Reactive Transport Modeling: A New Paradigm in the Design of In Situ Treatment Systems

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Reactive Transport Modeling

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- Provides 3-D insights into what is going on in the subsurface
- Allows designs to be carefully tailored to a site's unique hydrogeologic and geochemical conditions and the specific physical, chemical and biological characteristics of the IST technology
- Helps avoid ISTS falling short of expectations or failing altogether
- Saves time and money

Optimum Process Flow Diagram

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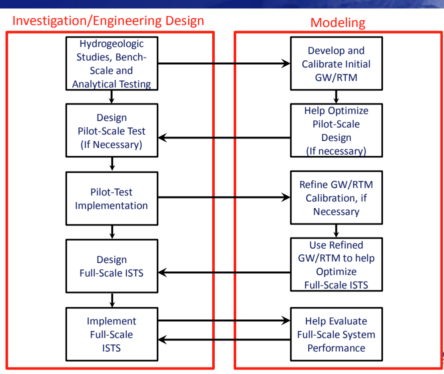

Model Hierarchy

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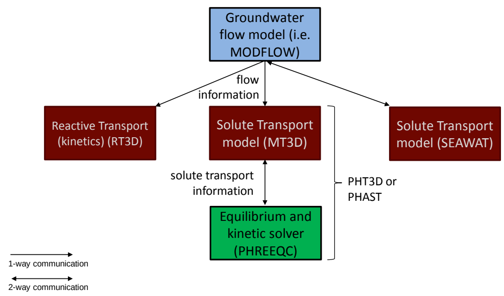

Reactive Transport Libraries

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Reactive transport libraries for modeling in-situ treatment:

- Reduction of Cr(VI) by calcium polysulfide (CaS_x)
- ISCO of chlorinated solvents by CHP
- ISCO of chlorinated ethylenes by $KMnO_4$
- ISCO of chlorinated solvents and 1,4-dioxane by activated persulfate
- Enhanced reductive dechlorination using emulsified vegetable oil
- pH adjustment of aquifers via addition of acids and bases
- Numerous reductive dechlorination/MNA packages
  - PCE→TCE→DCE→VC →ethene
  - CTET→chloroform→methylene chloride→chloromethane

Enhanced Reductive Dechlorination Using Emulsified Vegetable Oil

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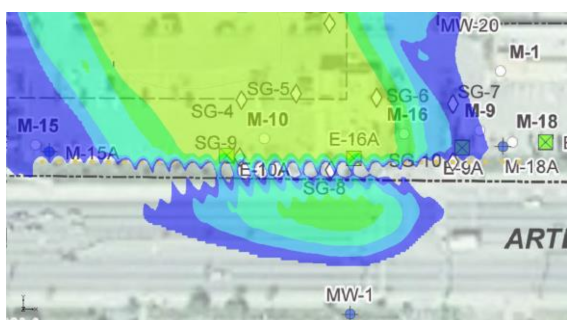

Modeling PRB Spacing & Effectiveness

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Mobile oil: $$\frac{\partial C_m}{\partial t} = \underbrace{\frac{\partial}{\partial x}\left(D\frac{\partial C_m}{\partial x}\right)}_{\text{dispersion}} - \underbrace{\frac{\partial}{\partial x}(vC_m)}_{\text{advection}} - \underbrace{K_A C_m}_{\text{attachment}}$$

Immobile oil: $$\frac{\partial C_{im}}{\partial t} = \underbrace{K_A C_m \frac{\phi}{\rho_b}}_{\text{attachment}}$$

Attachment rate: $$K_A = \frac{3v}{2}\left(\frac{1-\phi}{d_c}\right)\alpha'\left(\frac{C_{im}^{max} - C_{im}}{C_{im}^{max}}\right)\eta$$

Empty bed collector efficiency (α'); Maximum oil concentration (C_{im}^{max}); Single collector efficiency (η)

From Borden and co-workers:

