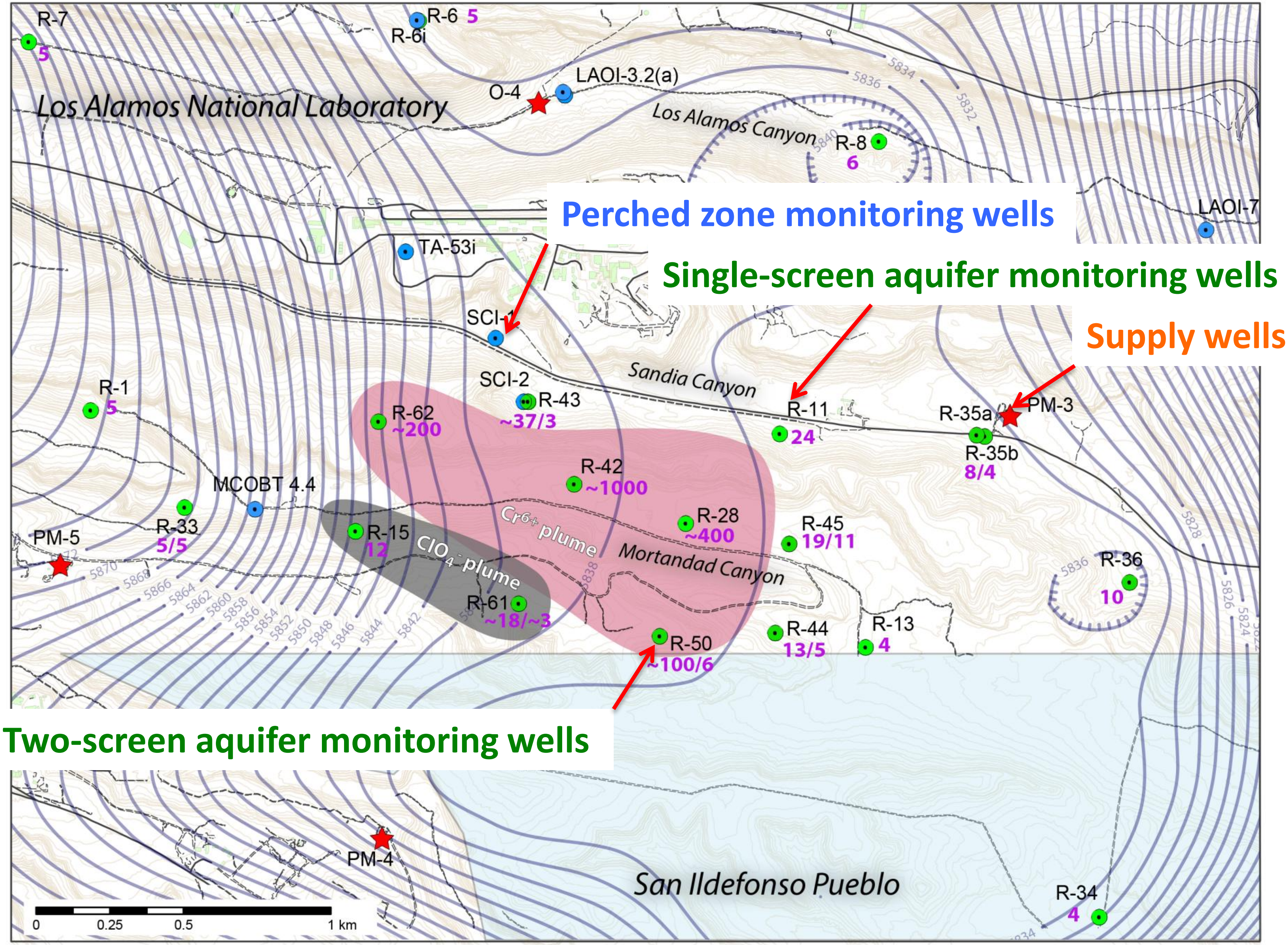

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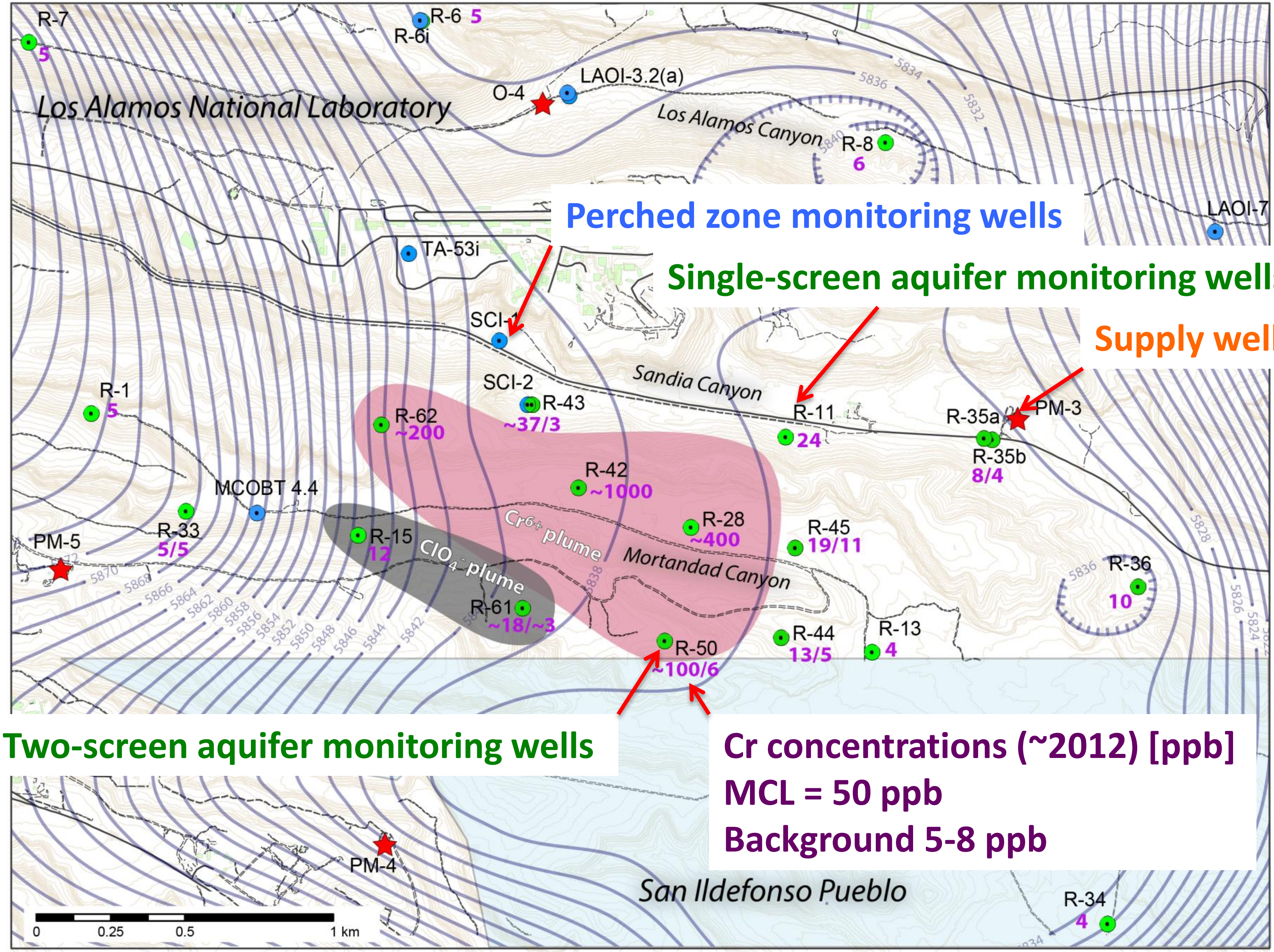

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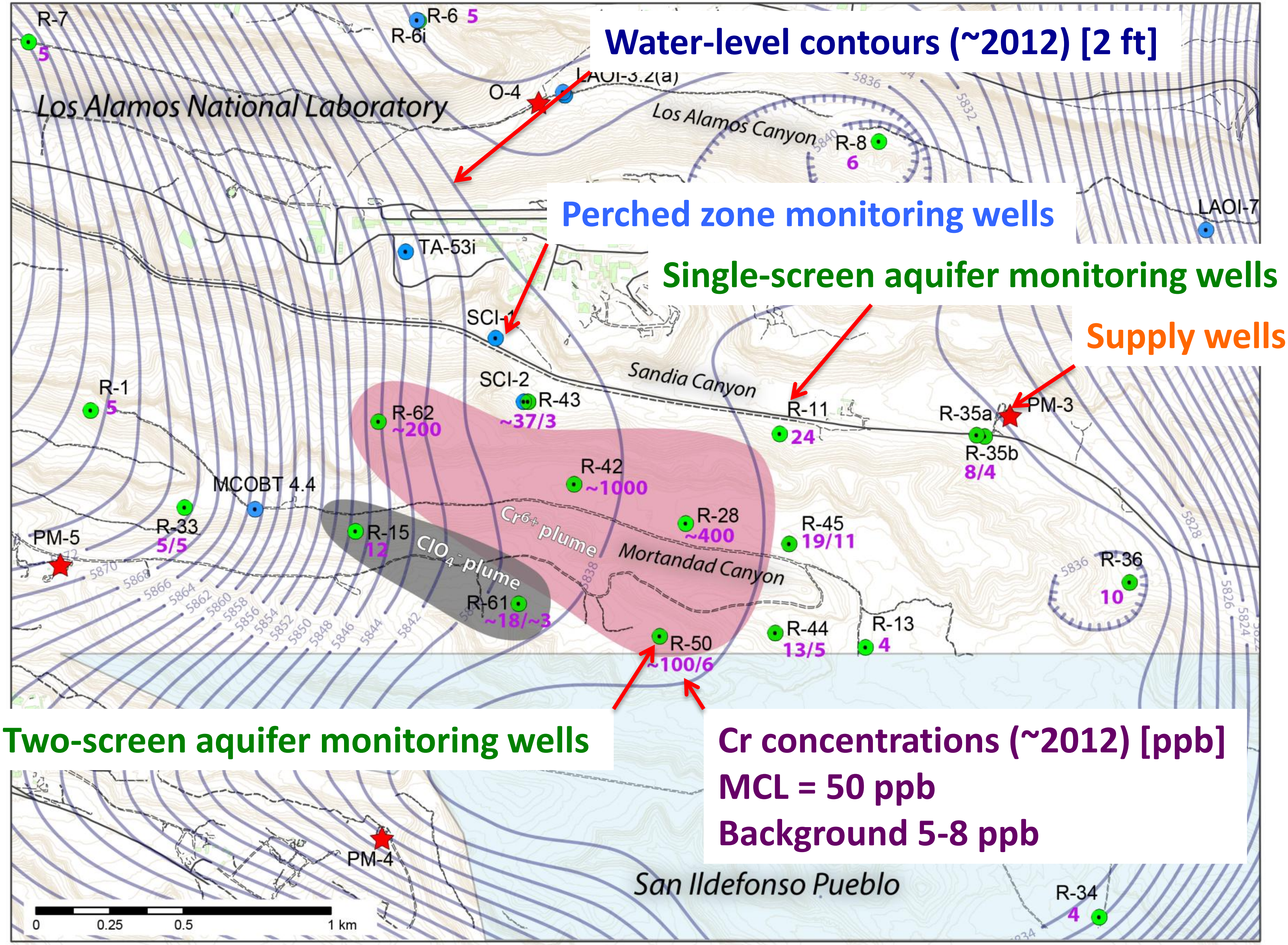

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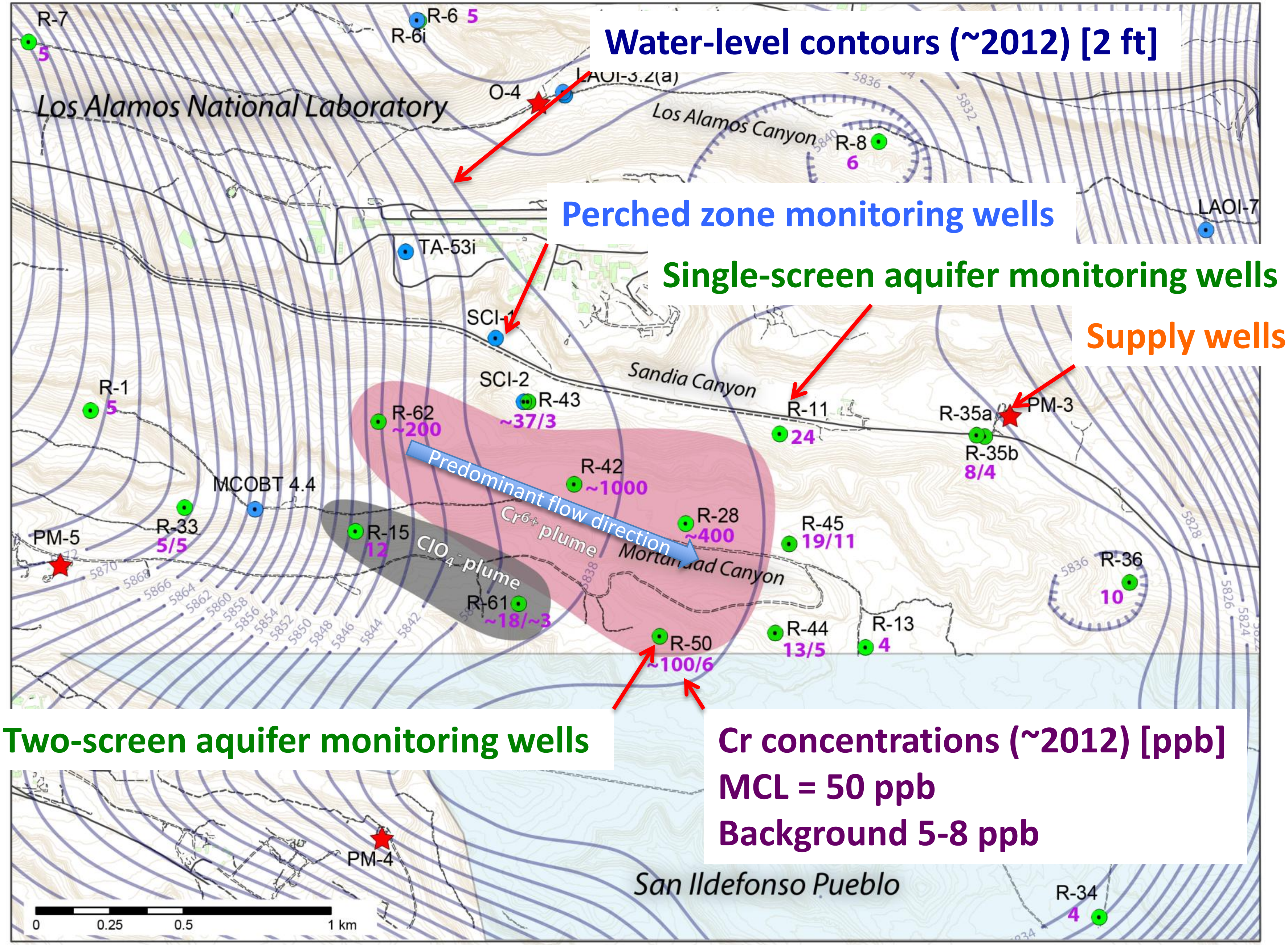

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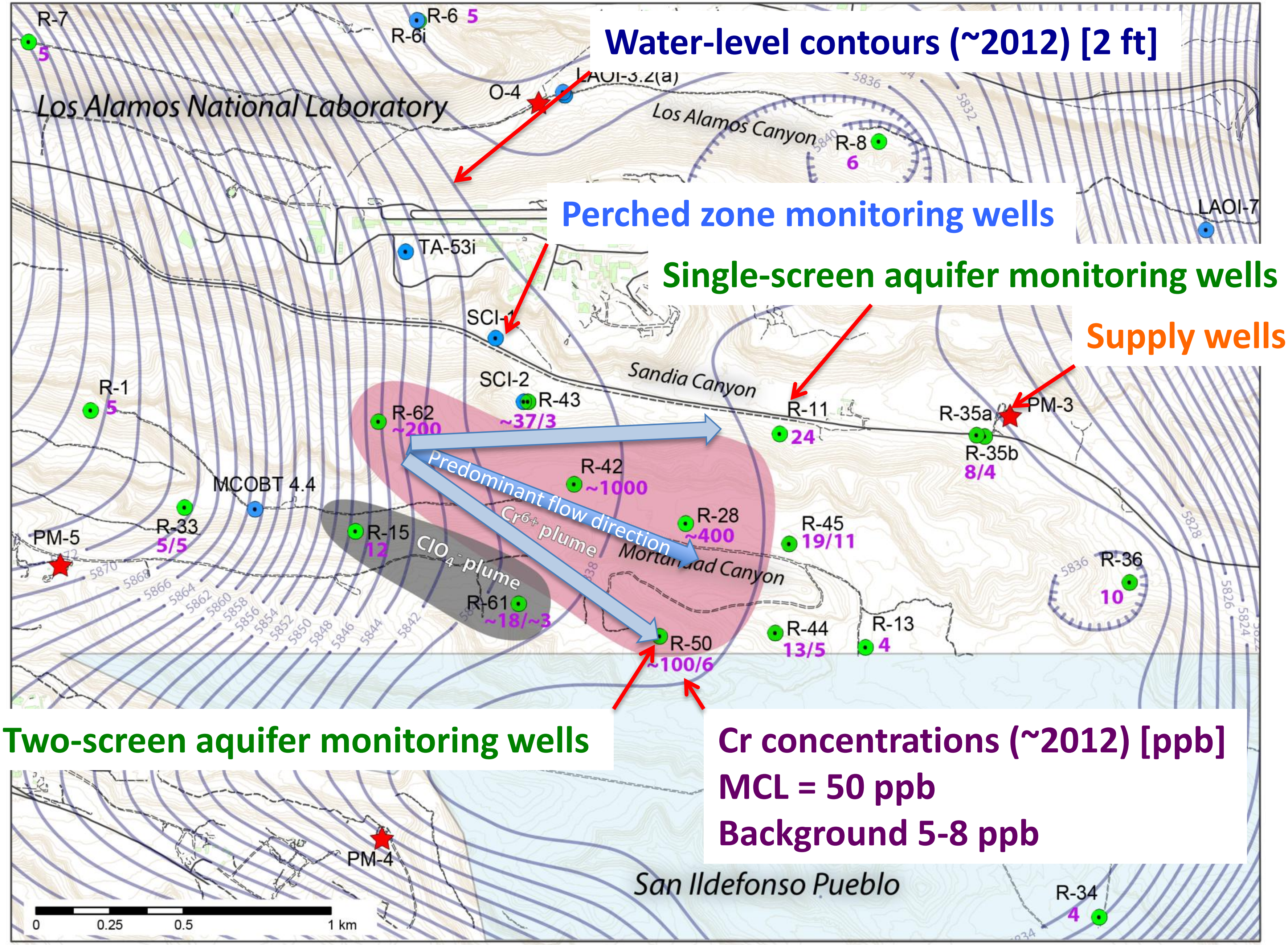
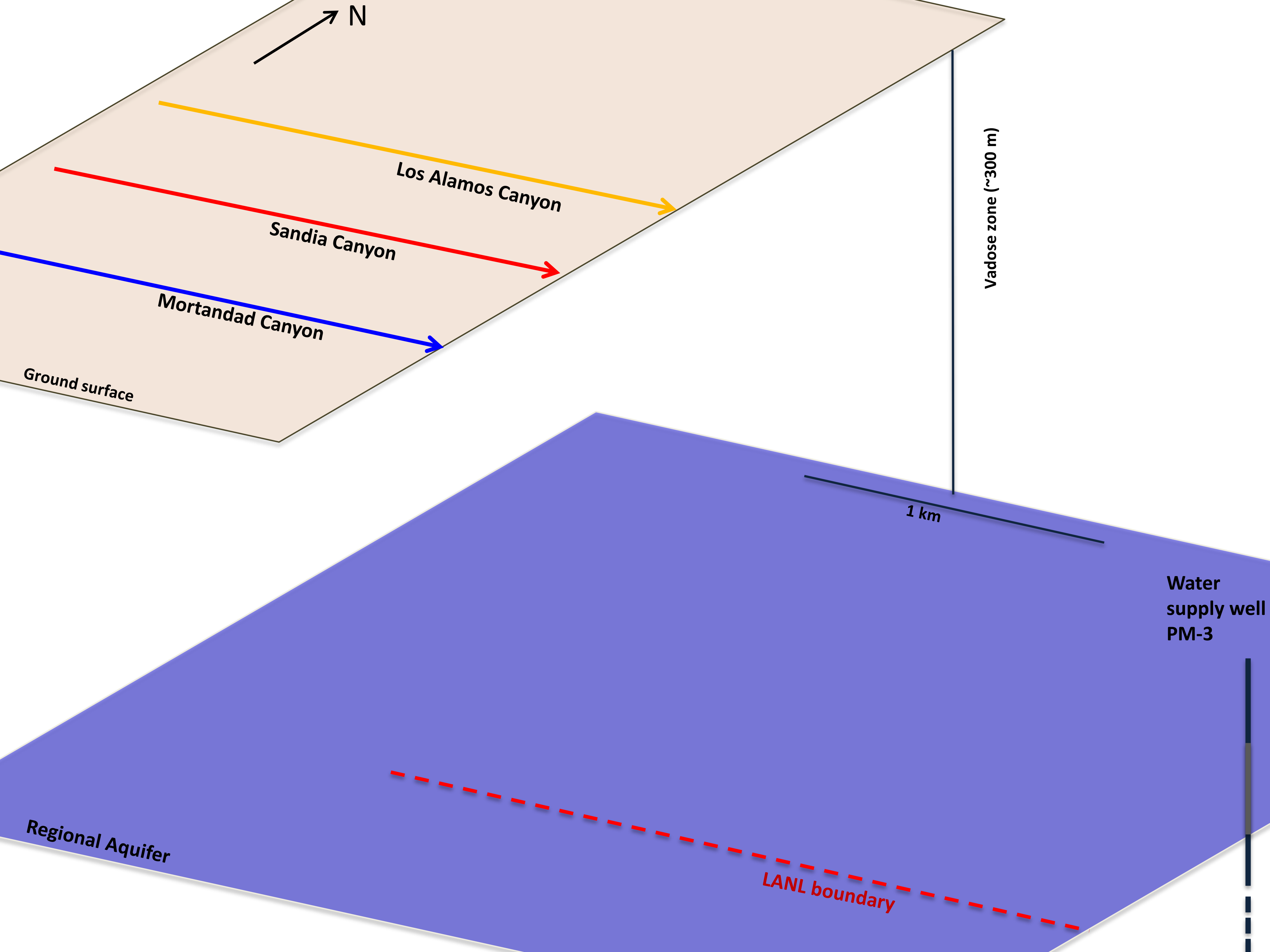
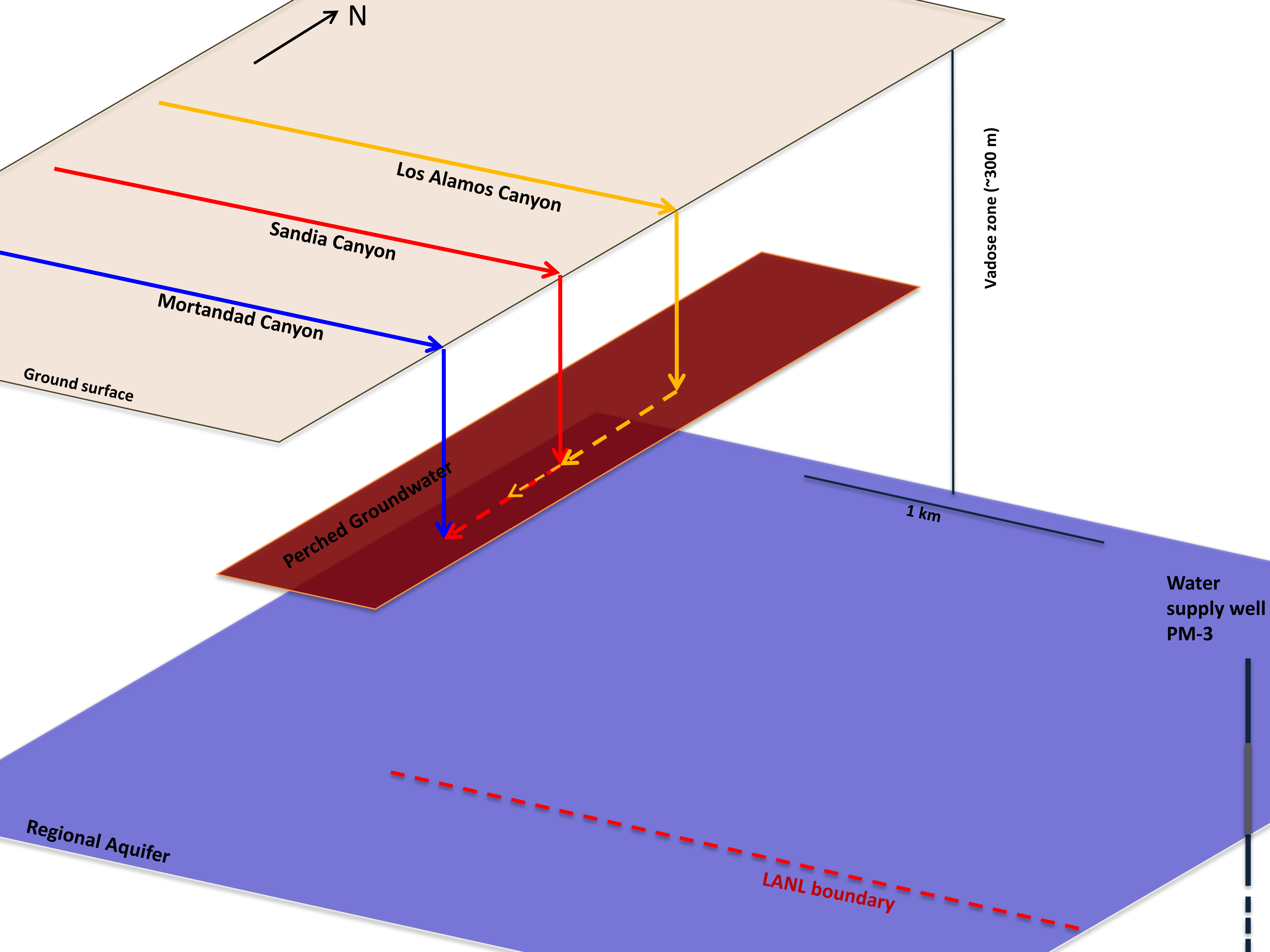