Modeling PRB Spacing & Effectiveness

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PCE, TCE etc. degradation is modeled as a second order reaction (first order with respect to immobile oil concentration):

$$\left(\frac{\partial C_{PCE}}{\partial t}\right)_{rxn} = -k_{PCE} C_{im} C_{PCE}$$

$$\left(\frac{\partial C_{TCE}}{\partial t}\right)_{rxn} = -k_{TCE} C_{im} C_{TCE} + k_{PCE} Y_{TCE/PCE} C_{im} C_{TCE}$$

$$\left(\frac{\partial C_{DCE}}{\partial t}\right)_{rxn} = -k_{DCE} C_{im} C_{DCE} + k_{TCE} Y_{DCE/TCE} C_{im} C_{DCE}$$

$$\left(\frac{\partial C_{VC}}{\partial t}\right)_{rxn} = -k_{VC} C_{im} C_{VC} + k_{DCE} Y_{VC/DCE} C_{im} C_{VC}$$

Rates of PCE, TCE dechlorination assumed dependent upon the concentration of immobile oil

(from Borden and co-workers)

Injection Parameters (from Work Plan)

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Parameter	Value
Number of injection wells	30
Wells injected simultaneously	10
Spacing	15 ft
Flow rate:	2 gpm (385 ft^3/d)
Injection duration:	1.15 d per well
Volume of water/oil injection:	100,000 gal (375,000 L)
Concentration of oil injected	41,000 mg/L
Total mass of oil delivered	32,000 lb (14,500 kg)

Reaction Module Parameters

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Parameter	Value
Effective porosity	0.10
$C_{oil,max}$	1,600 mg/kg
Empty bed collector efficiency, α	0.000025
Single collector efficiency, η	0.56
Collector diameter, d_c	0.0001 m
Pore velocity, v	0.094 m/d
Bulk density	1800 kg/m^3
PCE degradation rate constant	0.00014 kg soil/mg oil-d

In the absence of site-specific parameters, typical values were assumed from the literature

Modeling PRB Spacing & Effectiveness

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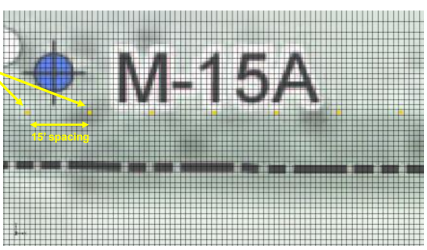
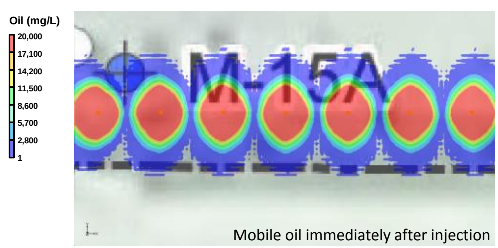
Injection points



Grid spacing: 1.25' x 1.25'

Run 3: Modeling PRB Spacing & Effectiveness

12



Run 3: Modeling PRB Spacing & Effectiveness

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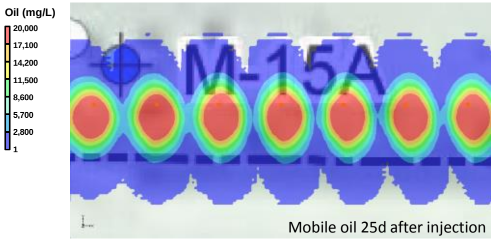

Mobile oil 25d after injection

Run 3: Modeling PRB Spacing & Effectiveness

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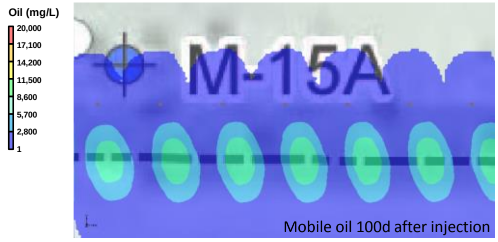

Mobile oil 100d after injection

Modeling PRB Spacing & Effectiveness

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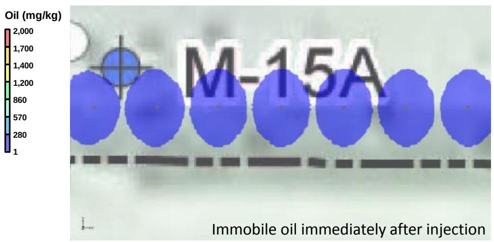