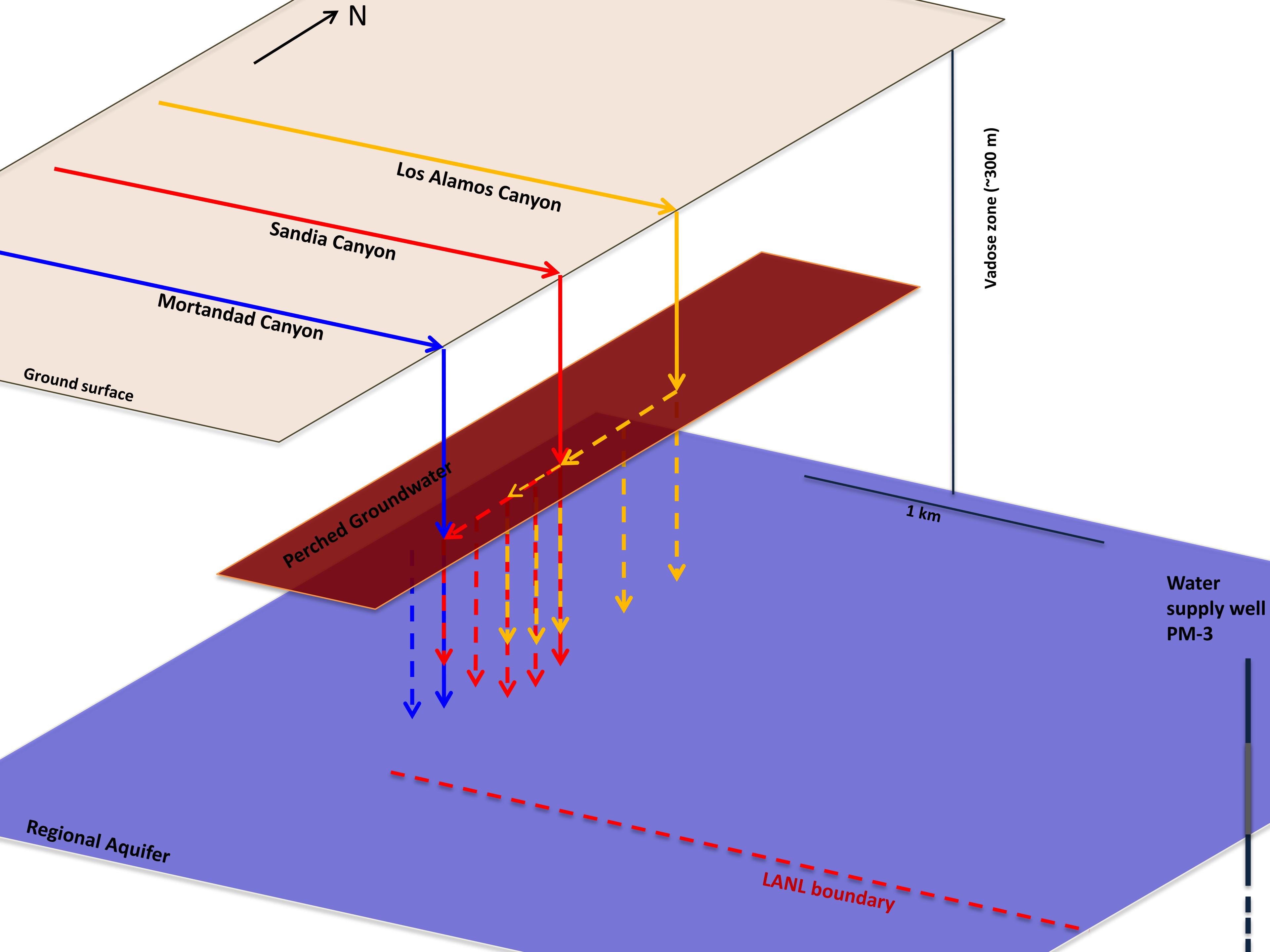
LANL Chromium site

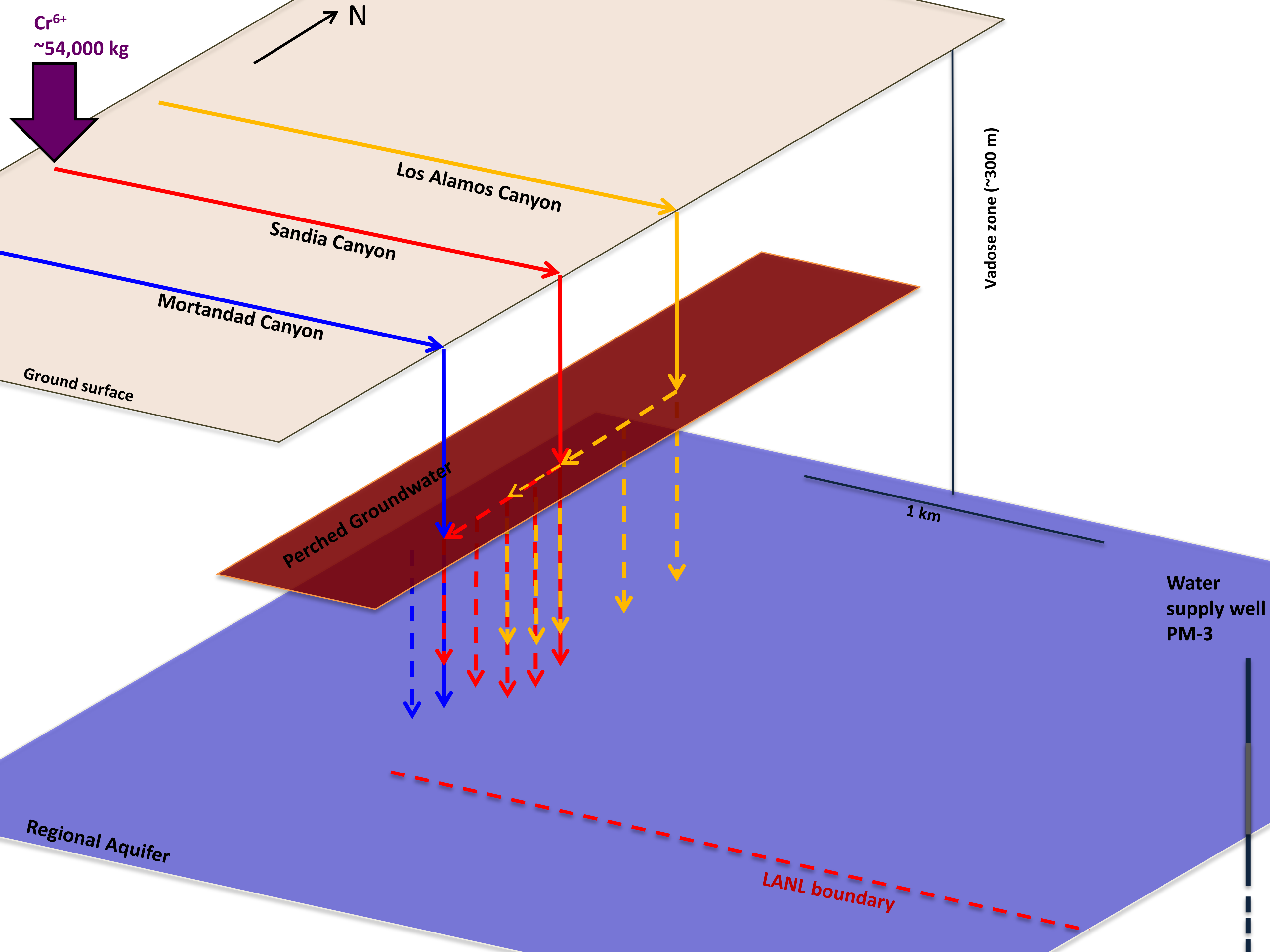
- ~54,000 kg of Cr^{6+} released in Sandia Canyon between 1956 and 1972
- Cr^{6+} detected above MCL (50 ppb; NM standard) in 4 monitoring wells in the regional aquifer beneath LANL
- Cr^{6+} plume size is about 2 km^2 (region above MCL)
- Cr^{6+} plume is located near LANL site boundary
- Series of water-supply wells are located nearby
- Contaminant source location and mass flux at the top of the regional aquifer are unknown due to complex 3D pathways through the vadose zone
- Limited remedial options due to aquifer depth (~300 m below the ground surface) and complexities in the subsurface flow
- Current conceptual model for chromium migration in the subsurface is supported by multiple lines of evidence (hydrogeological, geophysical geophysical, mineralogic, petrographic, and geochemical studies and model analyses)



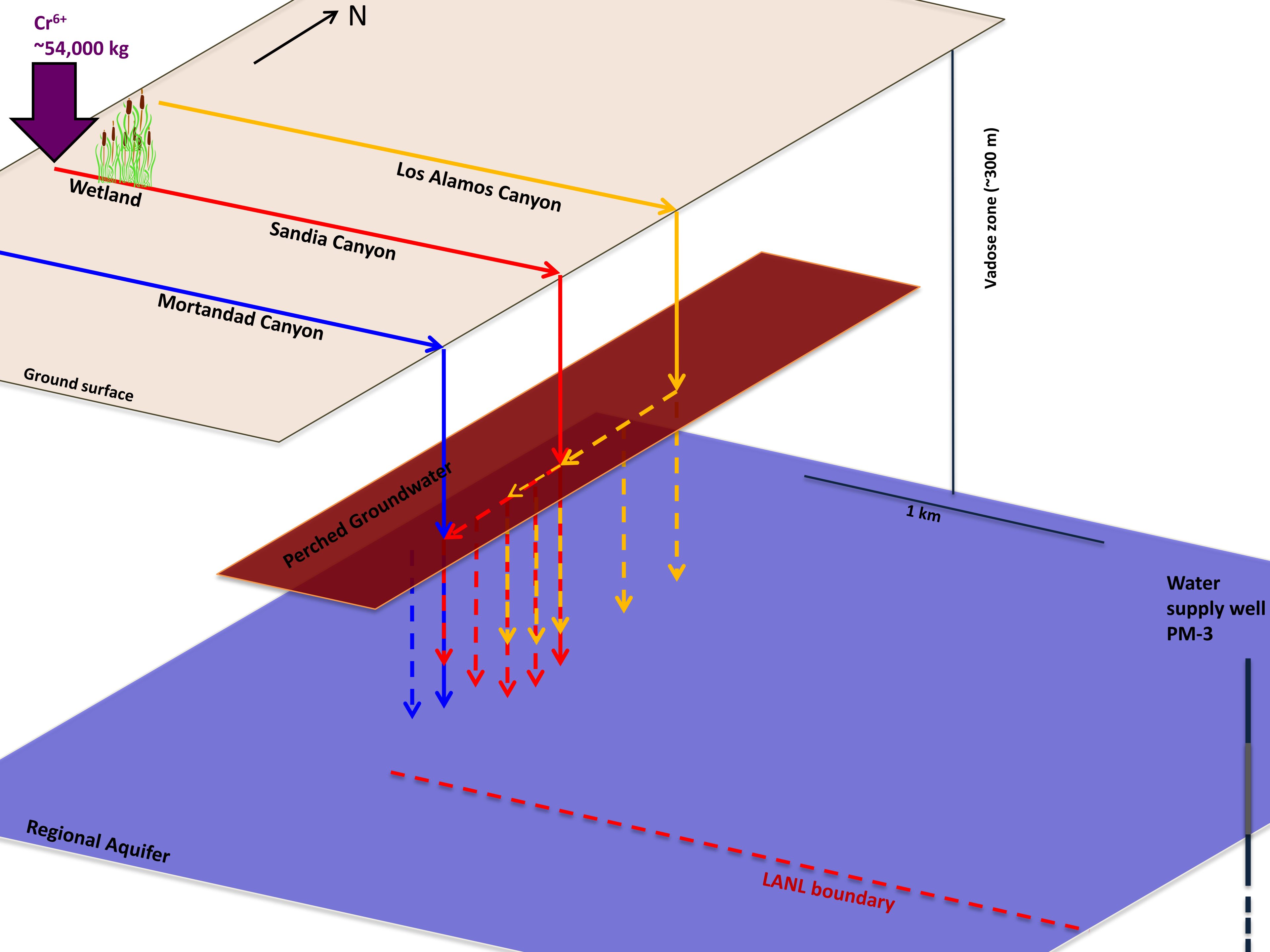
N
Los Alamos Canyon
Sandia Canyon
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary


N
Los Alamos Canyon
Sandia Canyon
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary

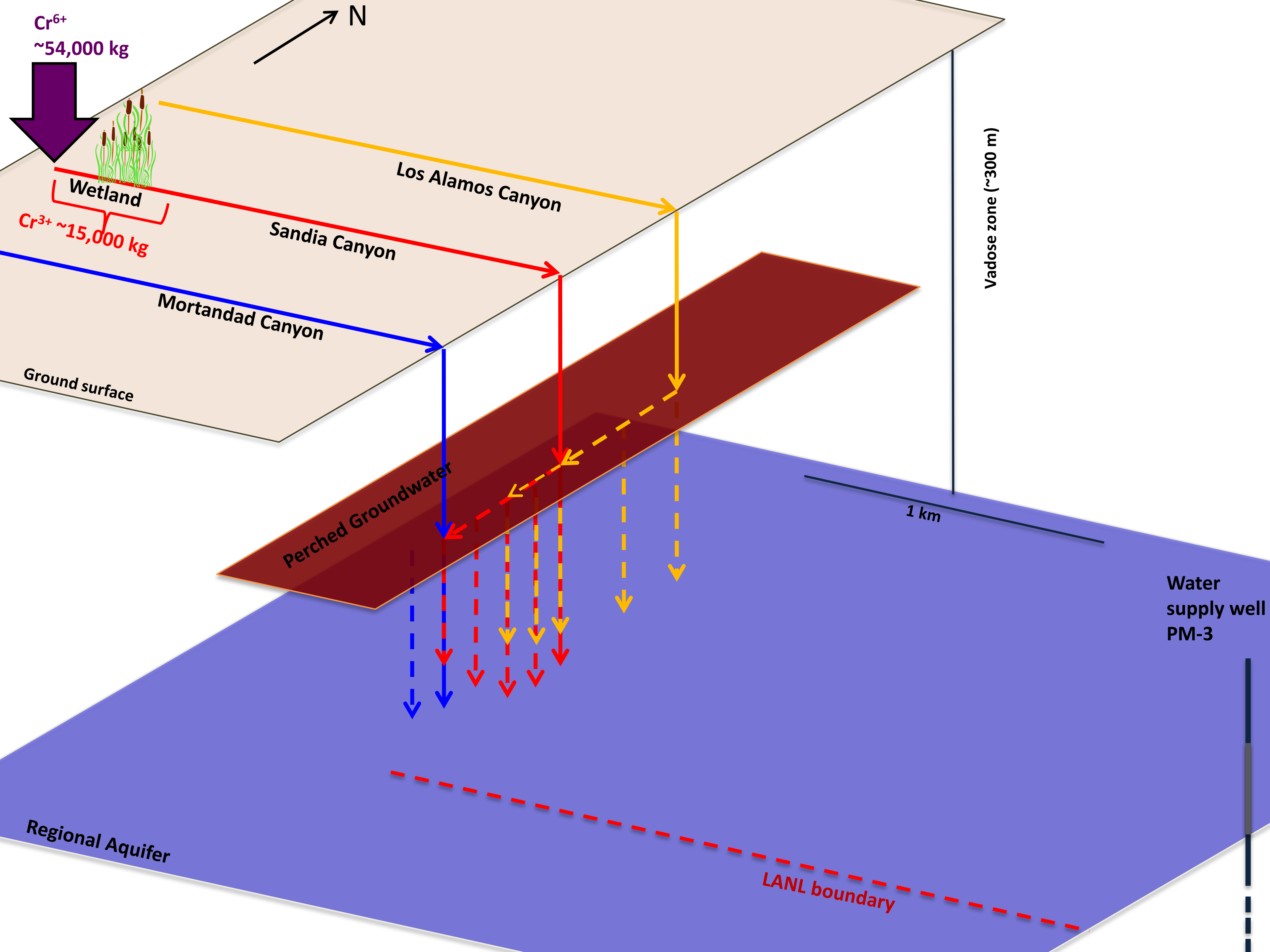

N
Los Alamos Canyon
Sandia Canyon
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary



Cr^{6+}
~54,000 kg
N
Los Alamos Canyon
Sandia Canyon
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
1 km
Water supply well PM-3
Regional Aquifer
LANL boundary



Cr6+
~54,000 kg
N
Wetland
Los Alamos Canyon
Sandia Canyon
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary



N
Cr6+
~54,000 kg
Wetland
Cr3+ ~15,000 kg
Los Alamos Canyon
Sandia Canyon
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
1 km
Water
supply well
PM-3
Regional Aquifer
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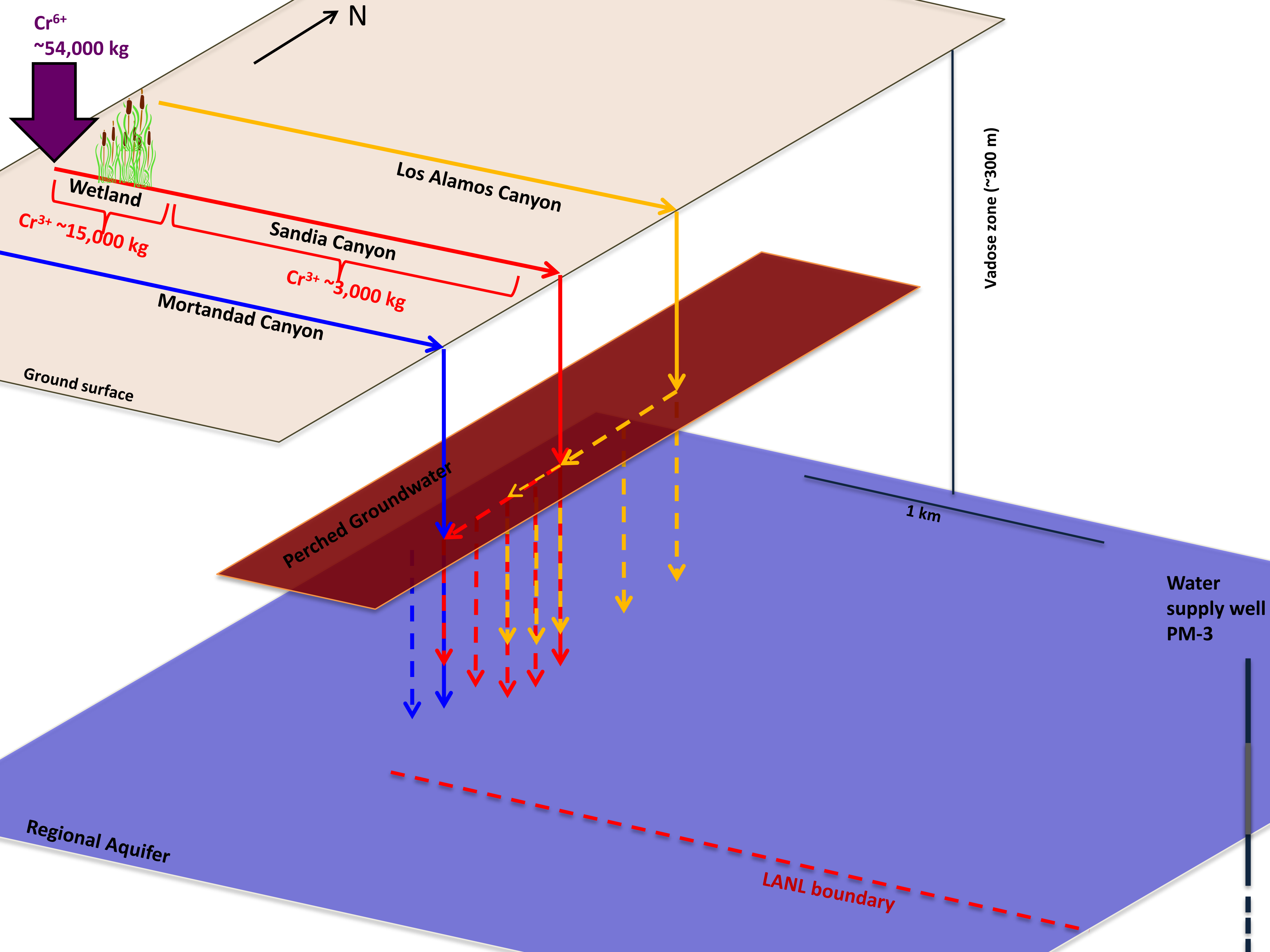

N
Cr^{6+}
~54,000 kg
Wetland
Cr^{3+} ~15,000 kg
Los Alamos Canyon
Sandia Canyon
Cr^{3+} ~3,000 kg
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
1 km
Water
supply well
PM-3
Regional Aquifer
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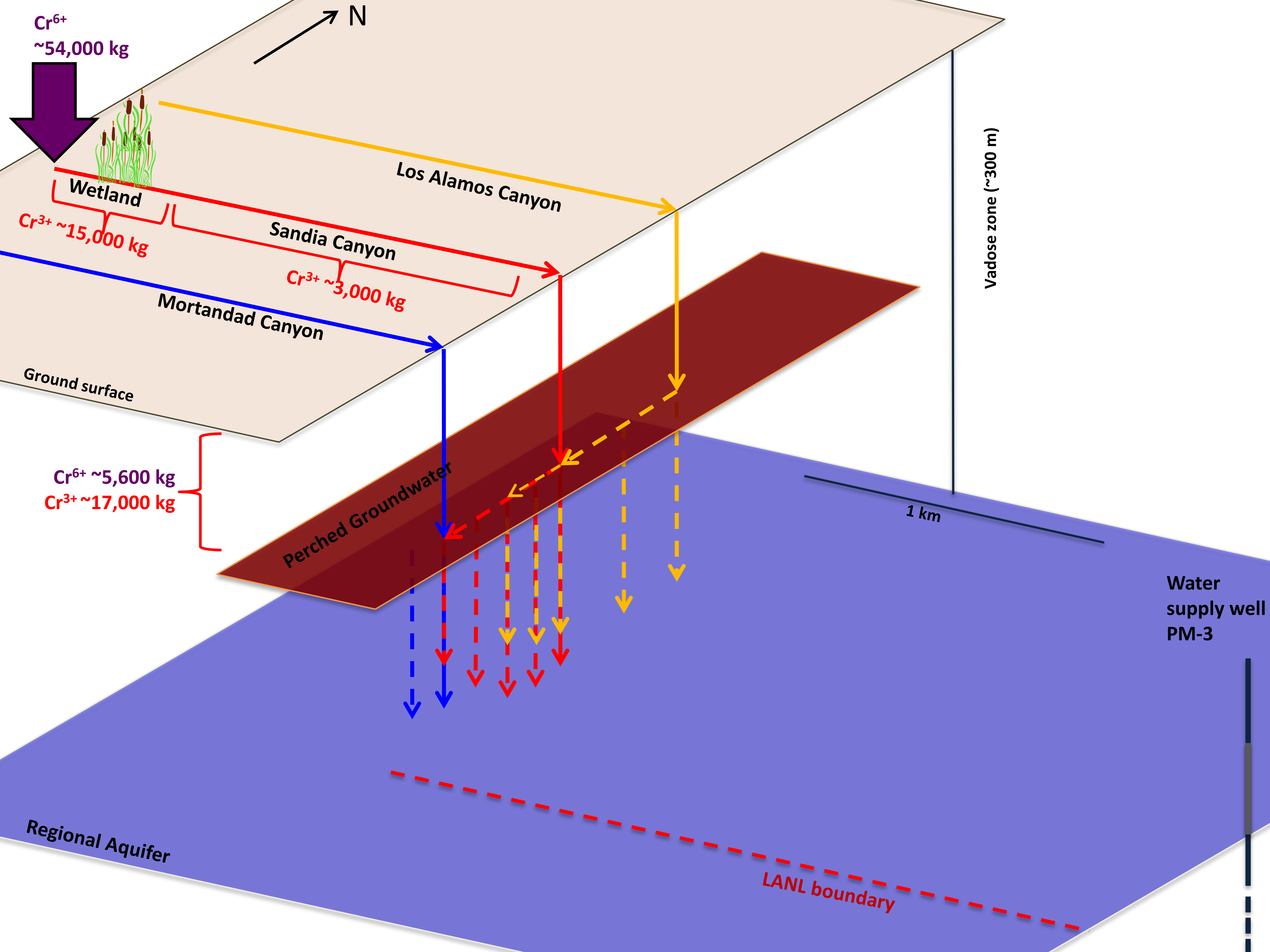
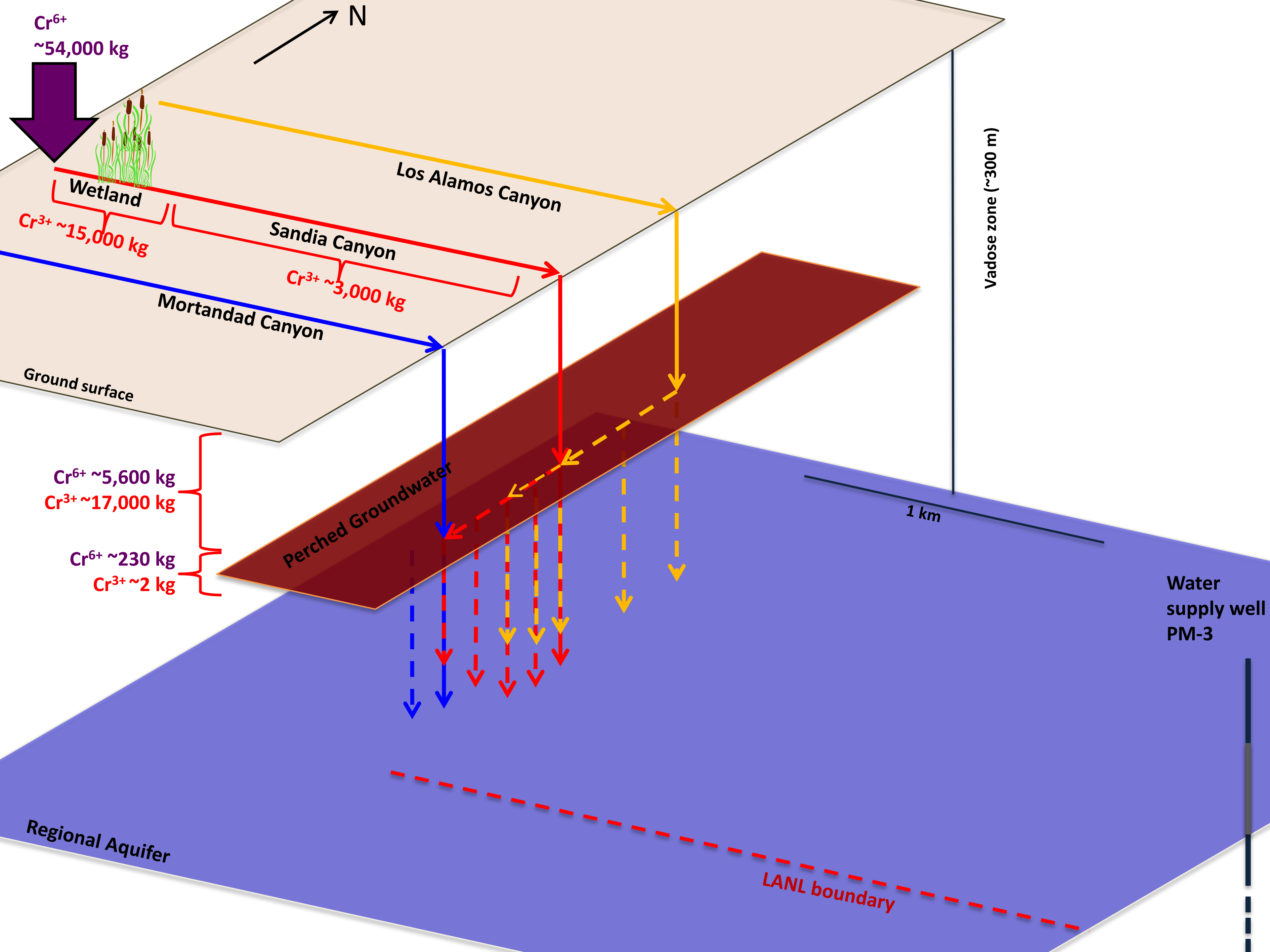
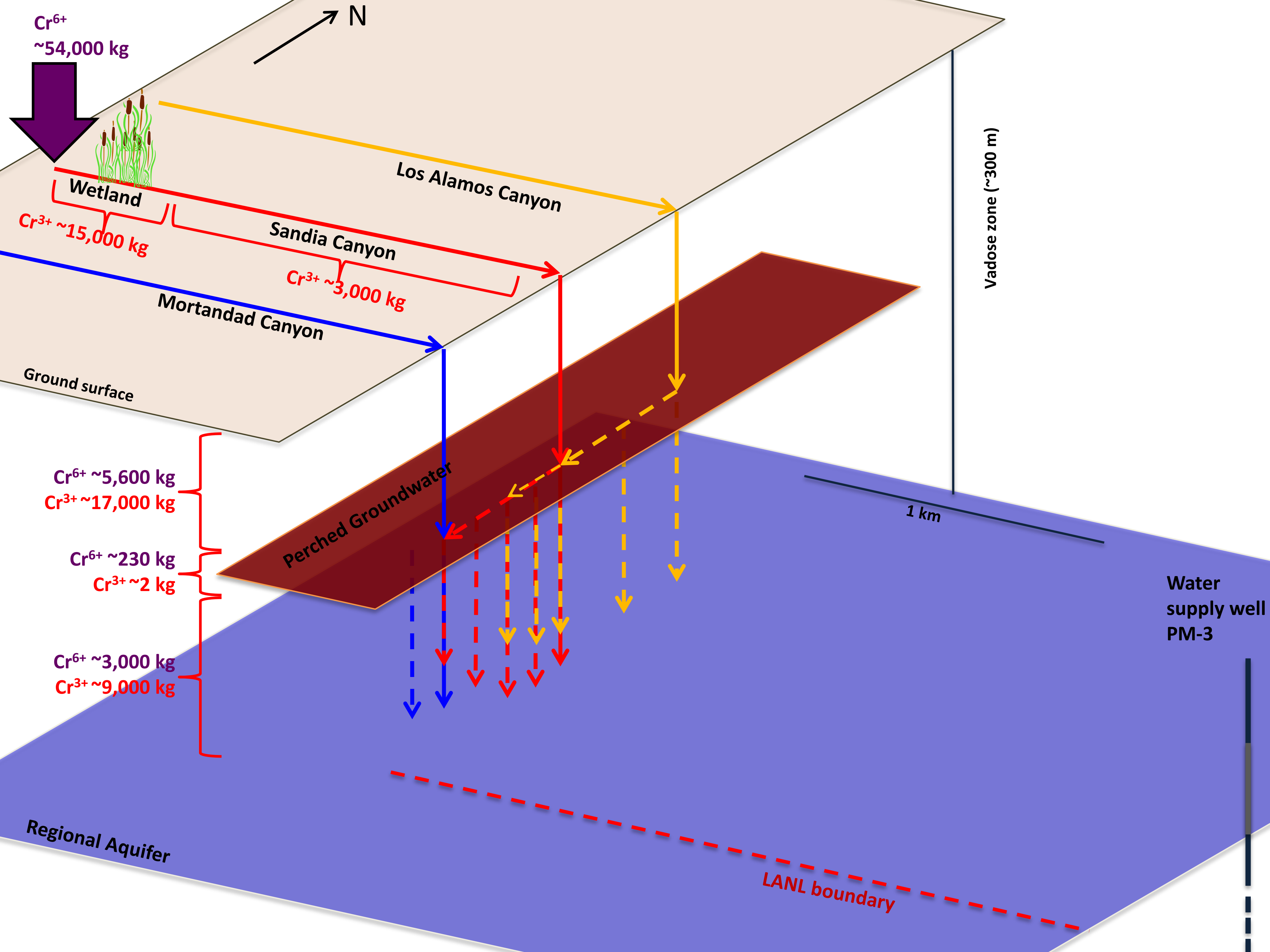


Cr6+
~54,000 kg
N
Wetland
Los Alamos Canyon
Sandia Canyon
Cr3+ ~15,000 kg
Cr3+ ~3,000 kg
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Cr6+ ~5,600 kg
Cr3+ ~17,000 kg
Perched Groundwater
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary



N
Cr6+
~54,000 kg
Wetland
Cr3+ ~15,000 kg
Los Alamos Canyon
Sandia Canyon
Cr3+ ~3,000 kg
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
Cr6+ ~5,600 kg
Cr3+ ~17,000 kg
Cr6+ ~230 kg
Cr3+ ~2 kg
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary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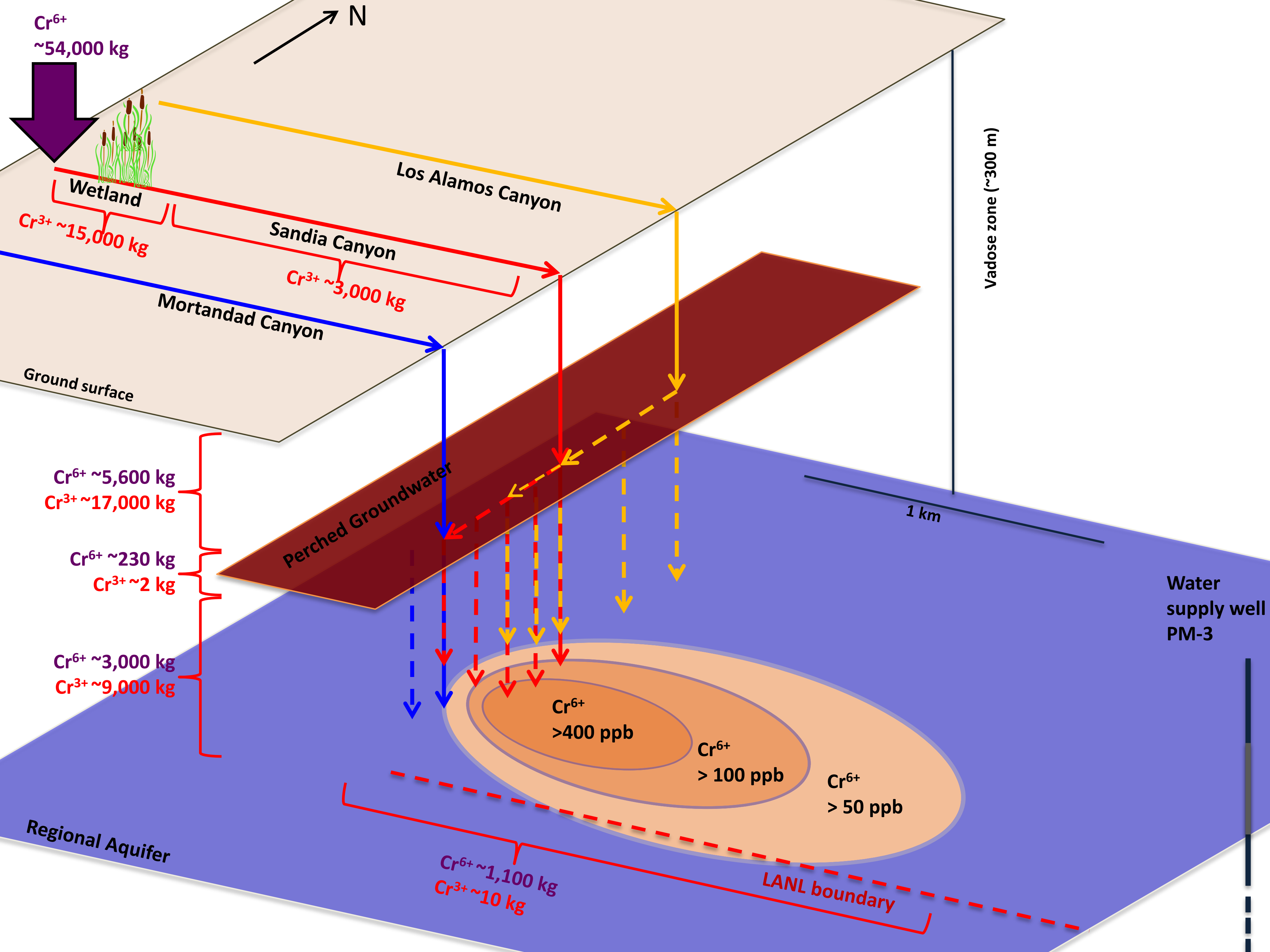
Cr6+
~54,000 kg
Wetland
Cr3+ ~15,000 kg
Los Alamos Canyon
Sandia Canyon
Cr3+ ~3,000 kg
Mortandad Canyon
Ground surface
Vadose zone (~300 m)
Perched Groundwater
Cr6+ ~5,600 kg
Cr3+ ~17,000 kg
Cr6+ ~230 kg
Cr3+ ~2 kg
Cr6+ ~3,000 kg
Cr3+ ~9,000 kg
1 km
Water
supply well
PM-3
Regional Aquifer
LANL boundary



Cr6+
~54,000 kg
N
Wetland
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Cr6+ ~230 kg
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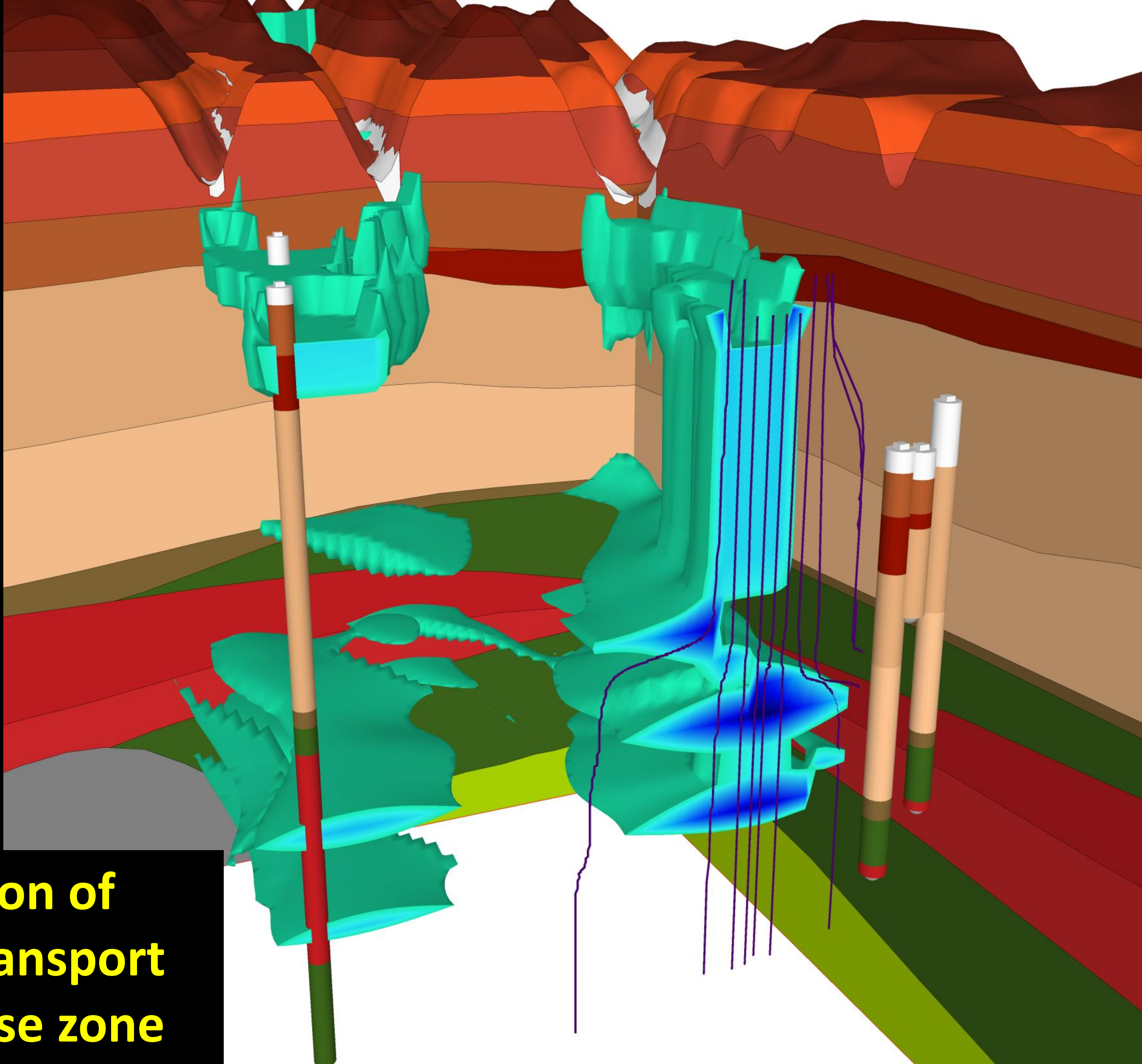
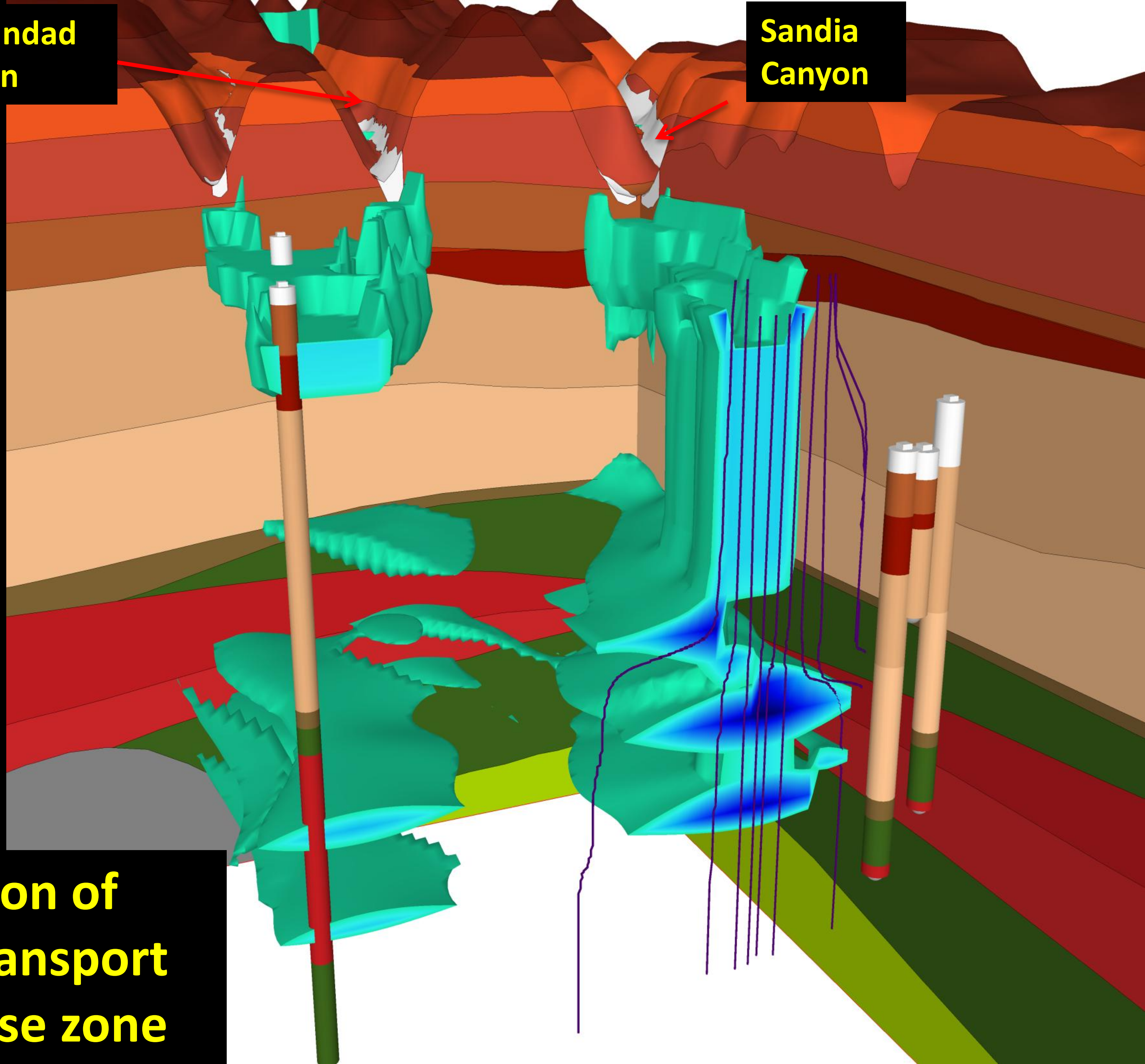
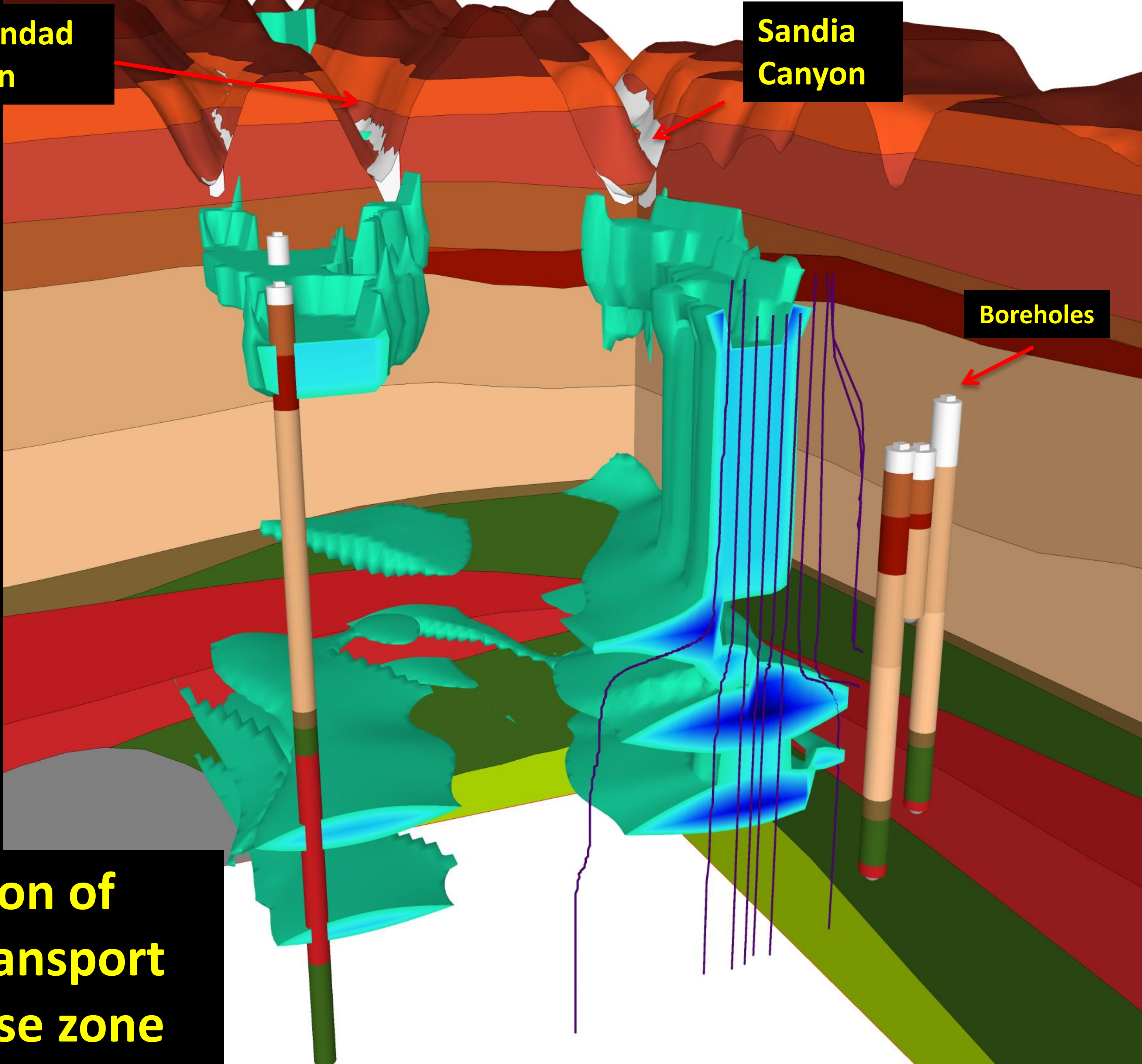
Cr6+ ~3,000 kg
Cr3+ ~9,000 kg
1 km
Water supply well PM-3
Cr6+ >400 ppb
Cr6+ > 100 ppb
Cr6+ > 50 ppb
Regional Aquifer
Cr6+ ~1,100 kg
Cr3+ ~10 kg
LANL boundary