Immobile oil immediately after injection

Run 3: Modeling PRB Spacing & Effectiveness

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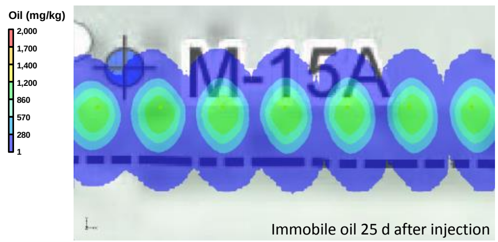
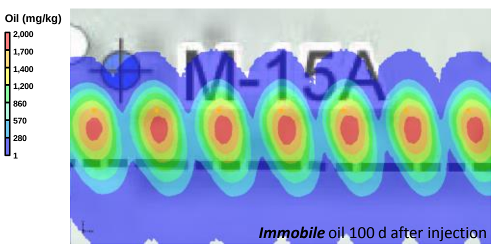


Immobile oil 25 d after injection

Run 3: Modeling PRB Spacing & Effectiveness

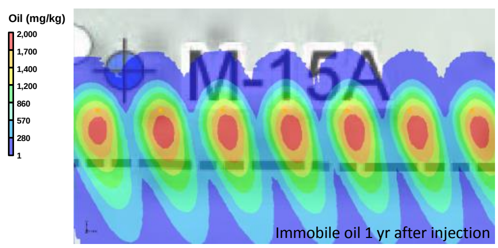
17



Immobile oil 100 d after injection

Run 3: Modeling PRB Spacing & Effectiveness

18

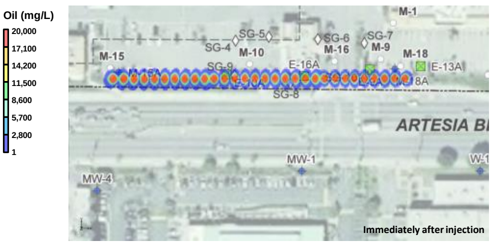


Immobile oil 1 yr after injection

Run 3: Mobile Oil

Run 3: Mobile Oil

Run 3: Mobile Oil

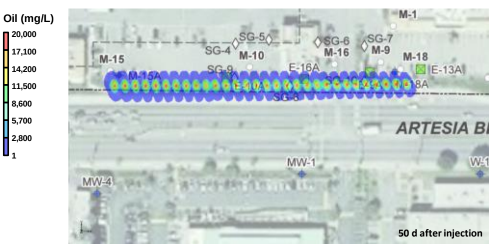


Immediately after injection

Run 3: Mobile Oil

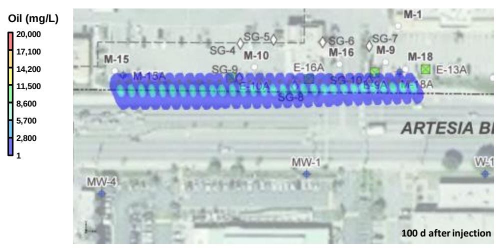
20 d after injection

Run 3: Mobile Oil



50 d after injection

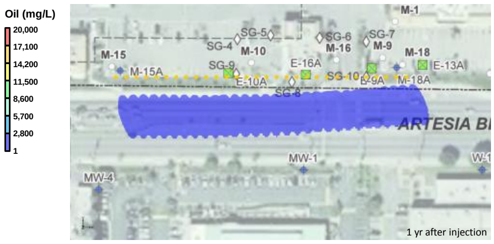
Run 3: Mobile Oil



100 d after injection

Run 3: Mobile Oil

25



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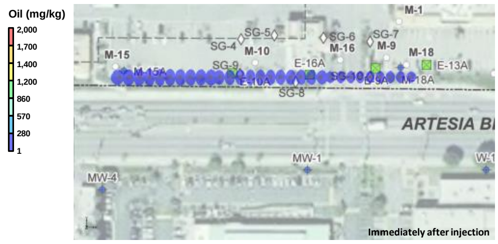
Run 3: *Immobile* Oil

26



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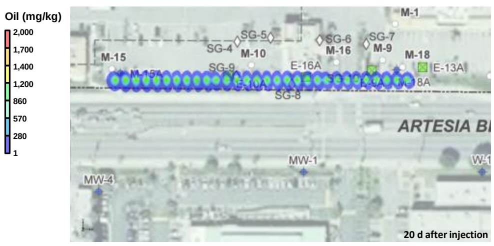
Run 3: *Immobile* Oil

27



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Run 3: *Immobile* Oil

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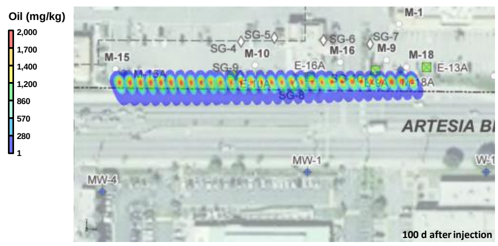

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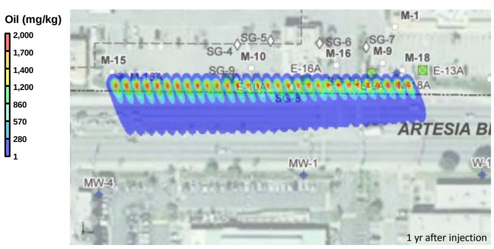
Run 3: *Immobile* Oil

29



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Run 3: Downgradient PCE

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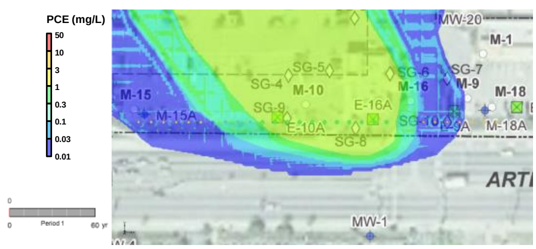

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Run 3: Downgradient PCE

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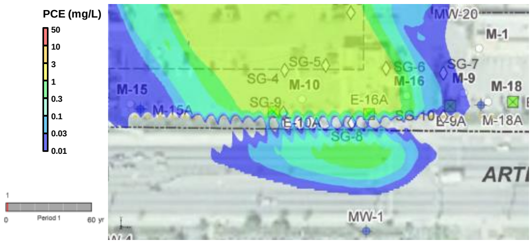

Run 3: Downgradient PCE

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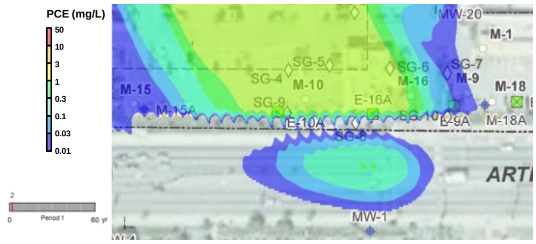

Run 3: Downgradient PCE

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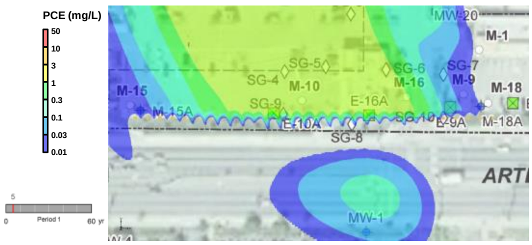

Run 3: Downgradient PCE

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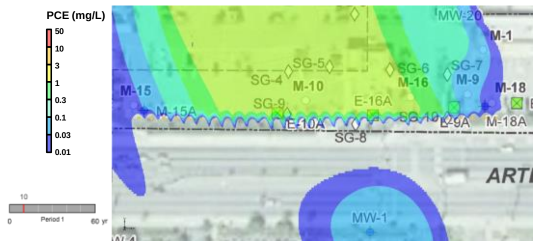

Persulfate ISCO Case Study

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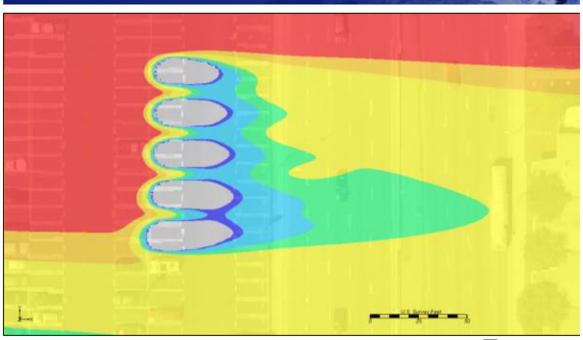