3D simulation of flow and transport in the vadose zone

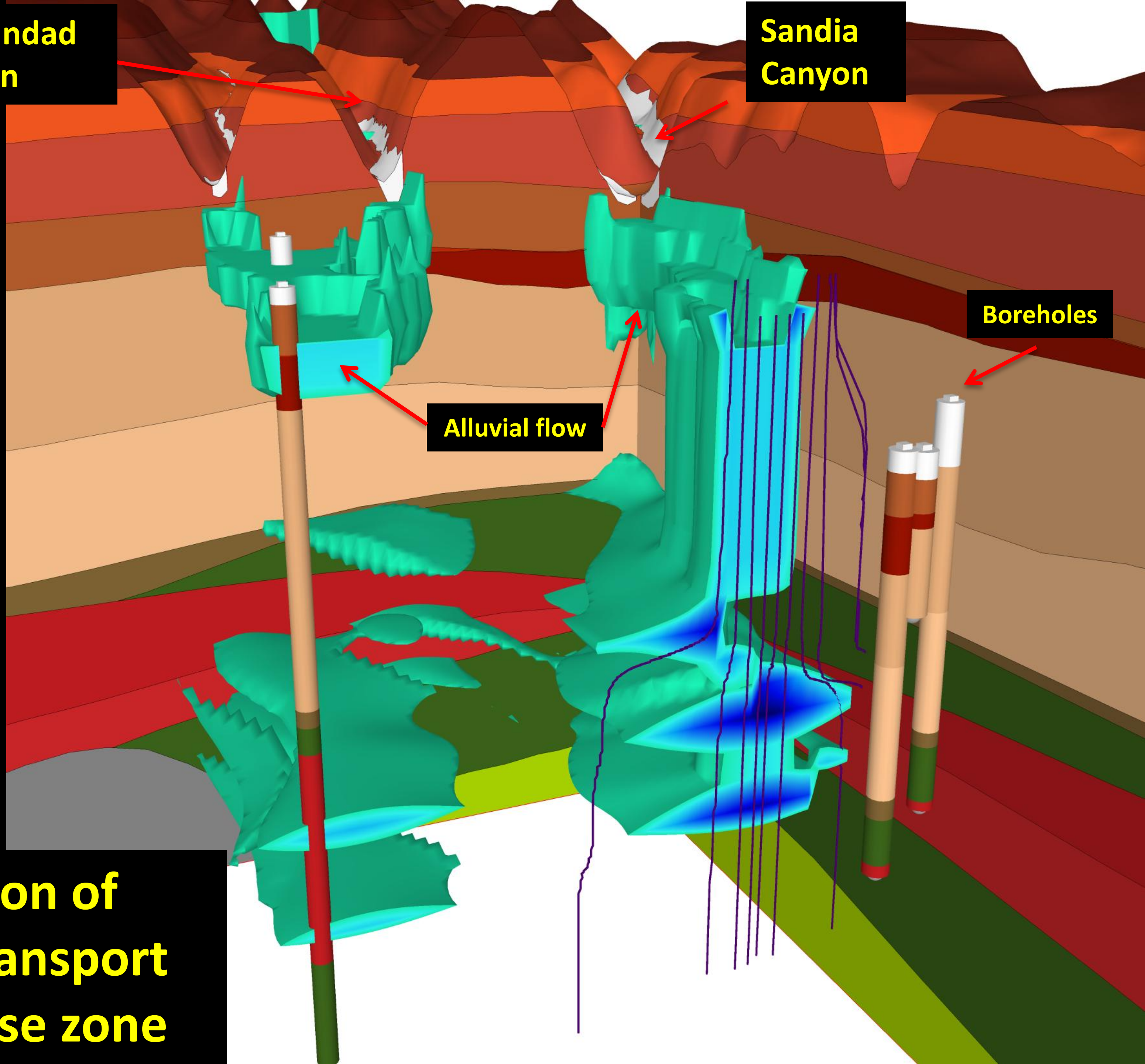


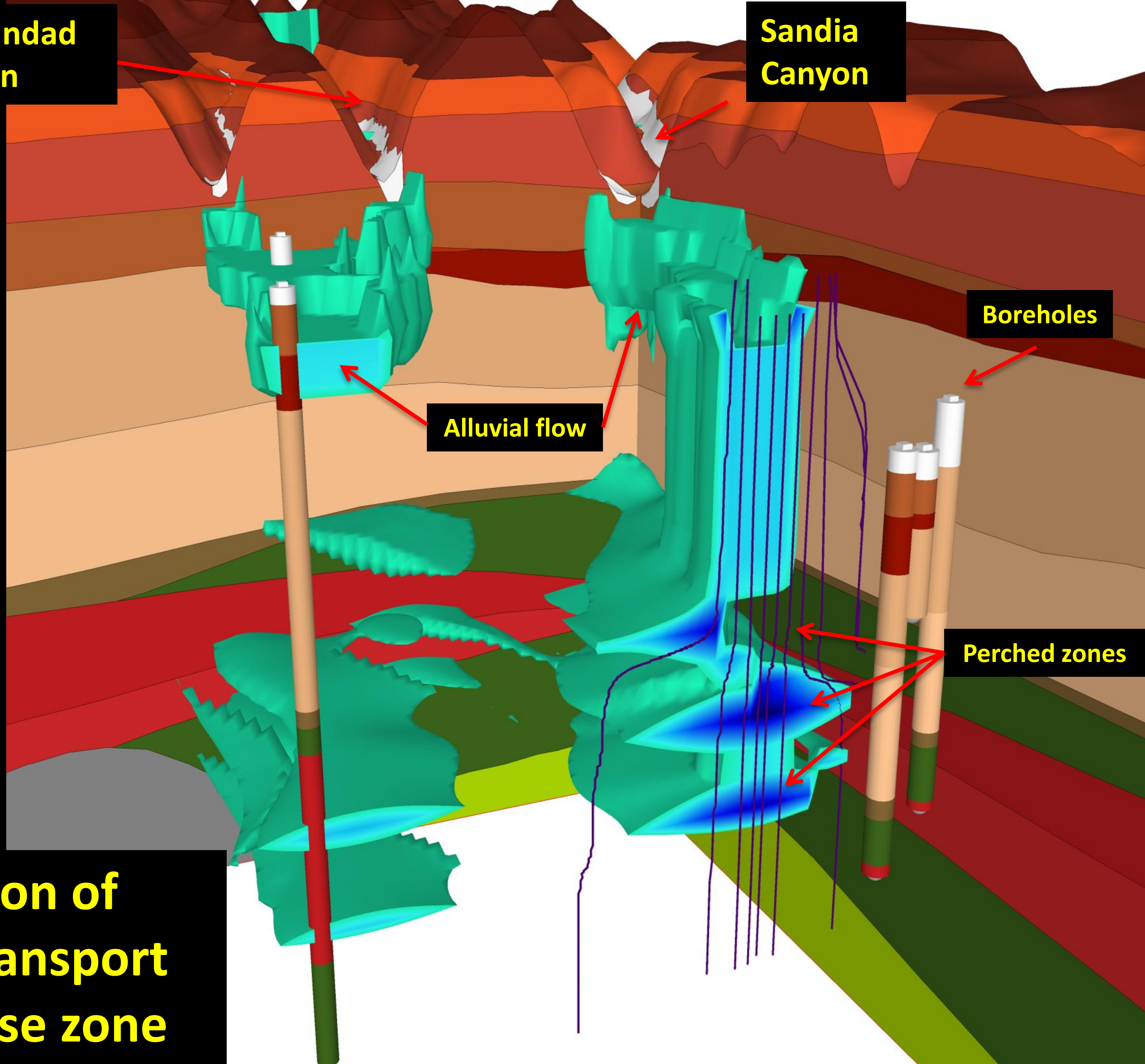
3D simulation of flow and transport in the vadose zone



3D simulation of flow and transport in the vadose zone

3D simulation of flow and transport in the vadose zone





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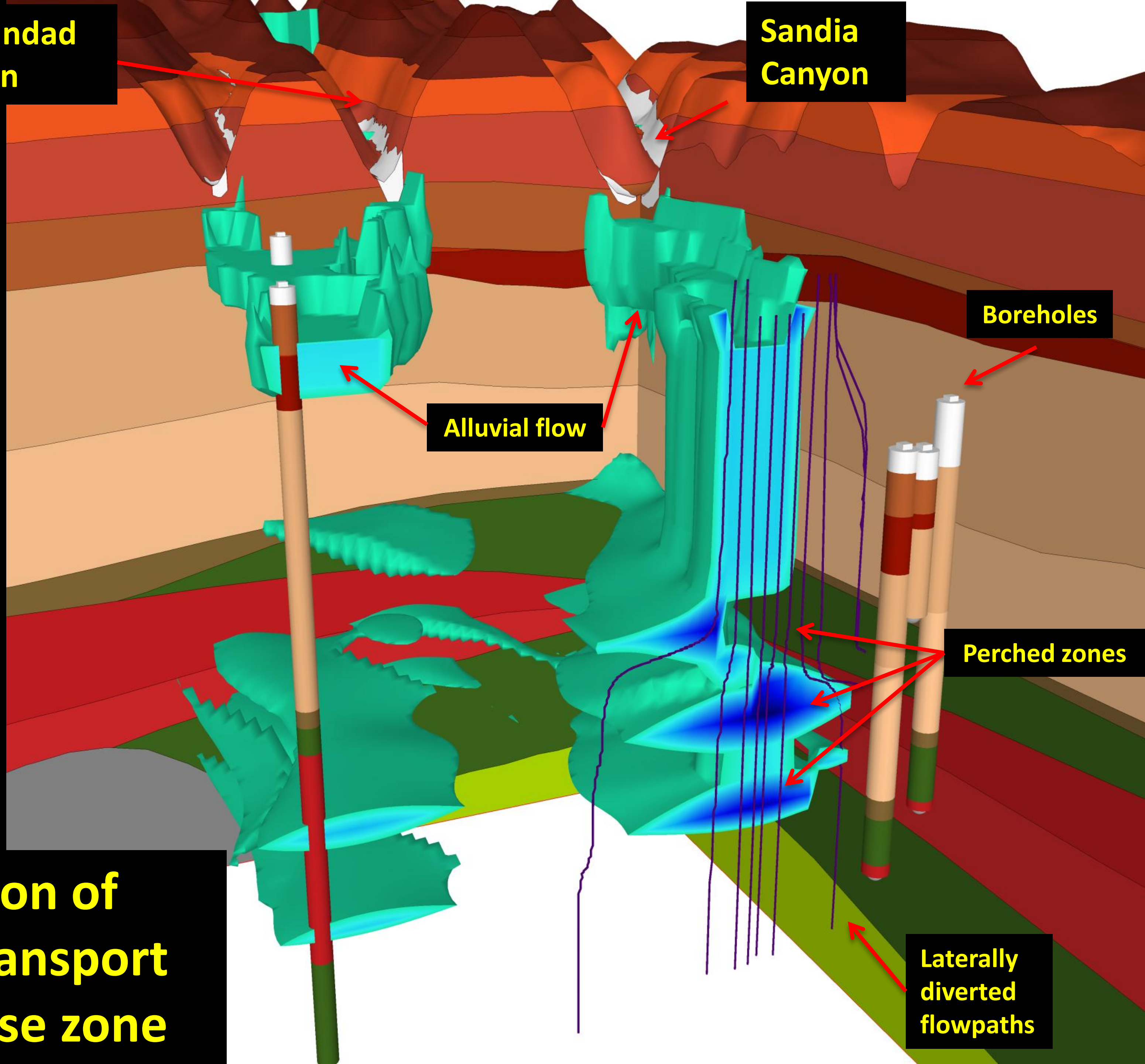
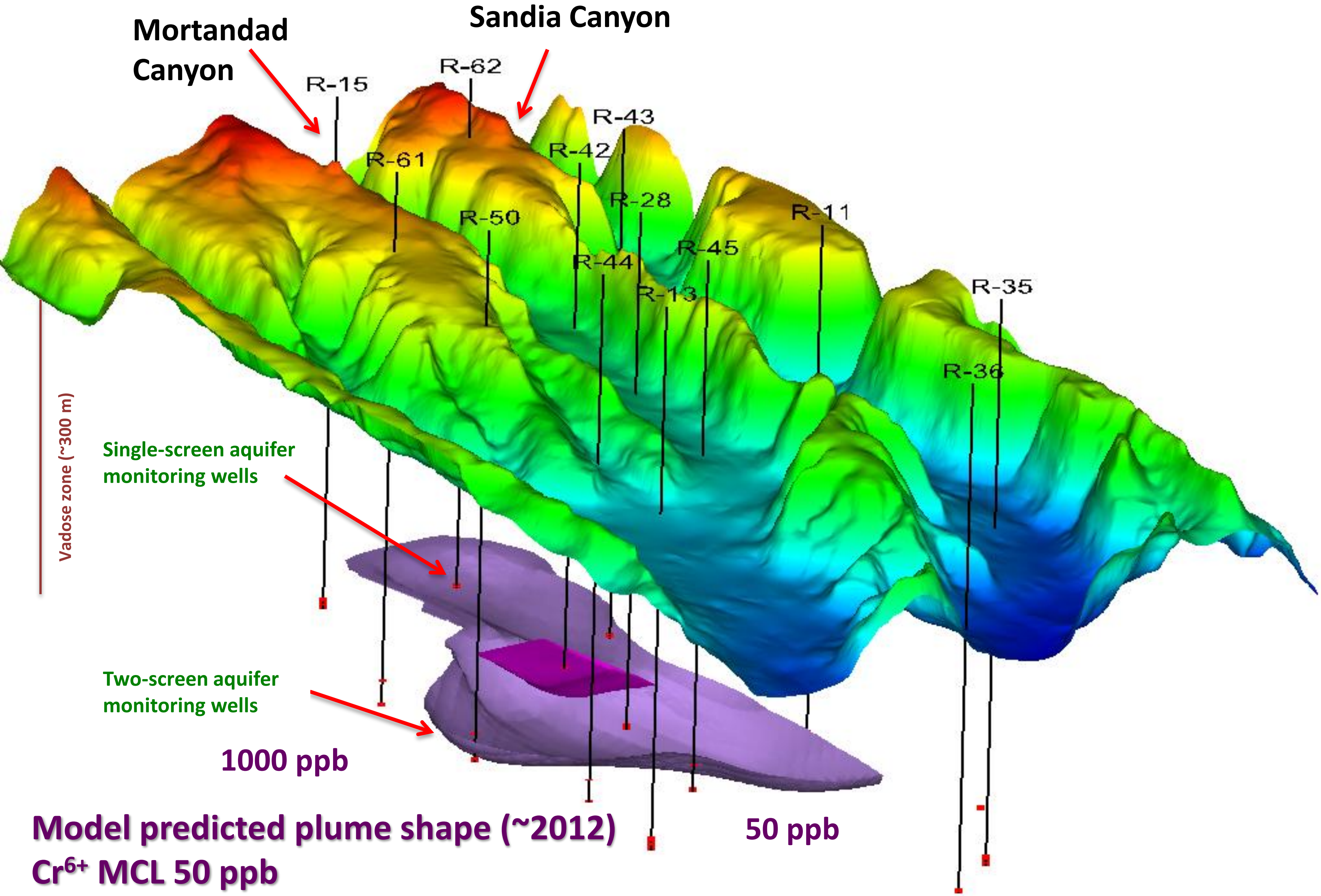


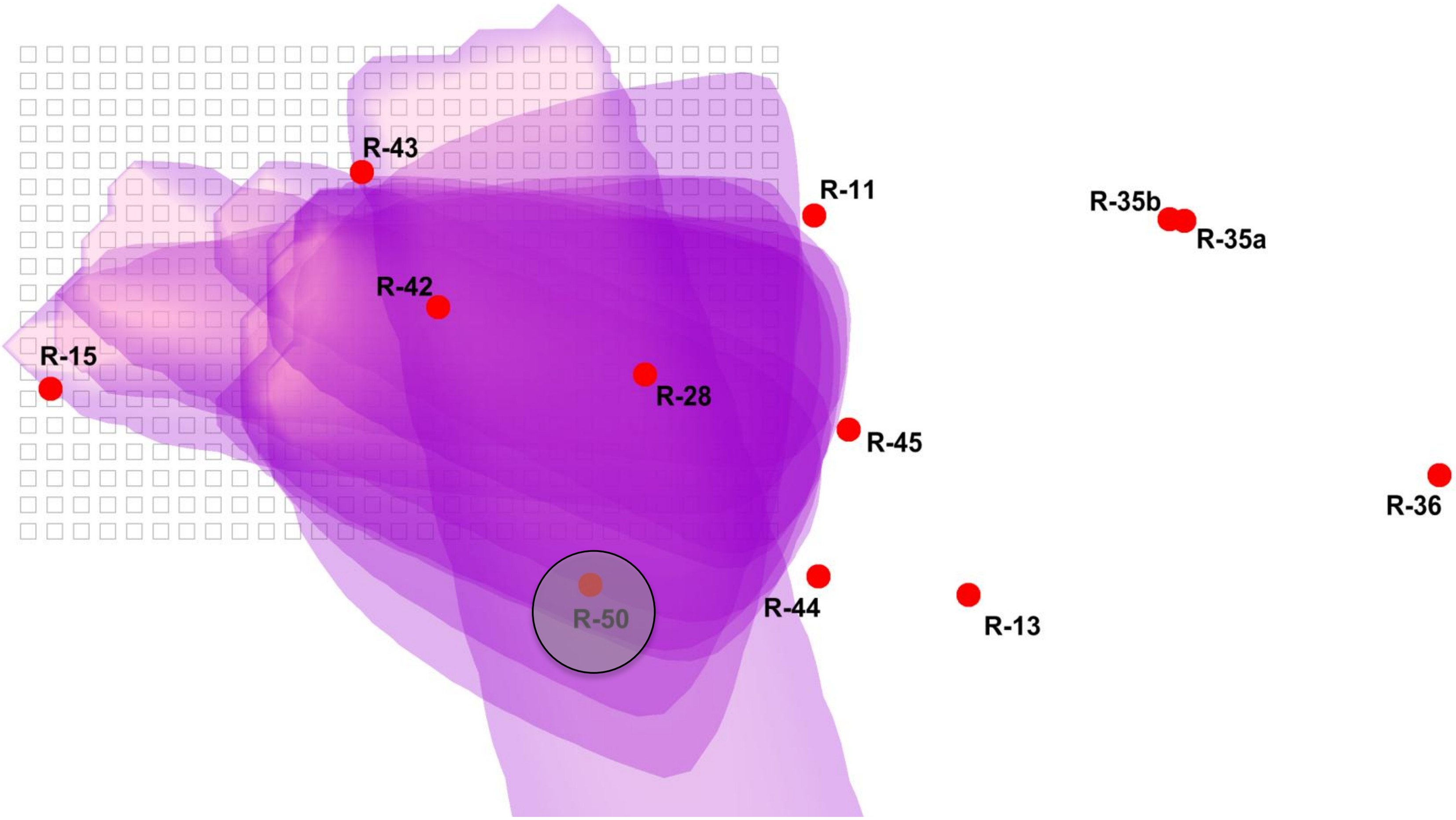
3D simulation of flow and transport in the vadose zone

LANL chromium site



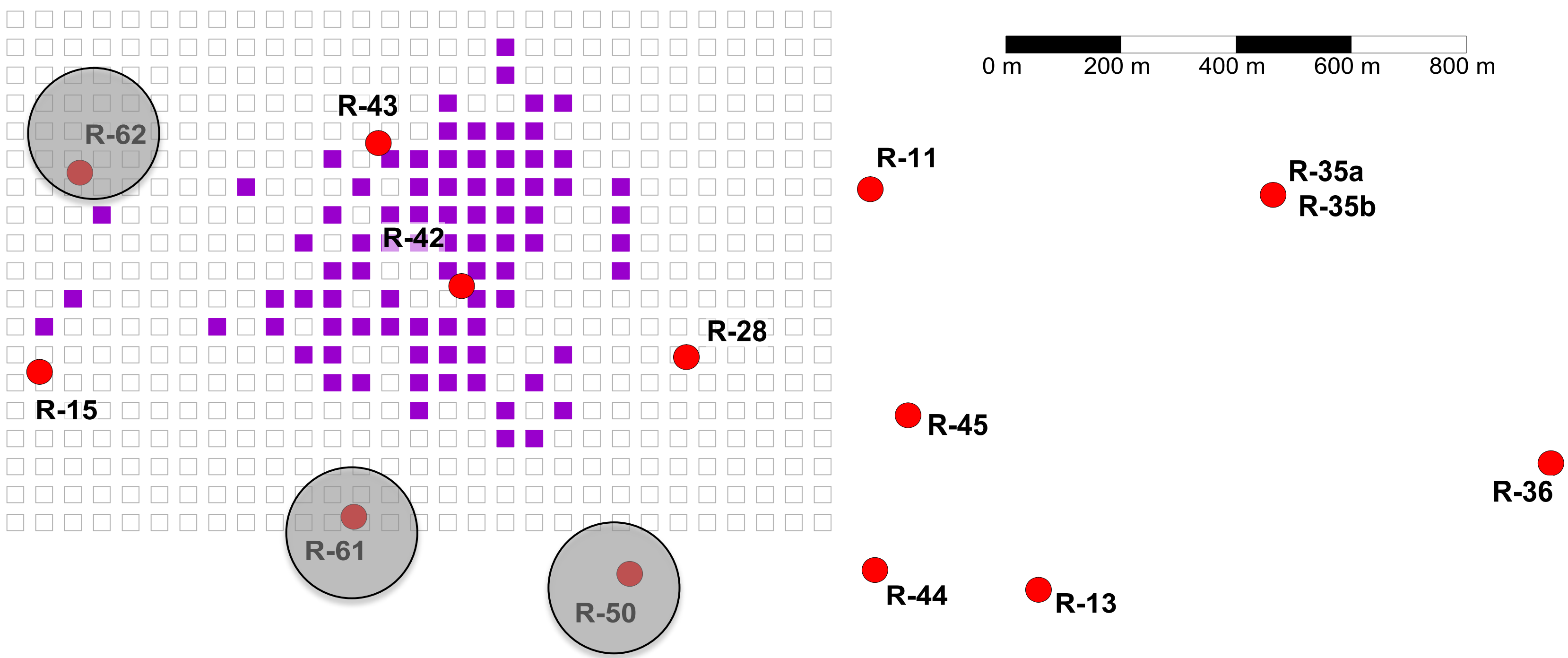
Model predicted plume shape (~2012)
Cr^{6+} MCL 50 ppb

2009 model analyses for source identification / network design



- Due to uncertainties, a series of alternative models (plumes) are plausible
- Model predictions are constrained by all the available regional-aquifer data (hydrogeological and geochemical)
- 11 out 83 plausible plumes shown

2009 model analyses for source identification / network design

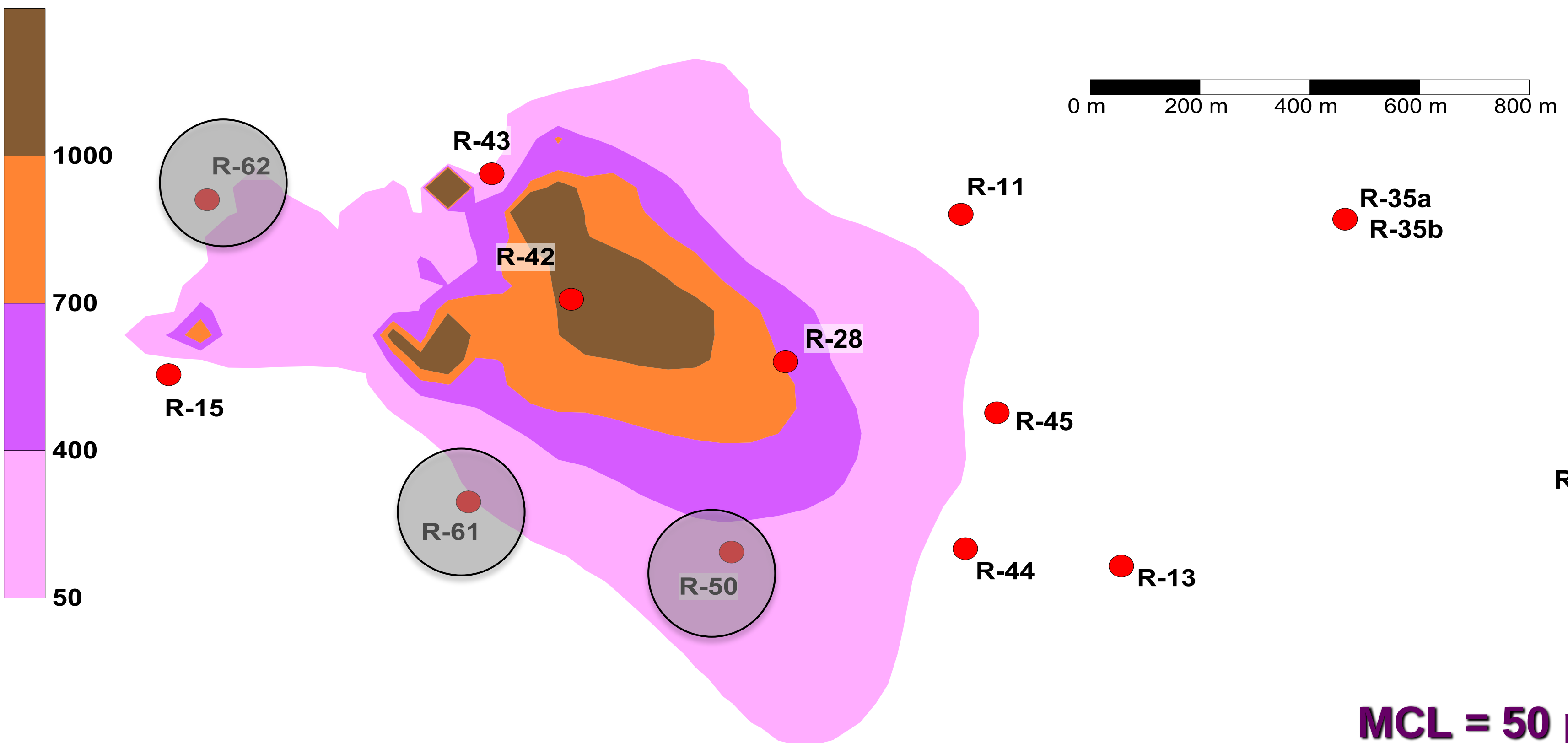


Plausible contaminant-arrival locations (83 out of 551)

Wells R-62, R-61 and R-50 were not drilled yet

2009 model estimate of the plausible Cr^{6+} [ppb] along the regional aquifer water table

- Wells R-62, R-61 and R-50 were not drilled yet
- Locations of wells R-62, R-61 and R-50 were optimized based on model analyses
- Observed concentrations at R-62, R-61 and R-50 confirmed model predictions
- R-43 concentration were at background when the analyses were performed
- Since 2010, R-43 concentrations are increasing and approaching the model predicted concentration



MCL = 50 ppb

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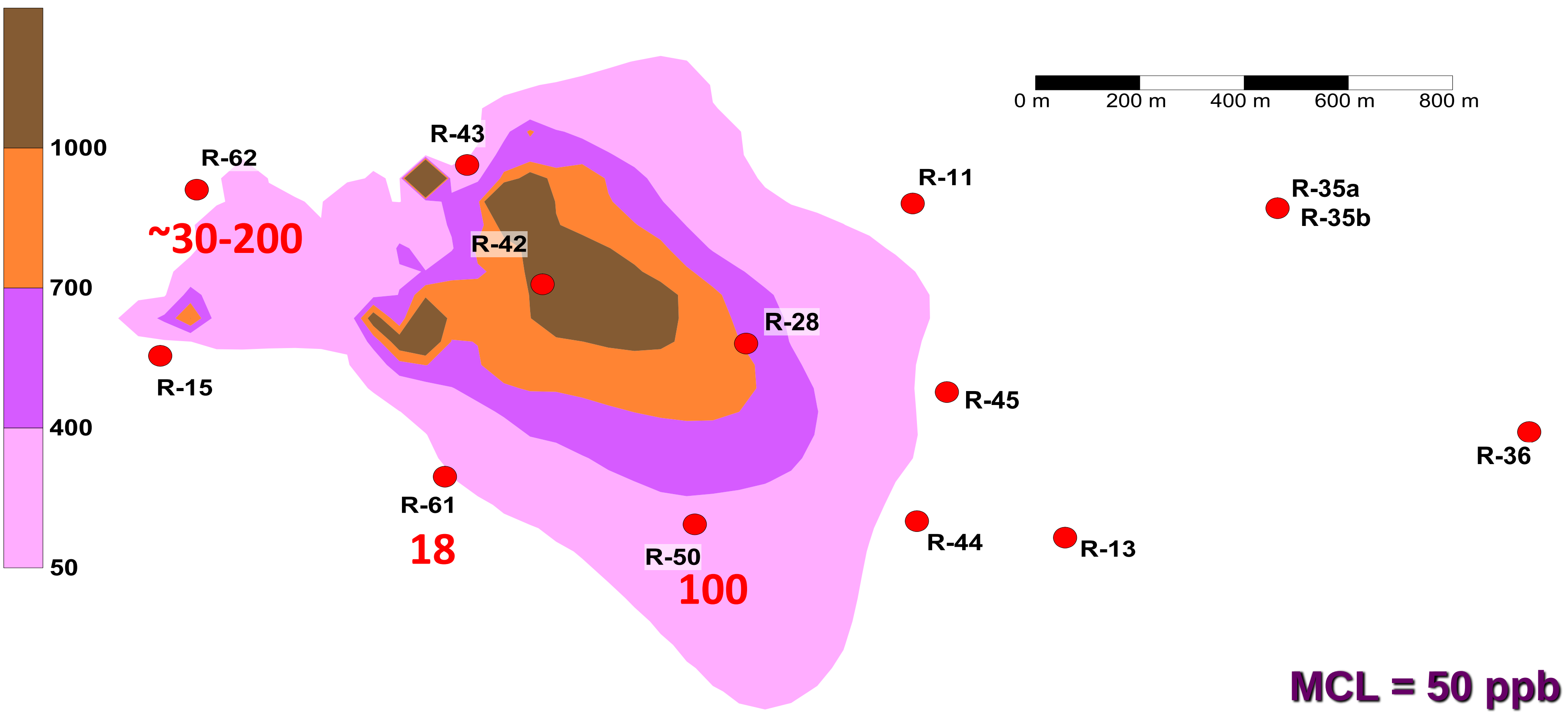

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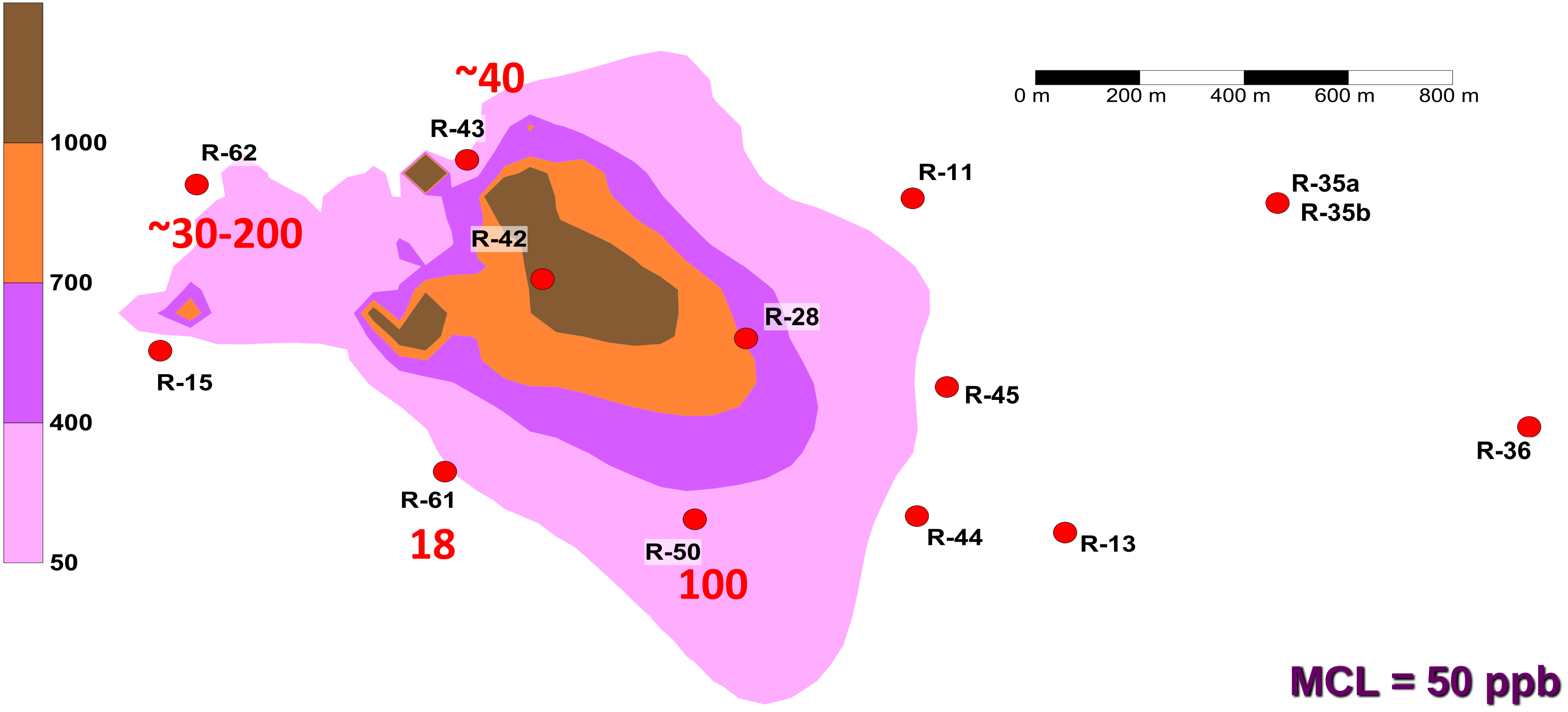
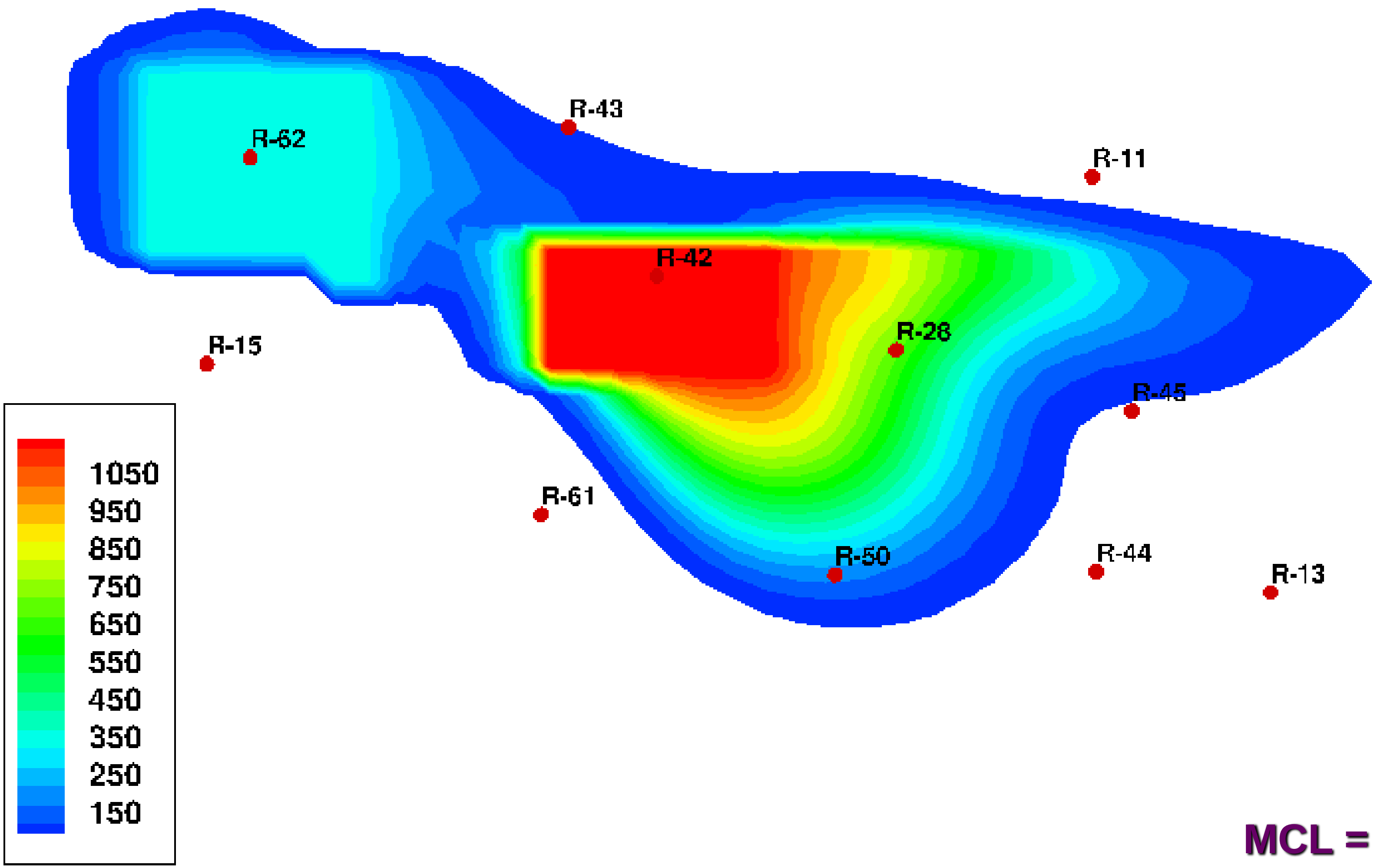
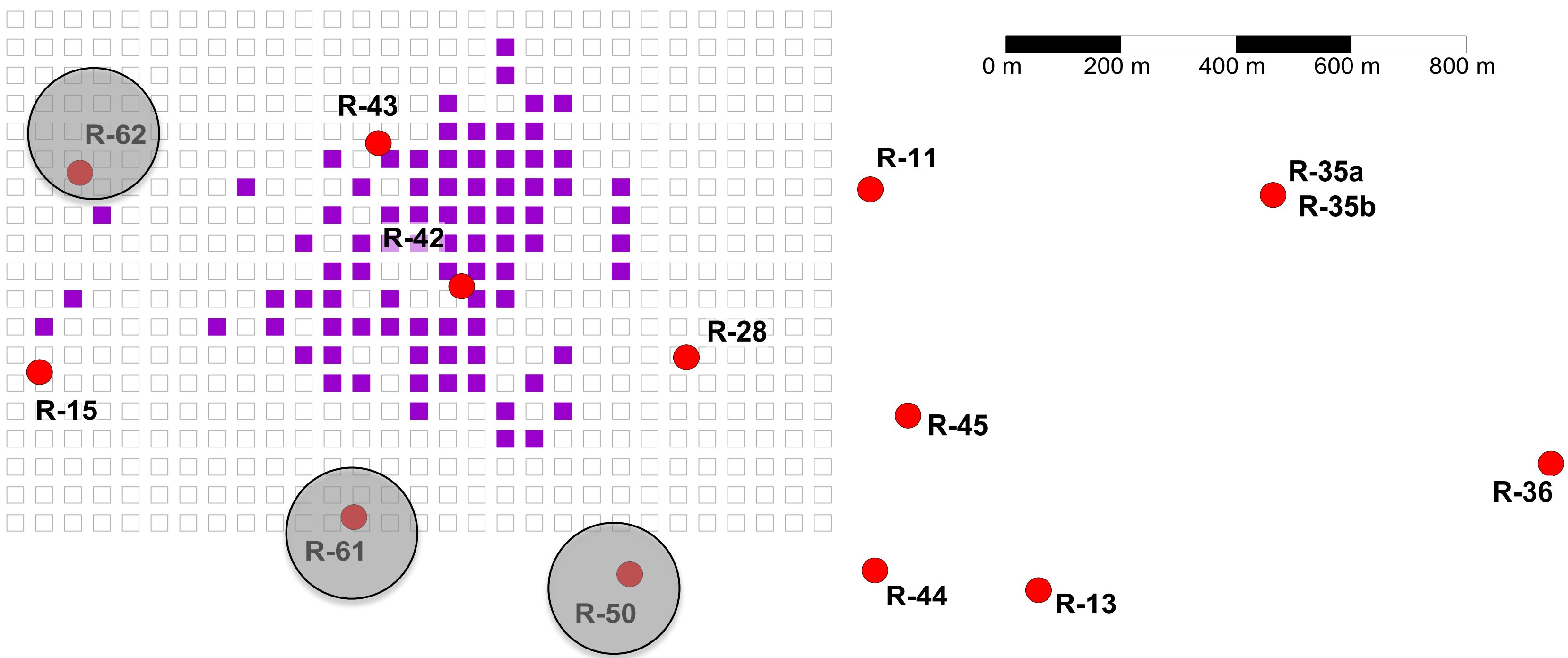


2012 model estimate of the plausible Cr^{6+} [ppb] along the regional aquifer water table



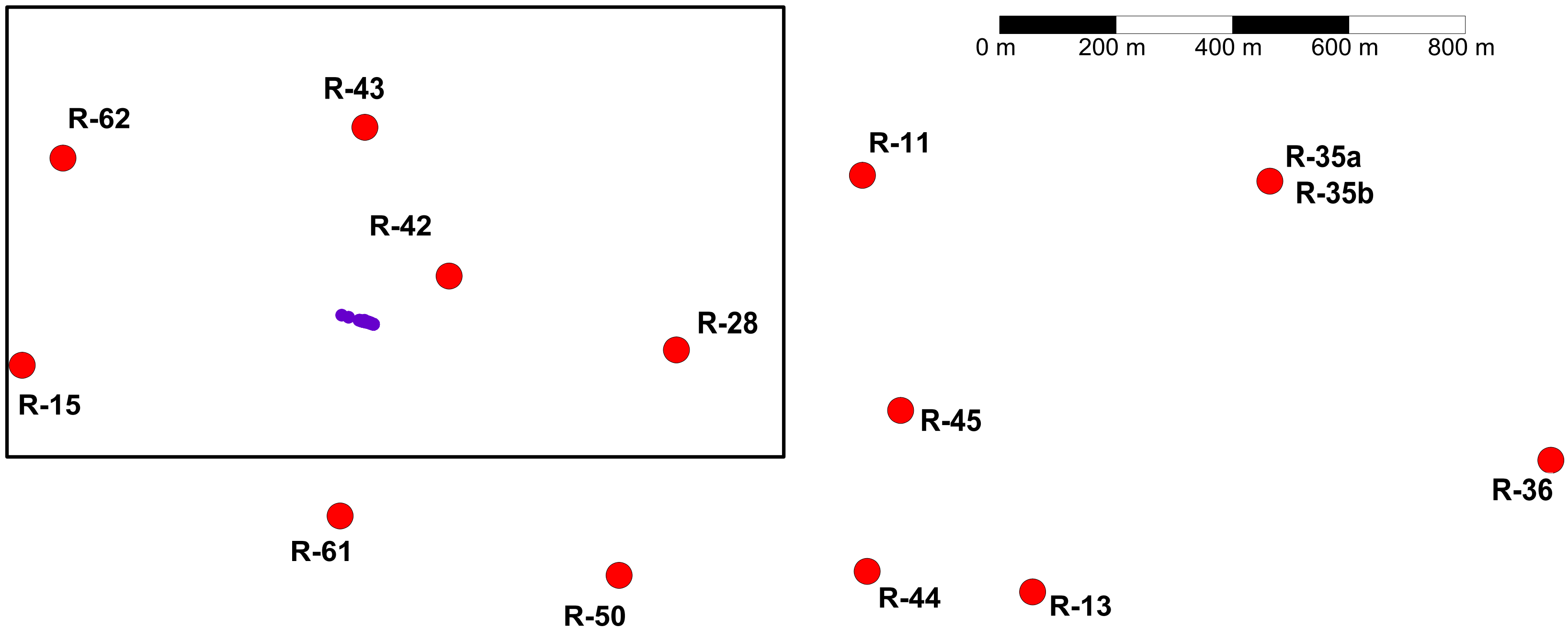
MCL = 50 ppb

2009 model analyses for source identification / network design



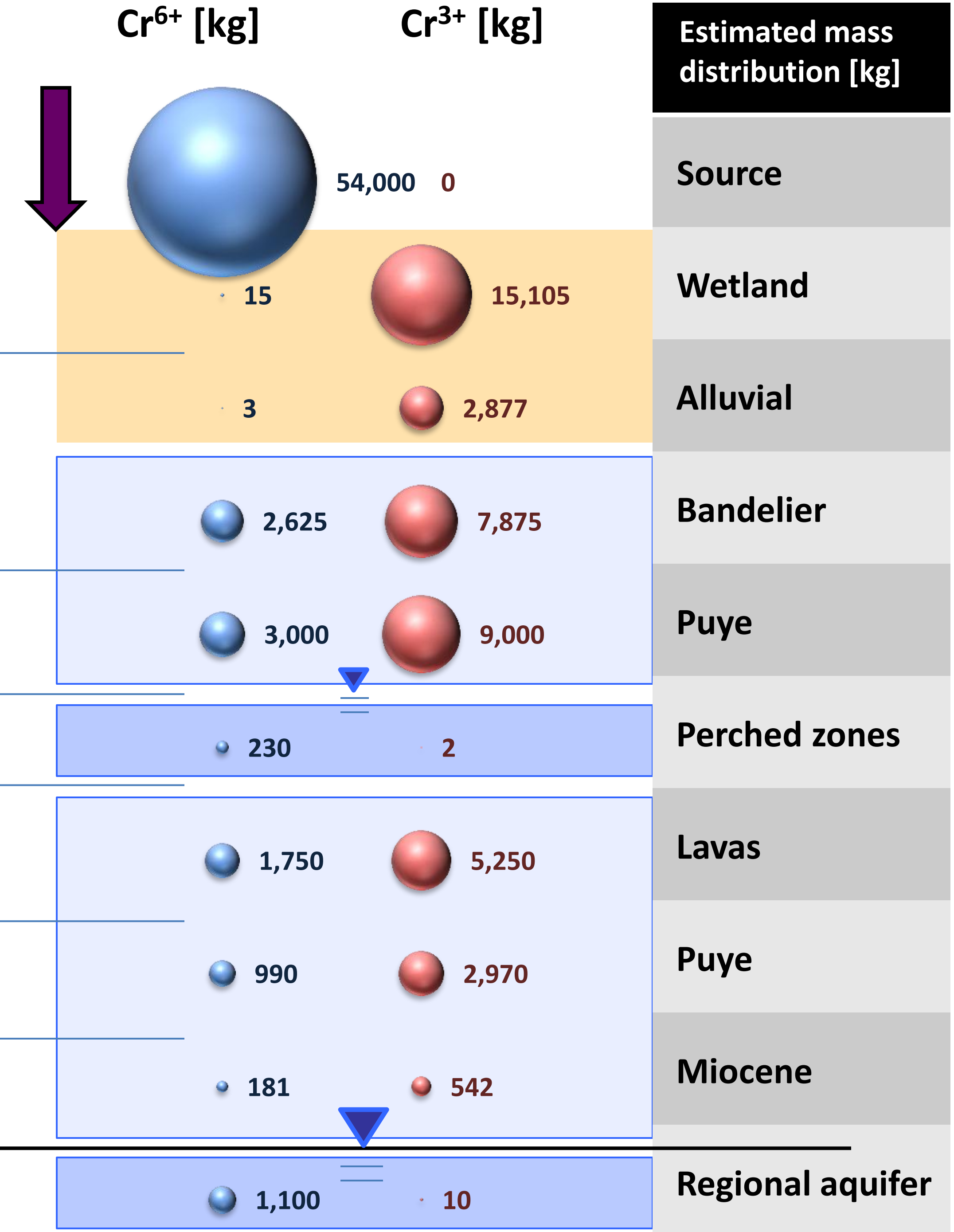
Plausible contaminant-arrival locations (83 out of 551)

2012 model analyses for source identification / network design



- Series of plausible contaminant-arrival locations in a well-constrained region
- All the obtained solutions (492) are almost equivalent
- Additional analyses are performed considering multiple contaminant arrival locations