Project Objectives

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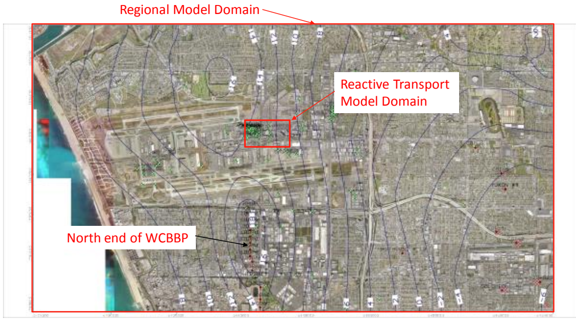
- Develop an IRM to reduce migration of chlorinated ethenes and 1,4-dioxane from the property
- IRM to operate while source control measures are implemented
- Evaluate whether an ISCO PRB was feasible in this hydrogeologic regime and could be cost-competitive with groundwater pump & treat
- Working collaboratively with AMEC FW

Regional and Reactive Transport Model Domains and Model-Predicted Potentiometric Contours in Gage Aquifer



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Modeling Objectives

- Model injection of activated persulfate to treat plume containing 1,4-dioxane and 1,1-DCE
  - Estimate barrier replenishment frequency (i.e. reinjection recurrence period)
  - Estimate mass flux reduction
  - Provide estimates of downgradient sulfate and chromate plumes

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Reactive Transport Model Development

- Current version of model has the following state variables:
  - Persulfate
  - 1,4-Dioxane
  - 1,1-DCE
  - Tracer
  - NOD (immobile)
  - Sulfate
  - Chromate
- Starting concentrations of 1,4-dioxane and DCE are from recent plume mapping

40

Persulfate & NOD Modeling

Persulfate persistence modeled as a second order reaction with soil natural oxidant demand (NOD) and first-order auto-degradation rate:

$$\frac{dC_{per}}{dt} = -k_1 C_{per} NOD - k_{auto} C_{per}$$

$$\frac{dNOD}{dt} = -k_1 C_{per} NOD$$

Model parameters/unknowns:

- NOD for PZ-1 soil
- NOD for PZ-2 soil
- k_1
- k_{auto}

Coupled differential equations - no analytical solution
Equations solved numerically (explicit Euler)

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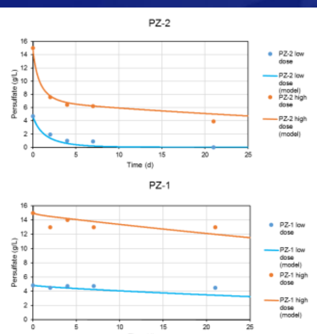
Persulfate & NOD Modeling



Data from all 4 experiments fit simultaneously:

- k_{auto} = 0.015 /d (half-life = 46 d)
- k_1 = 0.1 L/g/d
- PZ-1 NOD = 0.1 g/L
- PZ-2 NOD = 8.0 g/L

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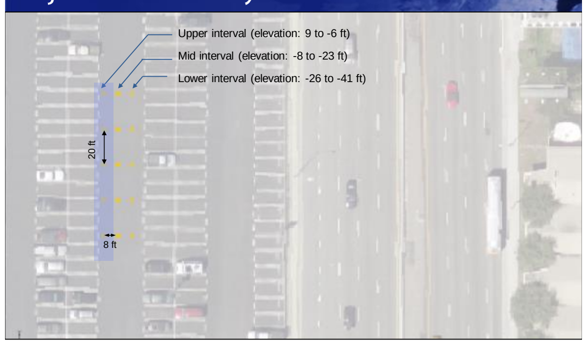
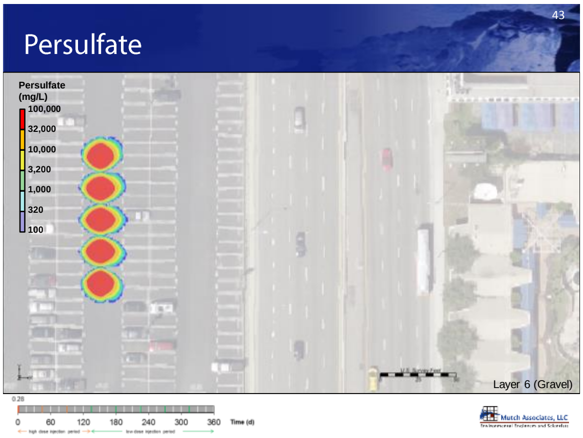
Injection Well Array