Cr^{6+} mass distribution



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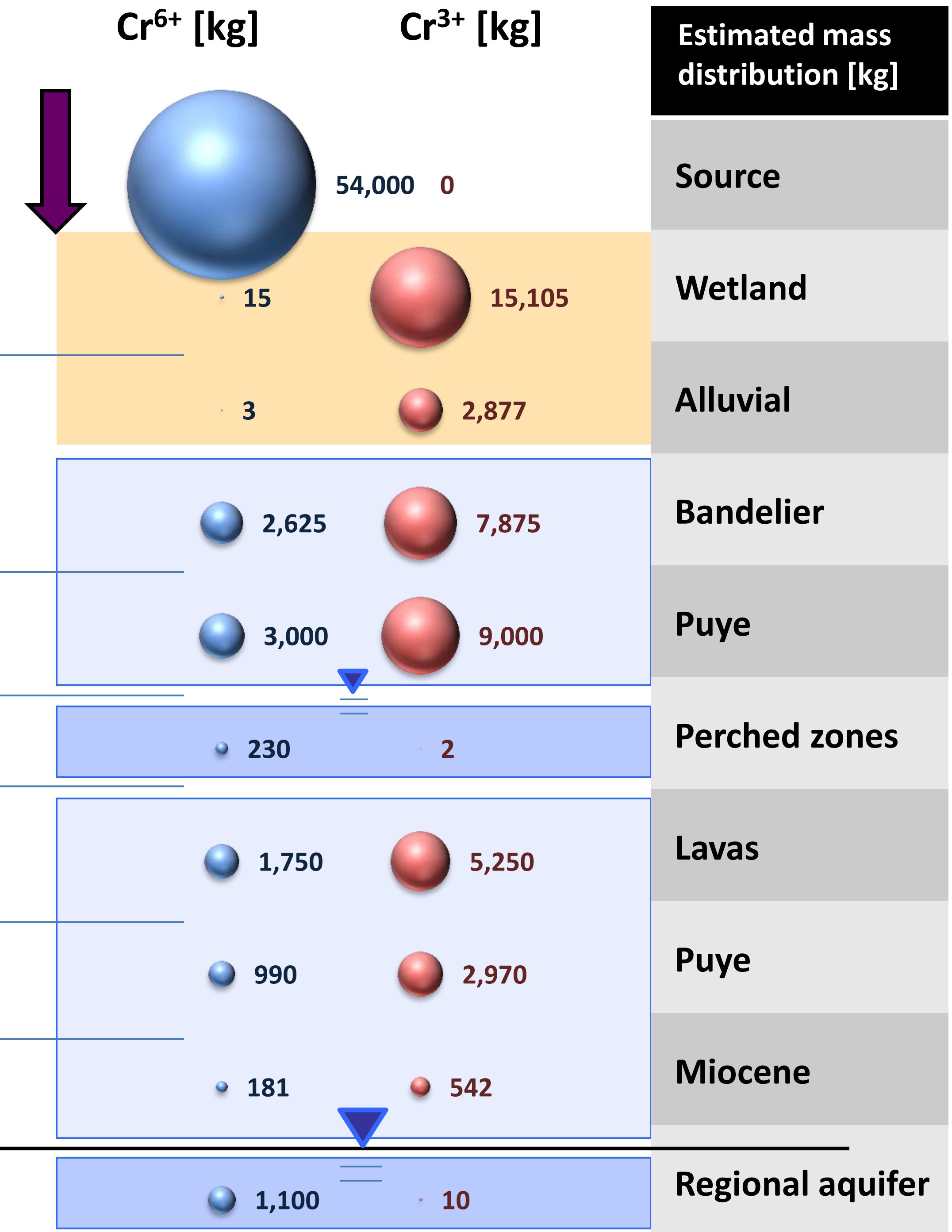
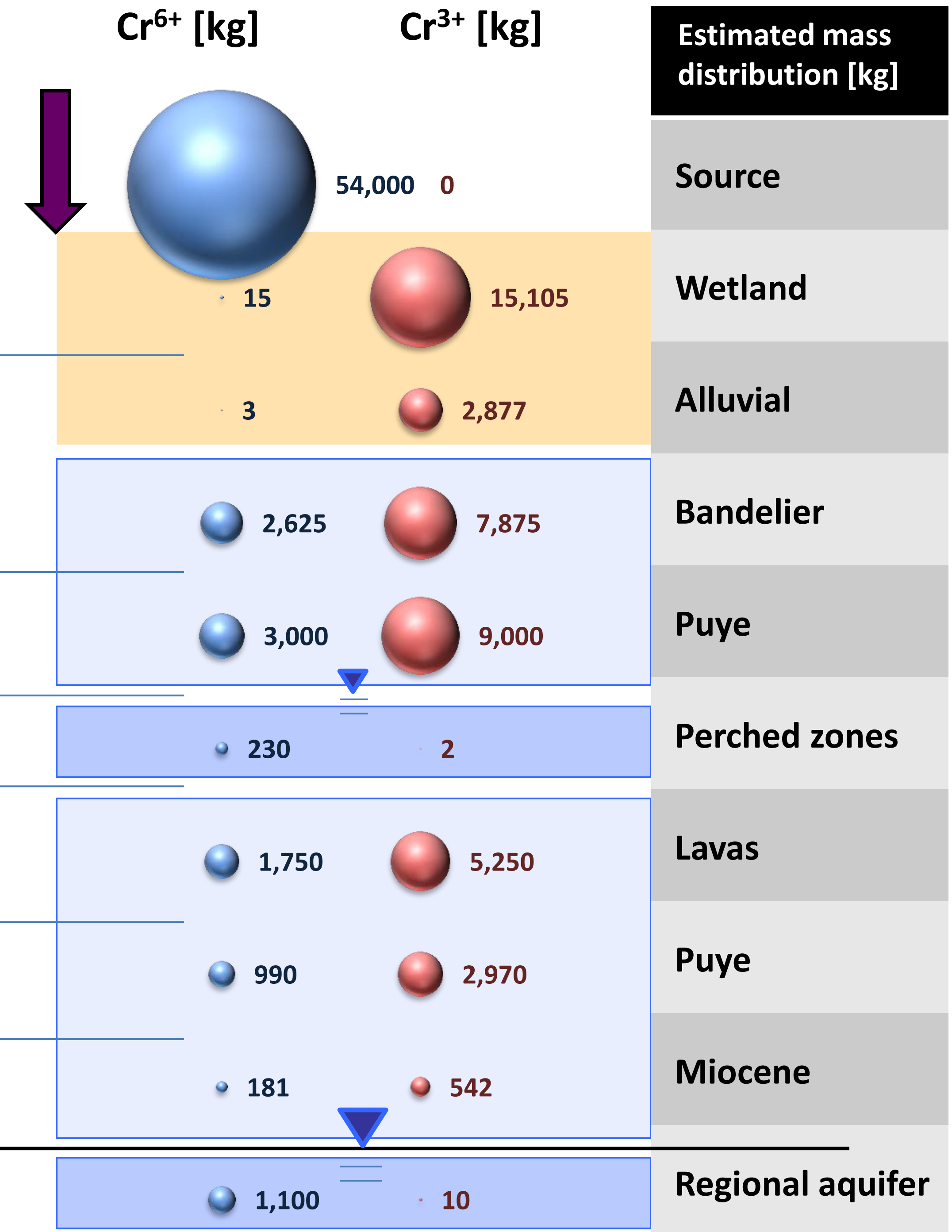


There are uncertainties associated with these estimates. For example, source mass may vary between 31,000 and 72,000 kg, and mass in the aquifer may vary between 300 and 3,300 kg.

Cr^{6+} mass distribution



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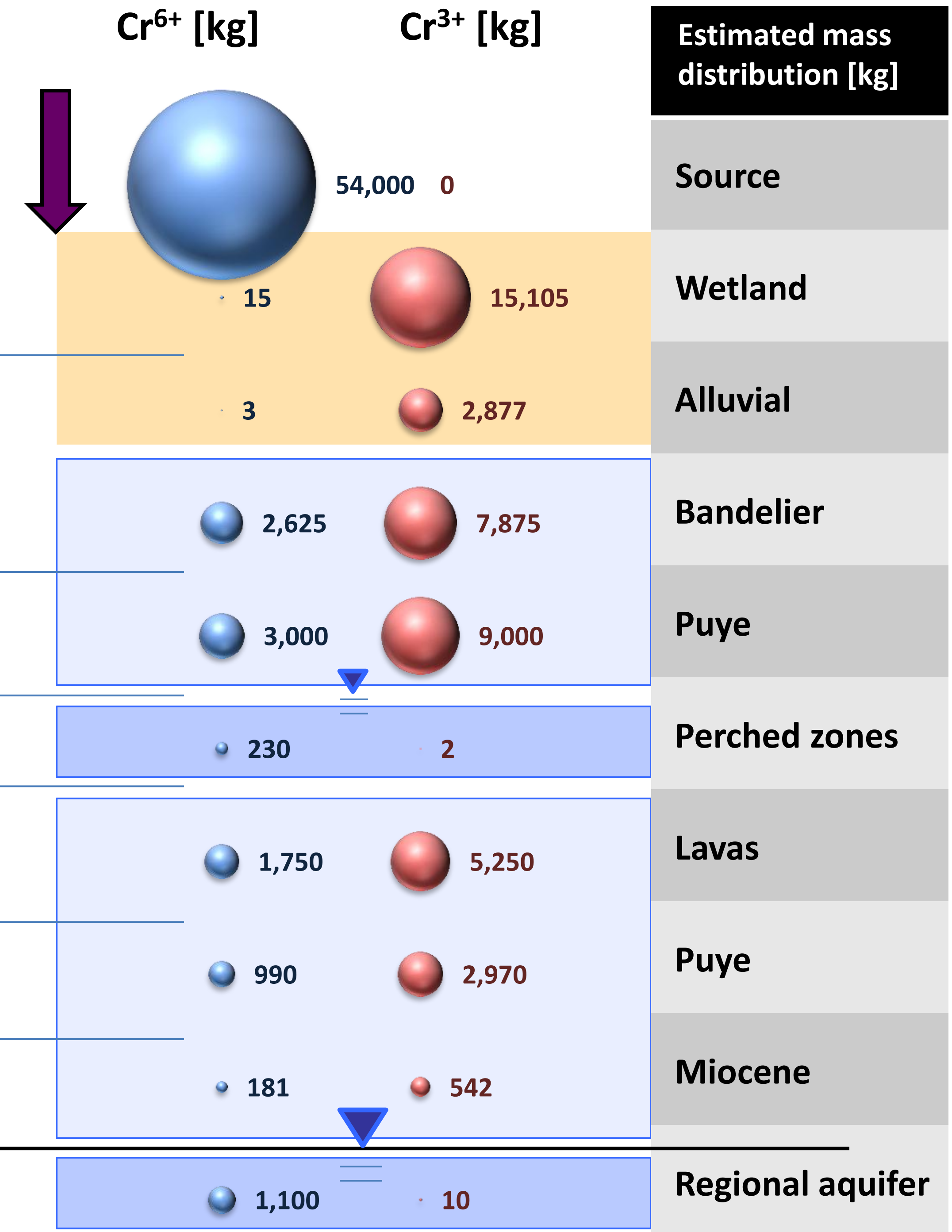
Series of additional activities are identified to reduce decision uncertainties related to contaminant mass distribution (source)



Planned activities

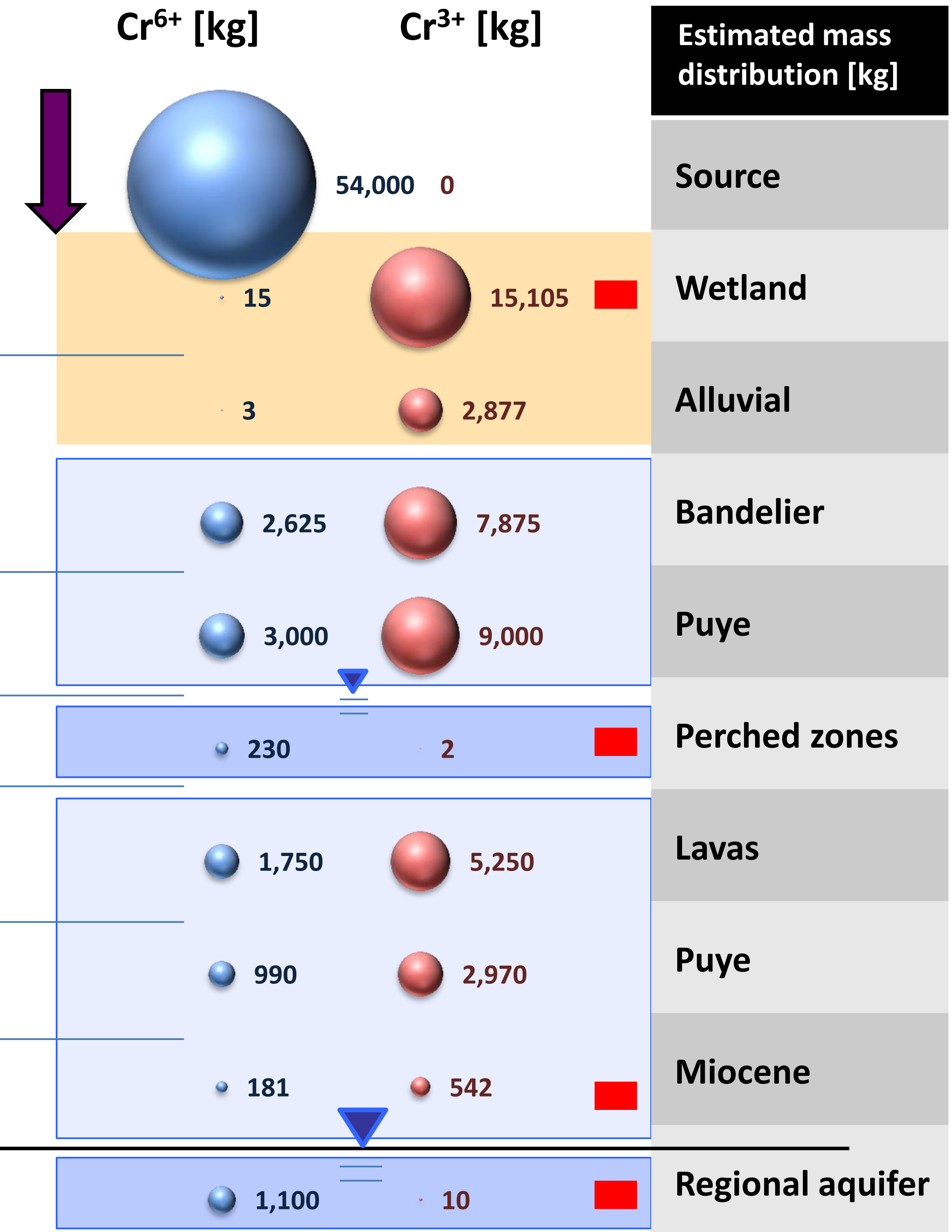
Grade Control Structure
- immediate effect
- stabilize wetland to control Cr, PCBs, and other

Reduced effluent volume (infiltration)
- mid-term effect
- reduce flux of secondary Cr source

Geochemical lab-scale analyses (cores)
- key support for optimizing CME – MNA
- attenuation potential
- reduction potential

Pumping/tracer tests at existing wells
- immediate affect
- source removal
- capture zone analysis
- characterize field–scale hydrogeologic and geochemical properties
- characterize secondary Cr source

Groundwater flow & transport modeling
- key for interpretation of the collected data
- key support for optimizing CME - MNA



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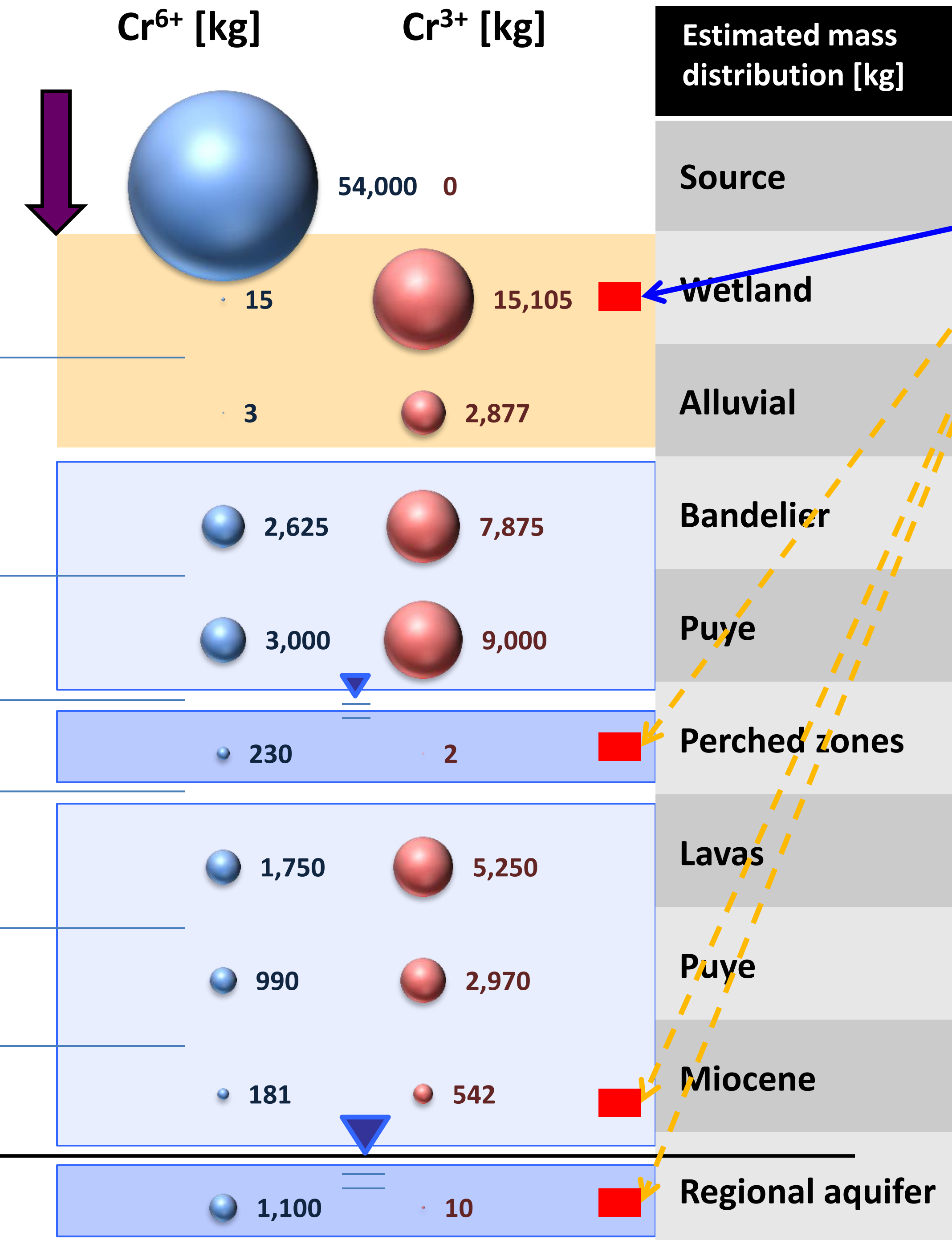

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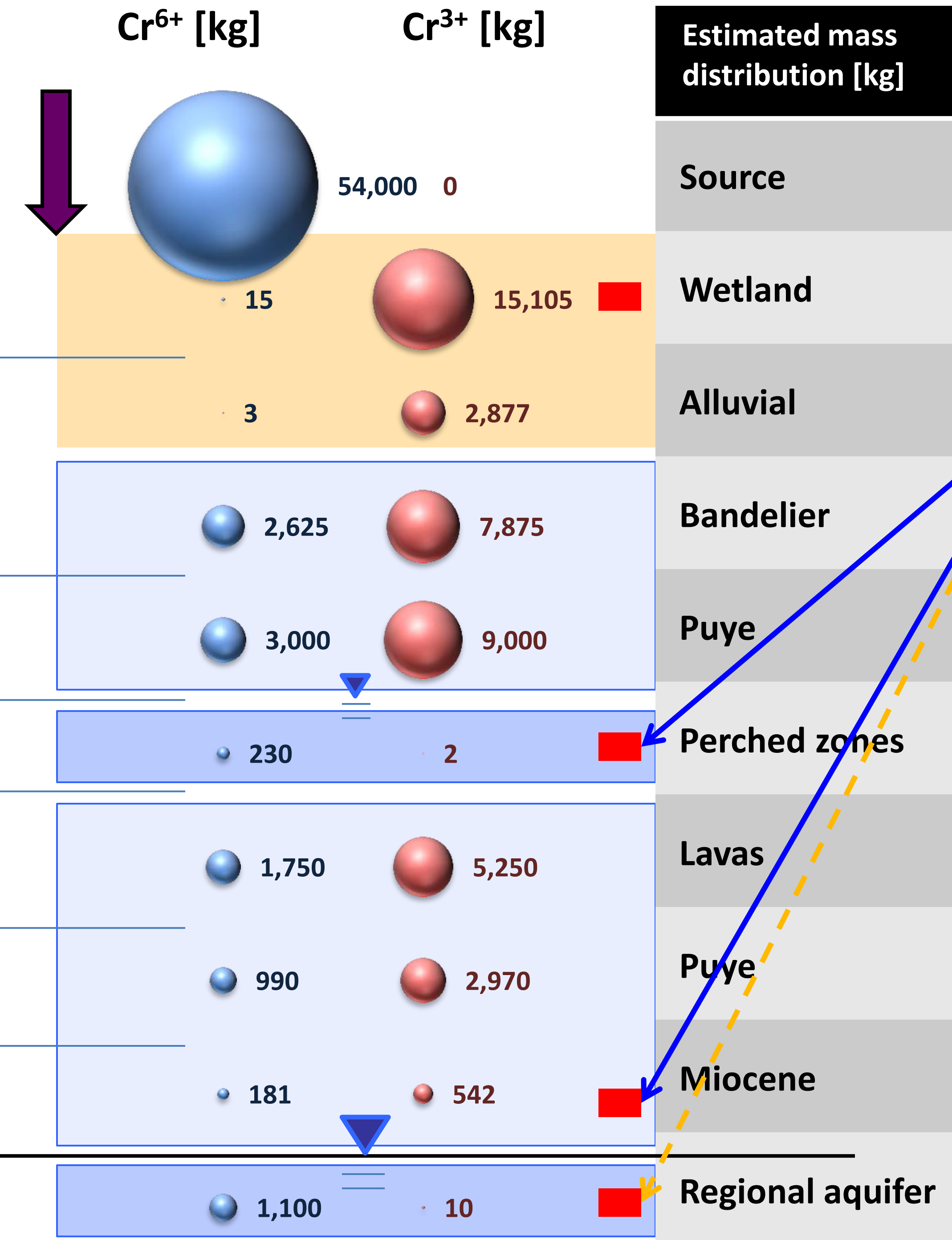

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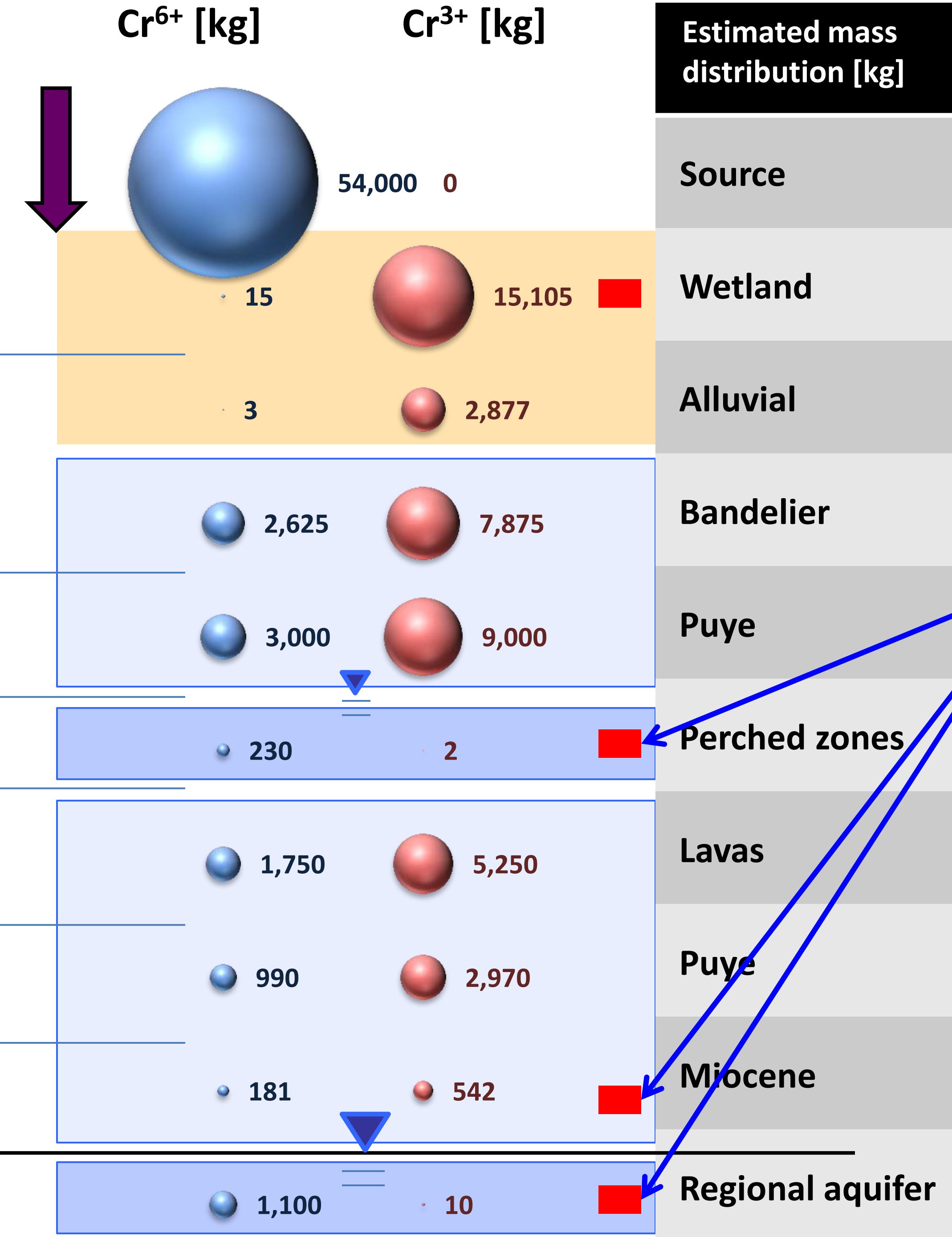

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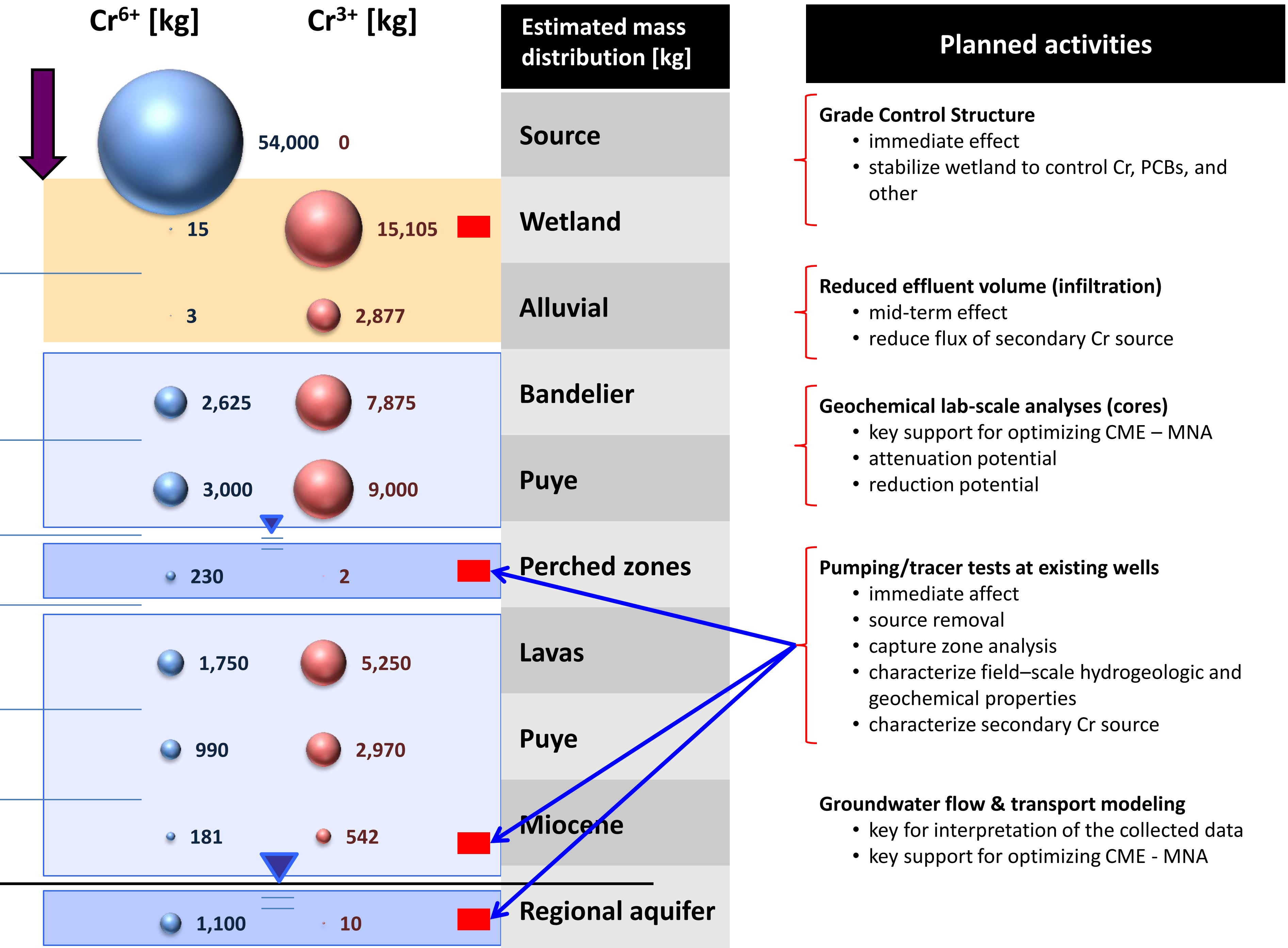

Cr6+ [kg]
Cr3+ [kg]
Estimated mass distribution [kg]
Source
54,000
0
Wetland
15
15,105
Alluvial
3
2,877
Bandelier
2,625
7,875
Puye
3,000
9,000
Perched zones
230
2
Lavas
1,750
5,250
Puye
990
2,970
Miocene
181
542
Regional aquifer
1,100
10
Planned activities
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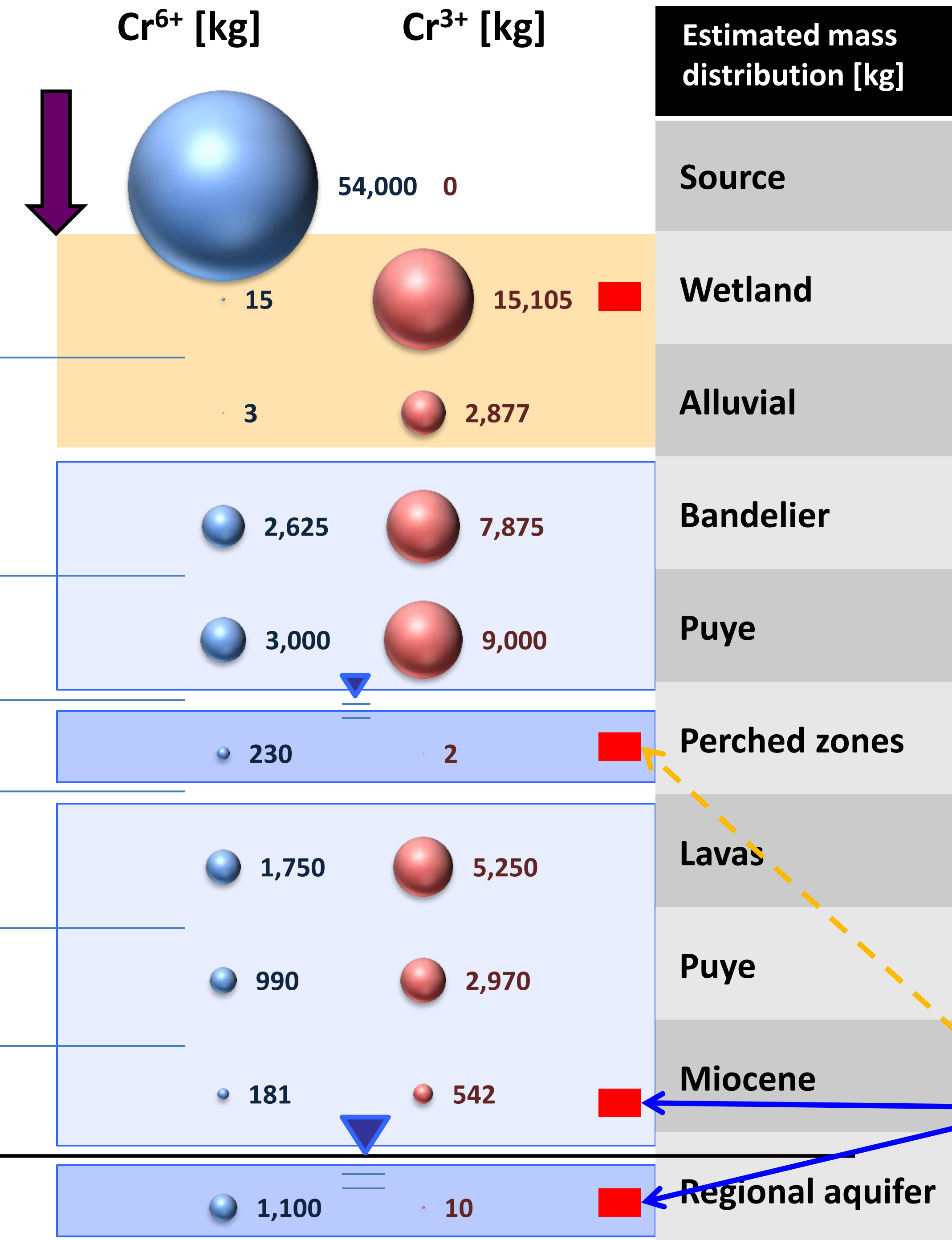

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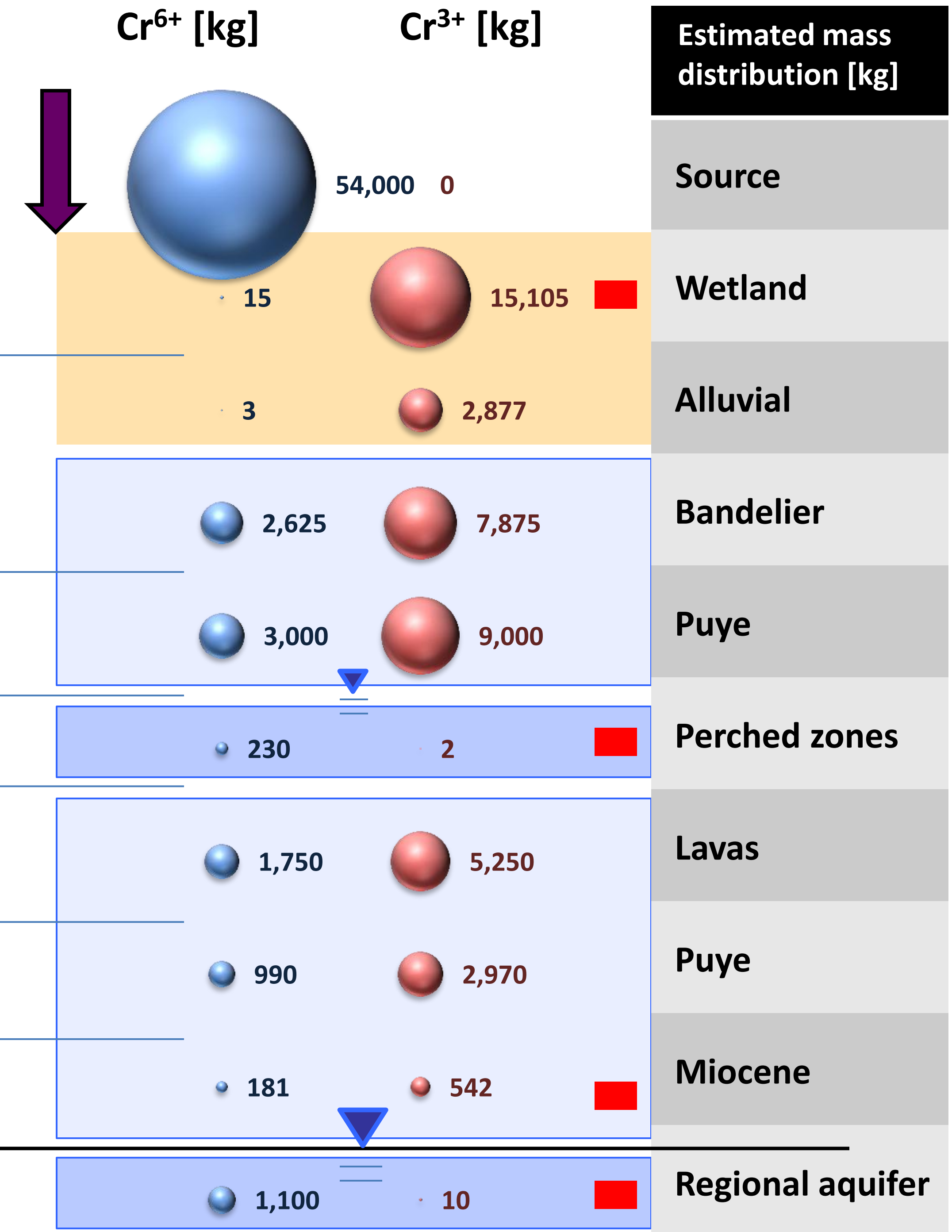

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MADS
Model Analysis and Decision Support

Los Alamos NATIONAL LABORATORY

- an open-source high-performance computational framework for Model Analyses and Decision Support (MADS)
- advanced adaptive computational techniques:
  - sensitivity analysis (local / global);
  - uncertainty quantification (local / global);
  - optimization / calibration / parameter estimation (local / global);
  - model ranking & selection
  - decision support (probabilistic / non-probabilistic)
- novel robust algorithms
  - Agent-Based Adaptive Global Uncertainty and Sensitivity (ABAGUS)
    Harp & Vesselinov (2012) An agent-based approach to global uncertainty and sensitivity analysis. *Computers & Geosciences*.
  - Adaptive hybrid (local/global) optimization strategy (Squads)
    Vesselinov & Harp (2012) Adaptive hybrid optimization strategy for calibration and parameter estimation of physical process models. *Computers & Geosciences*.
- internal coupling with analytical 3D contaminant transport solvers
- external coupling with any process simulator (e.g. ModFlow, FEHM, Amanzi, PFLOTRAN, STOMP/eSTOMP, TOUGH, TOUGHREACT, …)
- source code, examples, performance comparisons, and tutorials @ http://mads.lanl.gov
- MADS tools will be implemented in the ASCEM project

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Summary:

- ✧ Both Non-Probabilistic and Probabilistic uncertainties often exist in decision problems
- ✧ In the case of probabilistic methods, definition of prior probability distributions for model parameters with unknown/uncertain distribution can produce biased predictions and decision analyses
- ✧ In the case of non-probabilistic methods, lack of knowledge and severe uncertainties can be captured
- ✧ Non-probabilistic methodologies have been successfully applied for a series of synthetic and real-world problems, though less often for waste and environmental management
    - Harp & Vesselinov (2011). *Contaminant remediation decision analysis using information gap theory*.
    - Vesselinov & Harp (2013). *Model-driven decision support for monitoring network design using information gap theory*.
- ✧ MADS provides a computationally efficient framework for decision analyses using non-probabilistic and probabilistic methods (http://mads.lanl.gov)

Summary:

- ✧ Current conceptual model for chromium migration in the subsurface is supported by multiple lines of evidence (hydrogeological, geophysical geophysical, mineralogic, petrographic, and geochemical studies and model analyses)
- ✧ Data- and model-based (systems-based) decision analyses are successfully implemented to progress characterization and performance assessment at the site (monitoring network design, additional characterization activities)
- ✧ Plume characterization is a challenging and nonunique problem because multiple models are consistent with the site data and conceptual knowledge
- ✧ Decision analyses are facilitated by implementation of robust techniques and high-performance computing
- ✧ Activities are currently planned to constrain uncertainties impacting decision analyses:
    - aquifer heterogeneity: spatial distribution of low-permeable zones that can act as secondary contaminant sources
    - contaminant mass distribution
    - spatial and temporal distribution of contaminant mass flux to the aquifer
    - implementation of remedial activities


SEREN
DIP
ITY
MADS
Monty Vesselinov
(C) 2011

Chromium plume in the regional aquifer at LANL

Challenges:

✧ **define site conceptual model and existing uncertainties:**

- complex hydrostratigraphy, geochemistry, flow and transport regimes
- data characterized with different support volumes and uncertain due to various factors
- multiple contaminant pathways
- hydrogeological, geophysical geophysical, mineralogic, petrographic, and geochemical studies applied
- current conceptual model is supported by multiple lines of evidence

✧ **perform computationally efficient analyses:**

- parameter estimation (PE)
- model calibration
- uncertainty quantification (UQ)
- decision support (DS)

✧ **high computational demands for model simulations and analyses** (requiring utilization of LANL high-performance computing capabilities)

✧ **uncertainties associated with application of the remedial options**

Work related to LANL Chromium site

✧ **Model-driven decision support**

- **evaluation and optimization of additional characterization activities (e.g. field pumping and tracer tests)**
- **evaluation and optimization of monitoring network design (well locations)**
- **evaluation and optimization of remedial activities (ongoing)**

✧ **Characterization activities:**

- **exploration, analysis & evaluation of alternative conceptual models**
- **estimation of nature/extent/fate of contaminant plumes (Cr^{6+}, ClO_4^-)**
- **source identification (estimating location/flux of contaminant mass arriving at the top of regional aquifer)**
- **estimation of vadose zone & aquifer heterogeneity (hydrogeology and geochemistry)**

Estimates of chromium mass distribution in the subsurface including existing uncertainties

Estimates of chromium mass distribution	Cr^{6+} [kg]			Cr^{3+} [kg]			$Cr^{6+} + Cr^{3+}$ [kg]			Cr^{3+}/Cr^{6+} ratio [%]
	mean	min	max	mean	min	max	mean	min	max	
Source	54,000	31,000	72,000	0	0	0	54,000	31,000	72,000	0
Canyon alluvial sediments	18	6	27	17,982	5,694	26,973	18,000	5,700	27,000	99.9
---- Wetland	15	5	23	15,105	4,783	22,657	15,120	4,788	22,680	99.9
---- Downstream sedimen	3	1	4	2,877	911	4,316	2,880	912	4,320	99.9
Bandelier	2,625	250	12,750	7,875	750	38,250	10,500	1,000	51,000	75
Puye	3,000	600	15,000	9,000	1,800	45,000	12,000	2,400	60,000	75
Perched zones	230	100	500	0	0	0	230	100	500	0
Lavas	1,750	225	2,250	5,250	675	6,750	7,000	900	9,000	75
Puye	990	250	2,000	2,970	750	6,000	3,960	1,000	8,000	75
Miocene	181	25	1,000	542	75	3,000	722	100	4,000	75
Aquifer	1,100	270	3,300	0	0	0	1,100	270	3,300	0
Total	9,894	1,726	36,827	43,619	9,744	125,973	53,512	11,470	162,800	

Information Gap Decision Theory

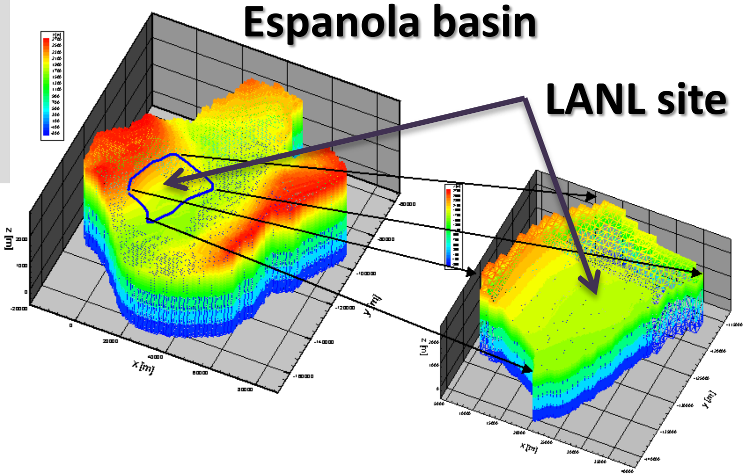
- ✧ Nominal (“best”) model prediction intended for decision making (based on nominal / “best estimates” model parameter set)
- ✧ Decision metric(s)
- ✧ Decision goal(s)
- ✧ Decision scenarios: a series of alternative decisions to compare
- ✧ Info-Gap Uncertainty Model
- ✧ Model predictions for each decision scenario constrained by Info-Gap Uncertainty Model

Ben-Haim (2006). *Info-gap decision theory: decisions under severe uncertainty*. Academic Press.

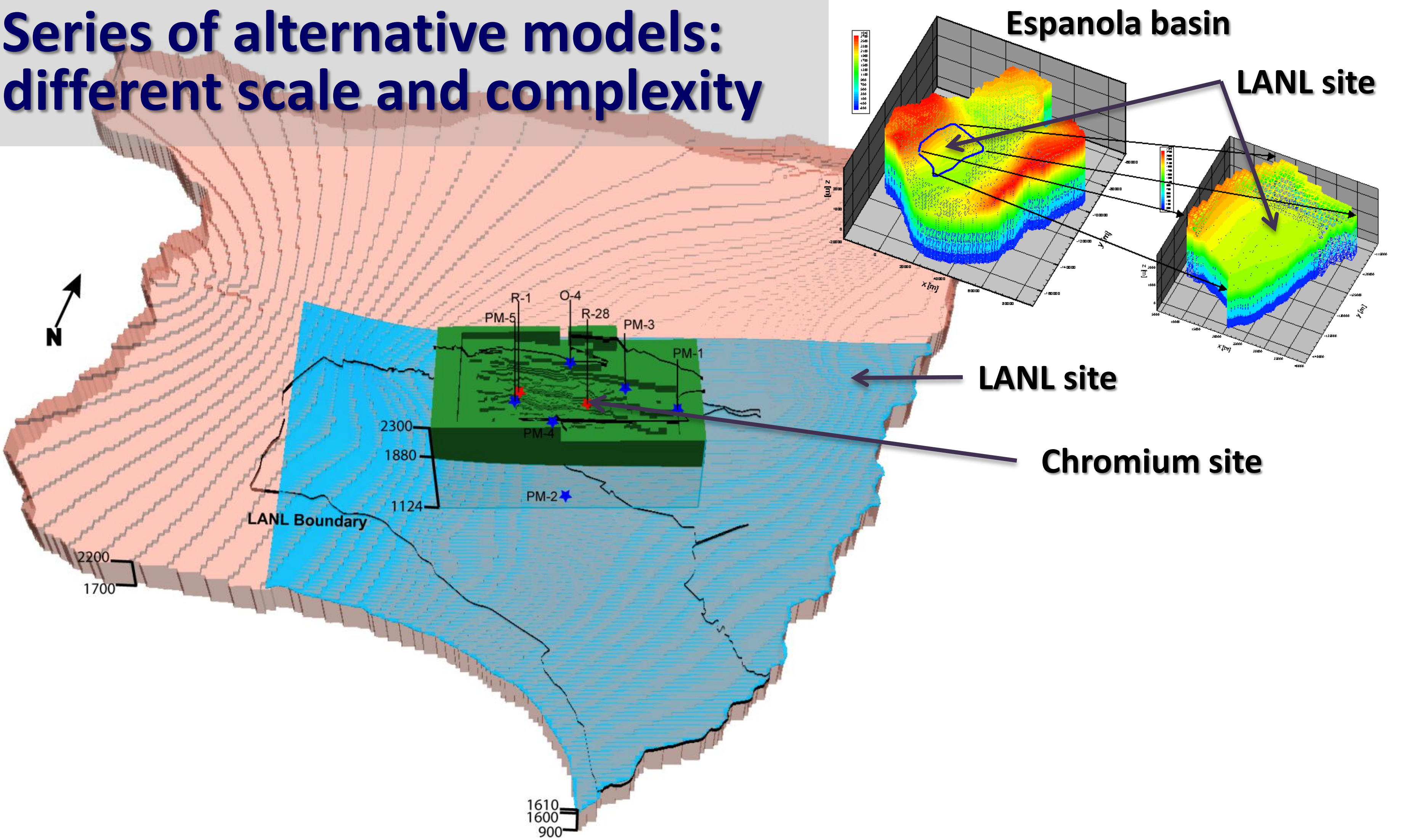
Info-Gap Analysis: Synthetic Network Design

- **Unknown model parameters (8) characterizing plume size:**
  - **source locations (coordinates x, y)**
  - **source lateral size (x_S, y_S)**
  - **flow direction**
  - **aquifer dispersivities (longitudinal, horizontal/vertical transverse)**
- **Uncertain concentration observations (calibration targets) (10) due to:**
  - **measurement errors**
  - **uncertain background concentrations**
  - **uncertain local hydrogeological and geochemical conditions**
- **Analytical model of the 3D contaminant flow**
- **Unknown model parameters estimated using inversion**
- **Decision question: which of the new proposed well location has the highest immunity of failure to detect concentrations above MCL ($c > 5$ ppm)**
  i.e. which well provides the most robust decision to improve the monitoring network

Series of alternative models: different scale and complexity



Series of alternative models: different scale and complexity



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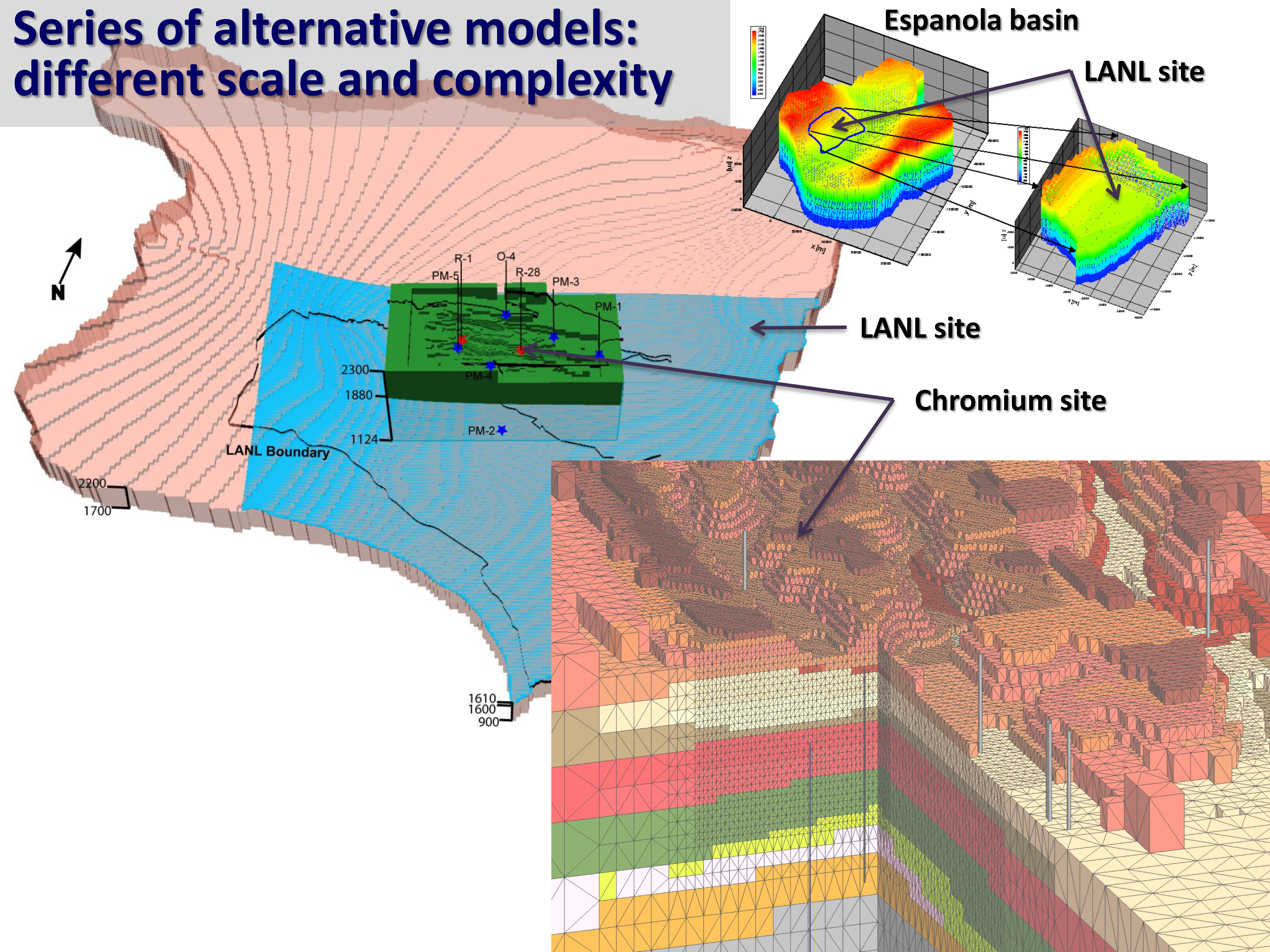