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Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
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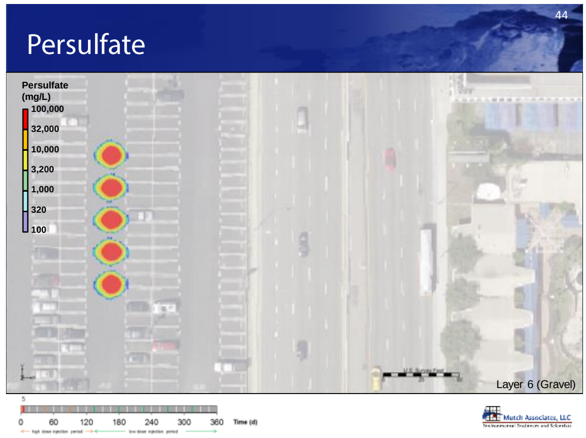
100
Layer 6 (Gravel)
0.28
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC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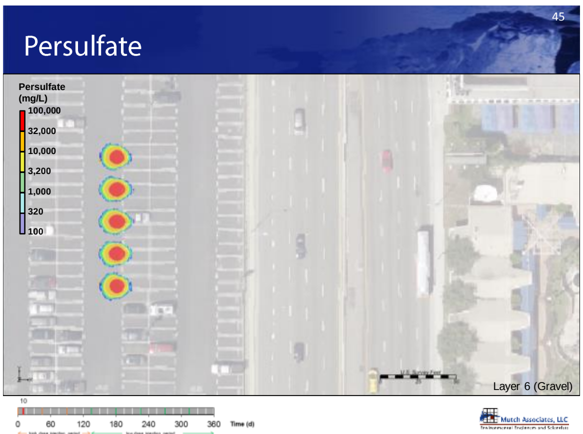
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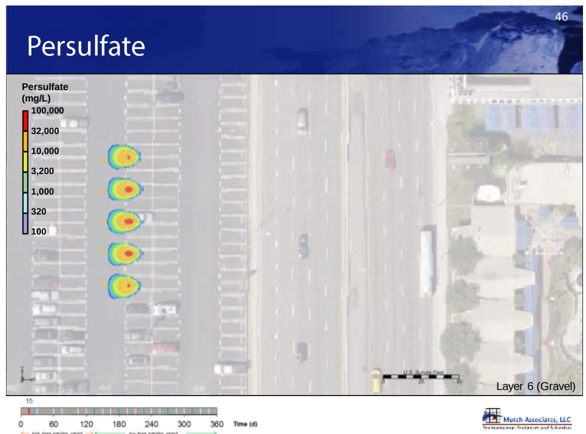
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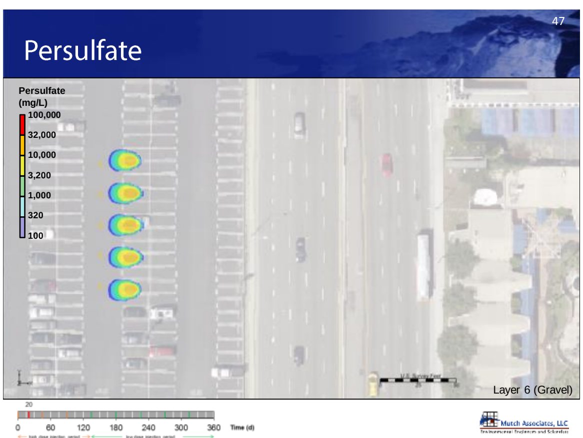
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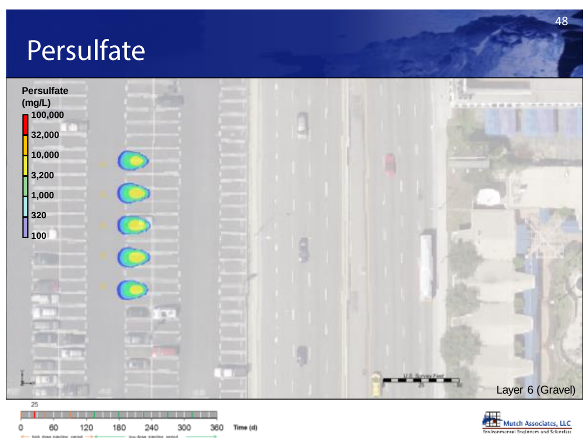