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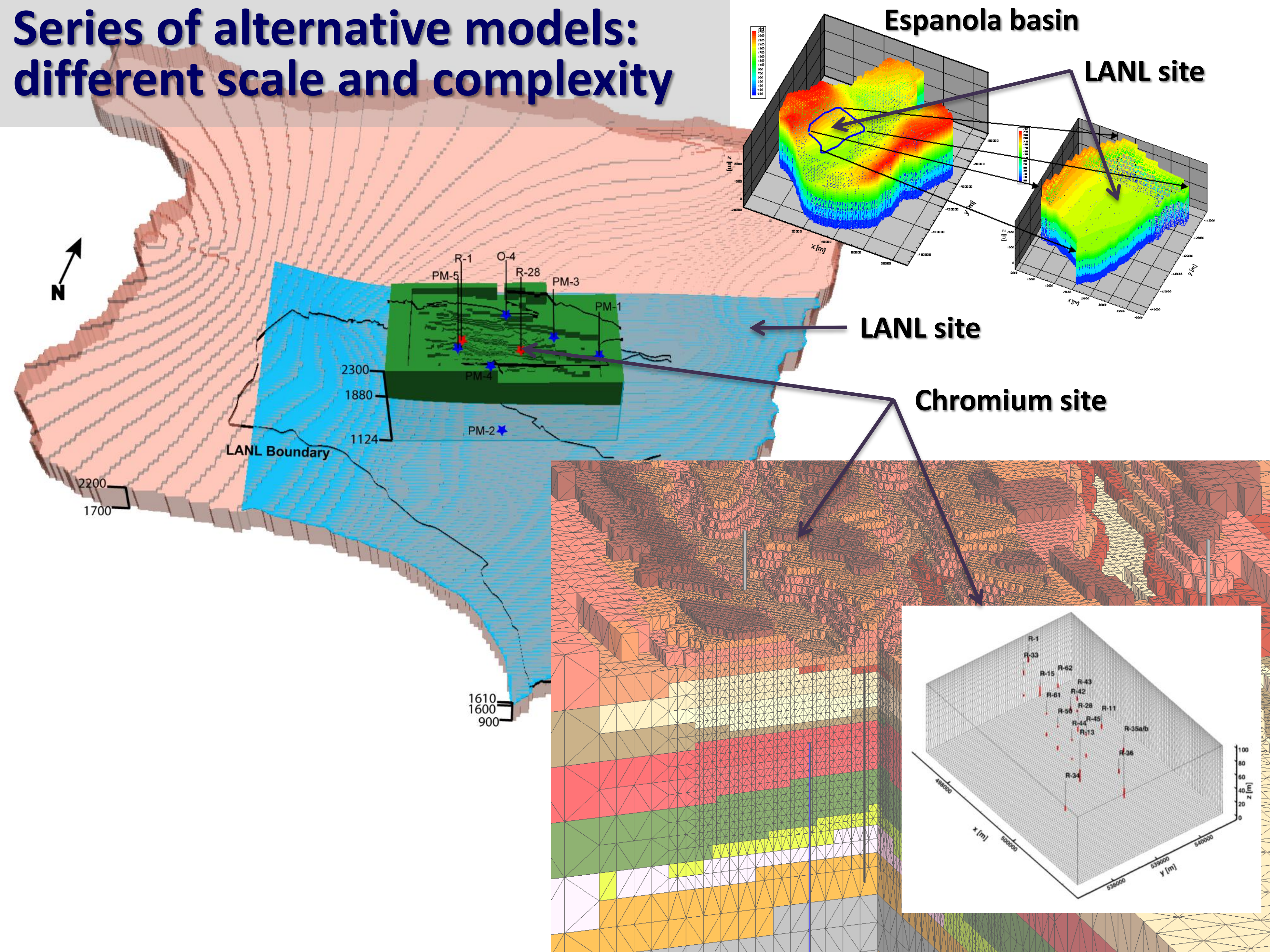
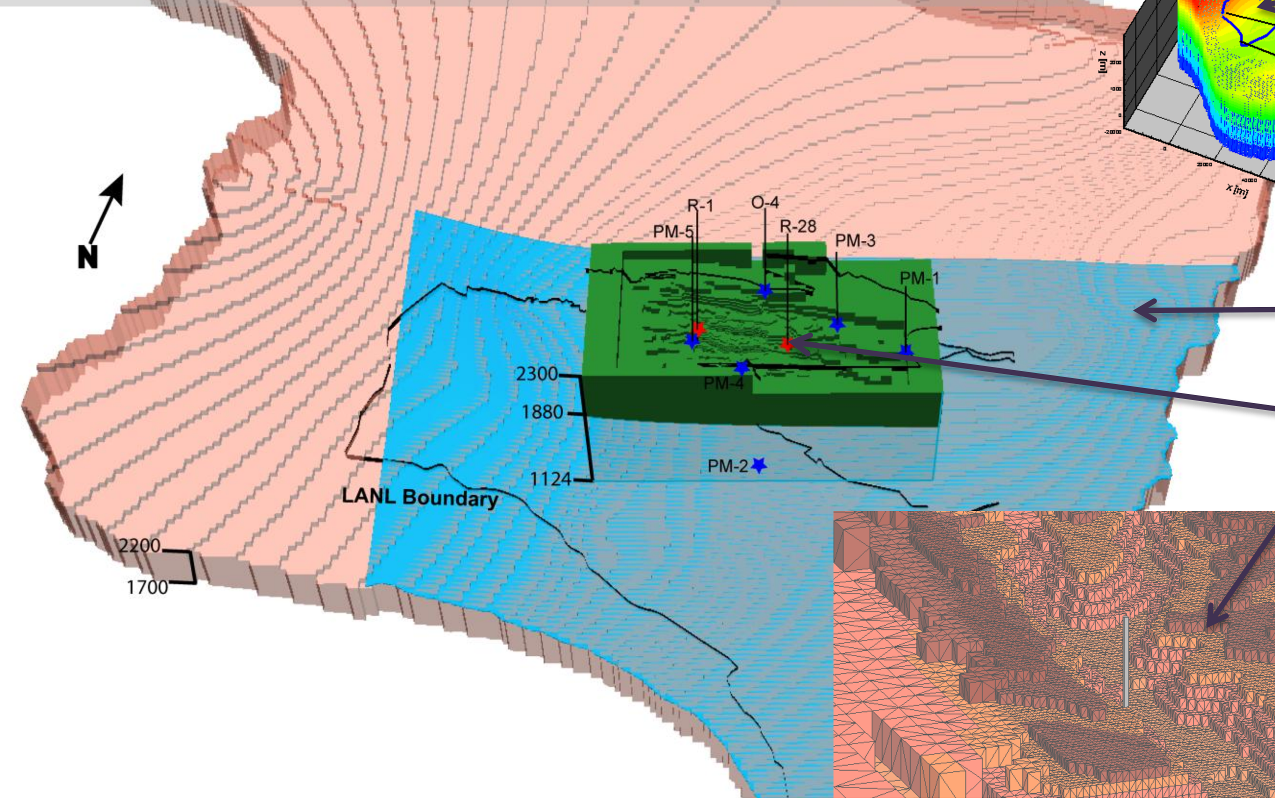
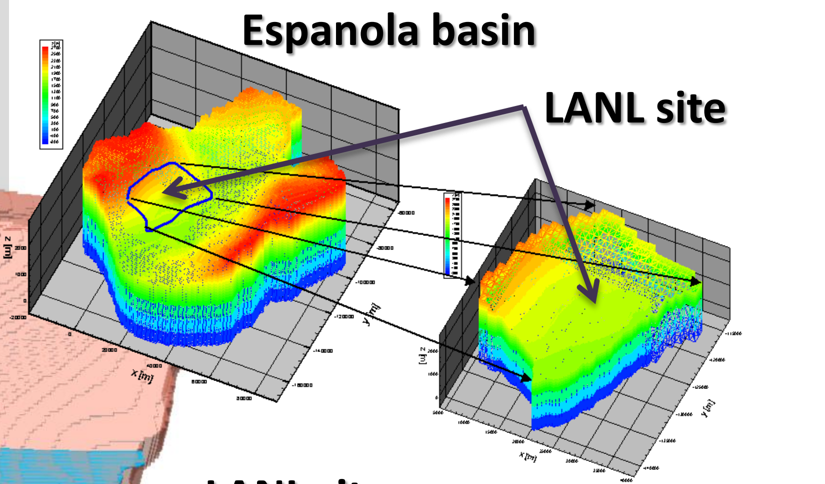
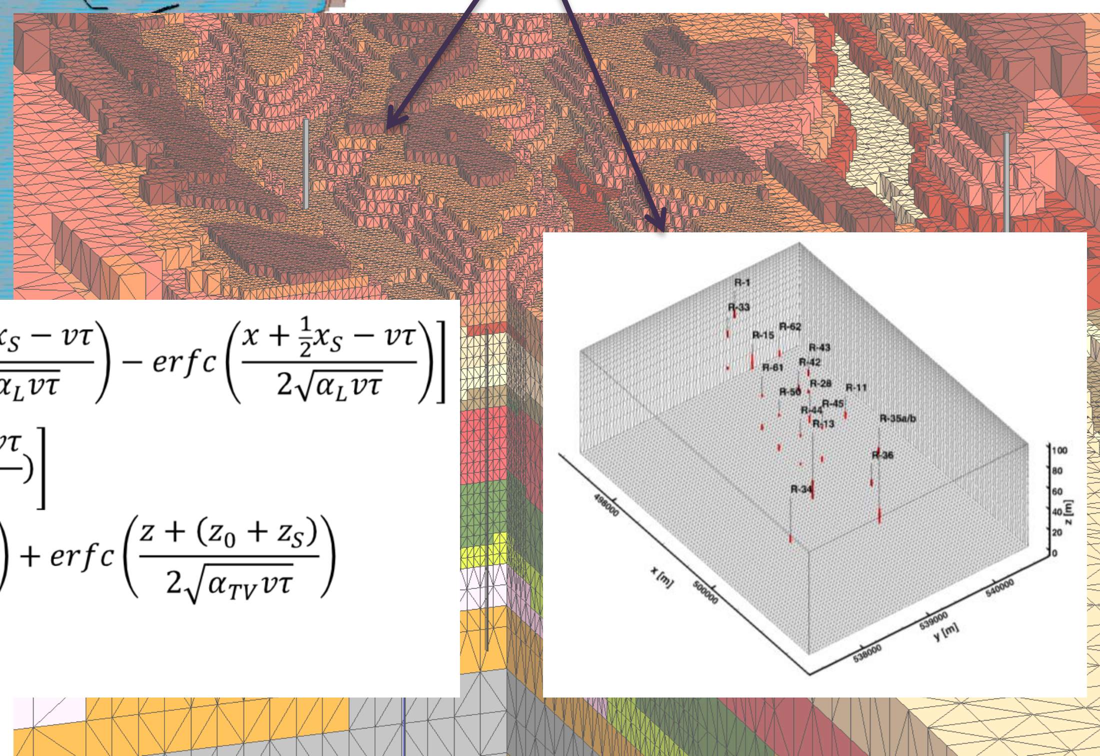


Series of alternative models: different scale and complexity

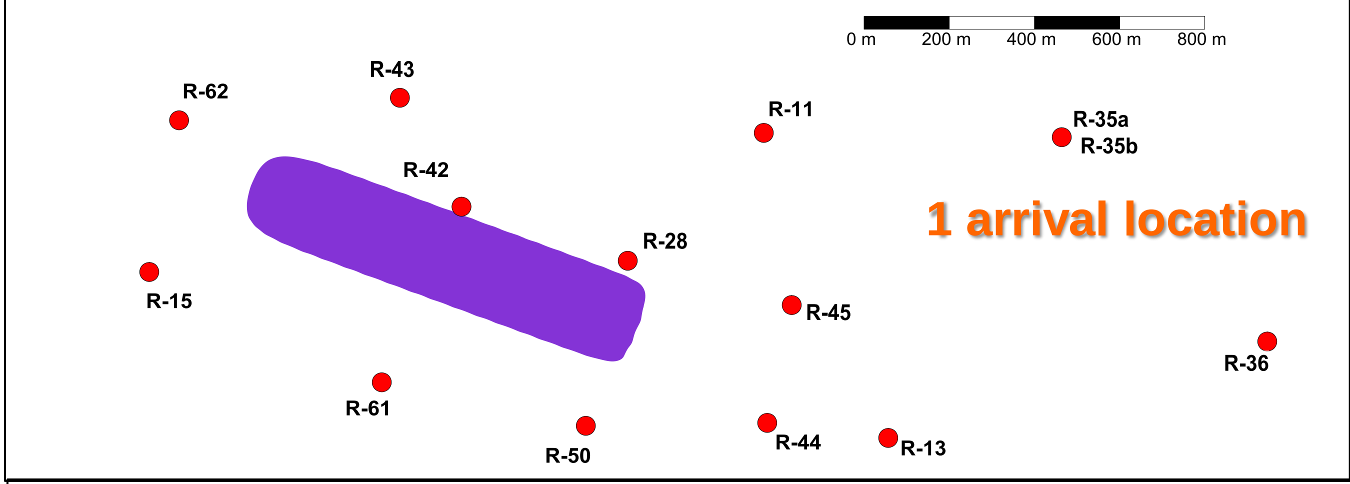


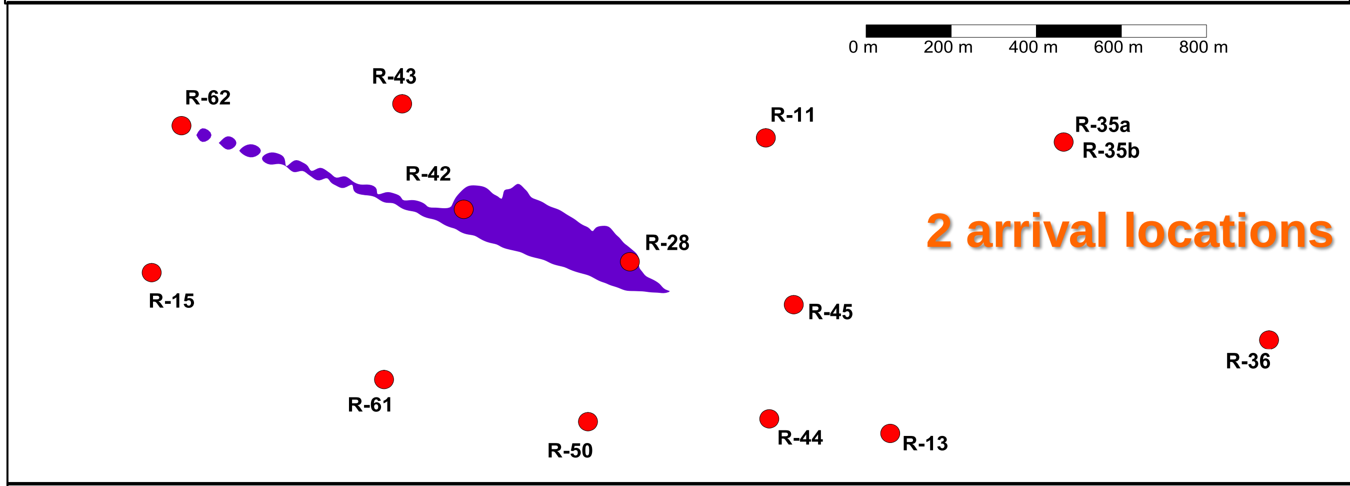


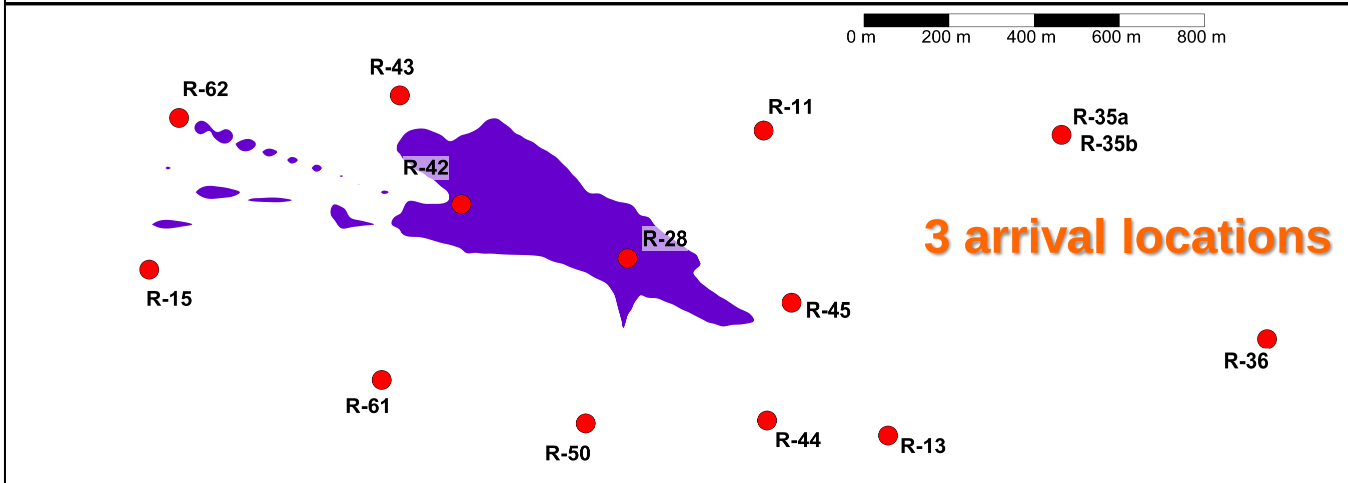


$$c(x,y,z,t) = \frac{1}{8\pi\theta x_S y_S z_S}\int_0^t I(t-\tau)\exp(-\lambda\tau)\left[erfc\left(\frac{x-\frac{1}{2}x_S - v\tau}{2\sqrt{\alpha_L v\tau}}\right) - erfc\left(\frac{x+\frac{1}{2}x_S - v\tau}{2\sqrt{\alpha_L v\tau}}\right)\right]$$
$$\times\left[erfc\left(\frac{y-\frac{1}{2}y_S - v\tau}{2\sqrt{\alpha_{TH} v\tau}}\right) - erfc\left(\frac{y+\frac{1}{2}y_S - v\tau}{2\sqrt{\alpha_{TH} v\tau}}\right)\right]$$
$$\times\left[erfc\left(\frac{z-(z_0+z_S)}{2\sqrt{\alpha_{TV} v\tau}}\right) - erfc\left(\frac{z-z_0}{2\sqrt{\alpha_{TV} v\tau}}\right) + erfc\left(\frac{z+(z_0+z_S)}{2\sqrt{\alpha_{TV} v\tau}}\right)\right.$$
$$\left. - erfc\left(\frac{z+z_0}{2\sqrt{\alpha_{TV} v\tau}}\right)\right] d\tau\alpha_L$$

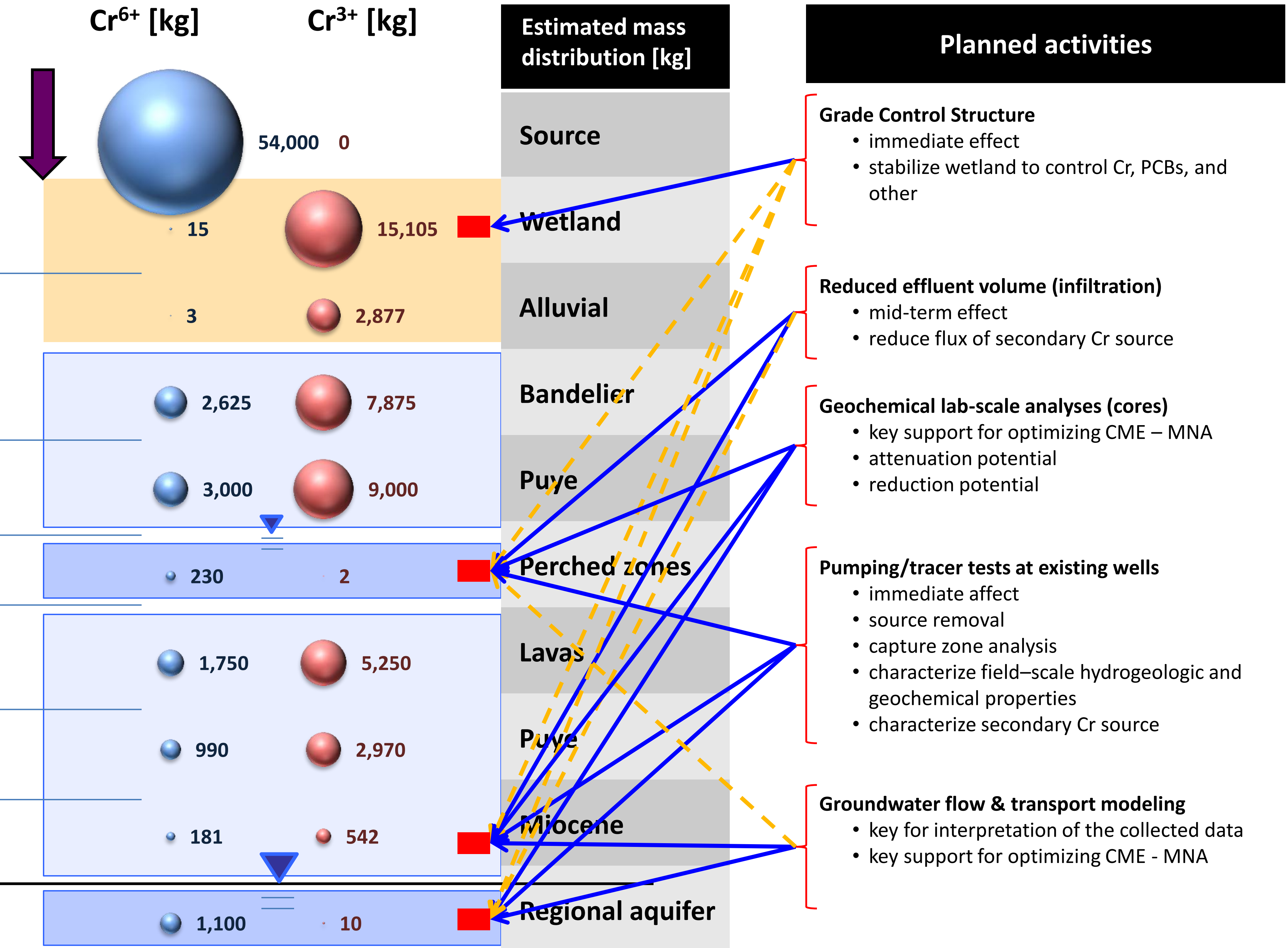
2012 model analyses







Regions along the top the regional aquifer where the calculated Cr^{6+} concentrations exceed 1500 ppb based on averaging of all the acceptable model solutions



Cr6+ [kg]
Cr3+ [kg]
Estimated mass distribution [kg]
Planned activities
54,000
0
Source
15
15,105
Wetland
3
2,877
Alluvial
2,625
7,875
Bandelier
3,000
9,000
Puye
230
2
Perched zones
1,750
5,250
Lavas
990
2,970
Puye
181
542
Miocene
1,100
10
Regional aquifer
Grade Control Structure
• immediate effect
• stabilize wetland to control Cr, PCBs, and other
Reduced effluent volume (infiltration)
• mid-term effect
• reduce flux of secondary Cr source
Geochemical lab-scale analyses (cores)
• key support for optimizing CME – MNA
• attenuation potential
• reduction potential
Pumping/tracer tests at existing wells
• immediate affect
• source removal
• capture zone analysis
• characterize field–scale hydrogeologic and geochemical properties
• characterize secondary Cr source
Groundwater flow & transport modeling
• key for interpretation of the collected data
• key support for optimizing CME - MNA