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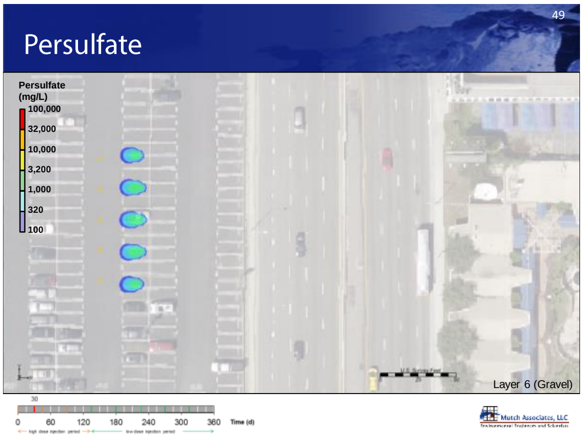
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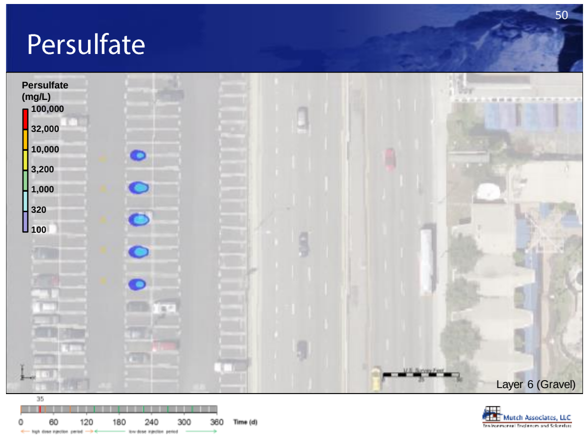
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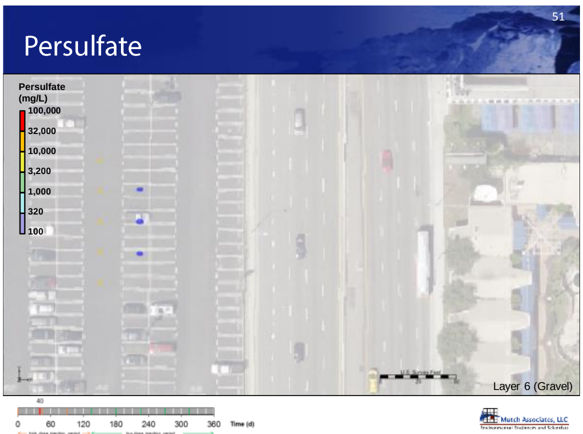
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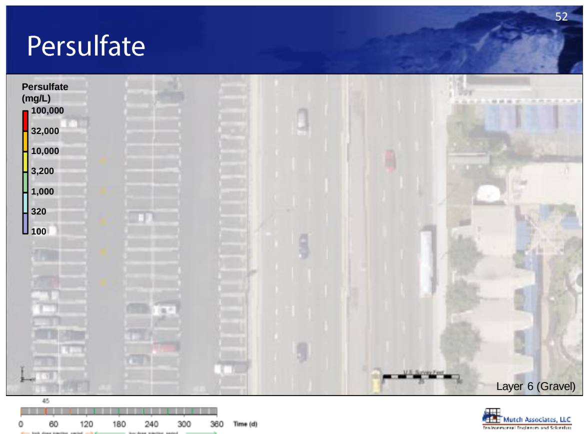
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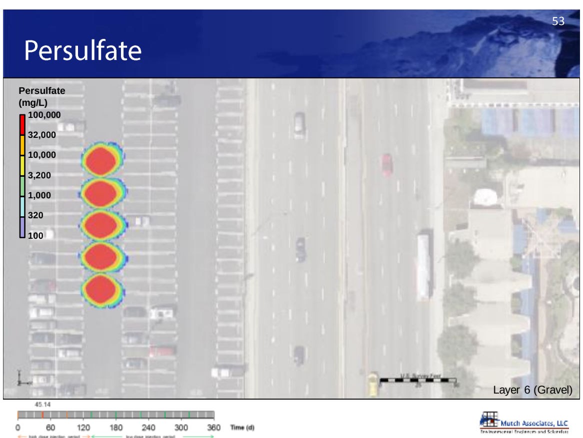
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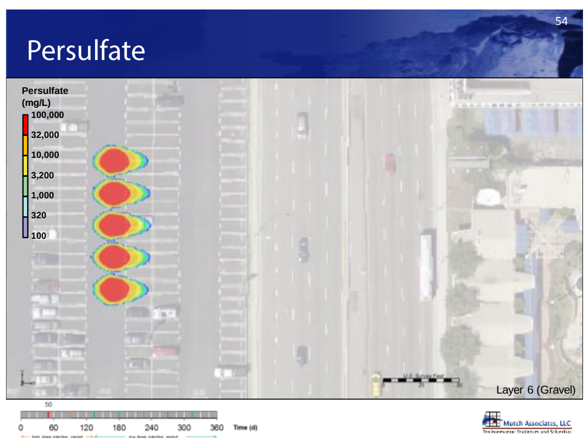
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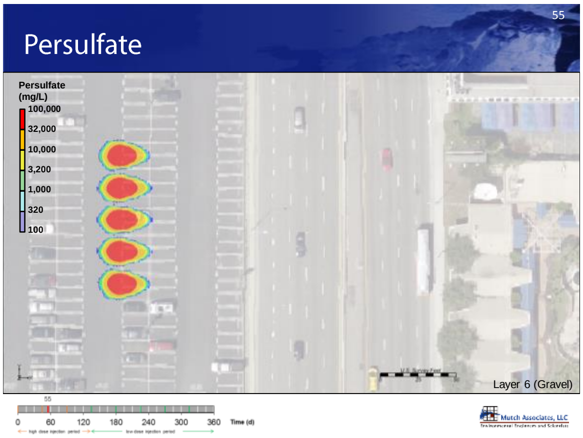
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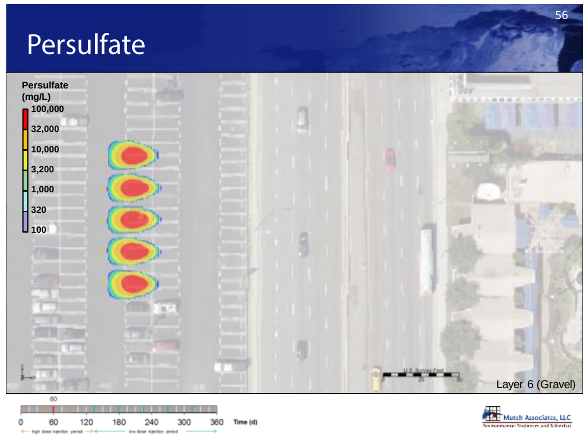
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(mg/L)
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Layer 6 (Gravel)
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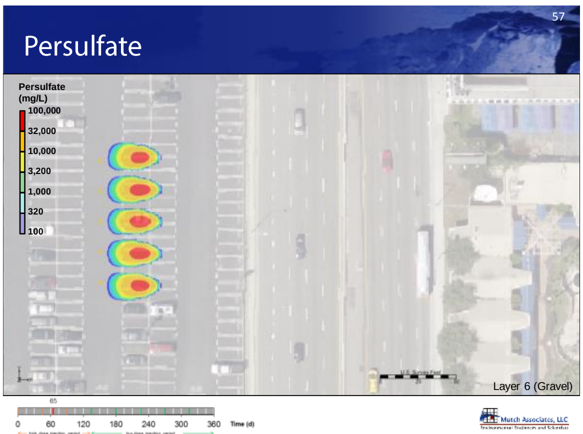
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Persulfate
(mg/L)
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10,000
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360
Time (d)
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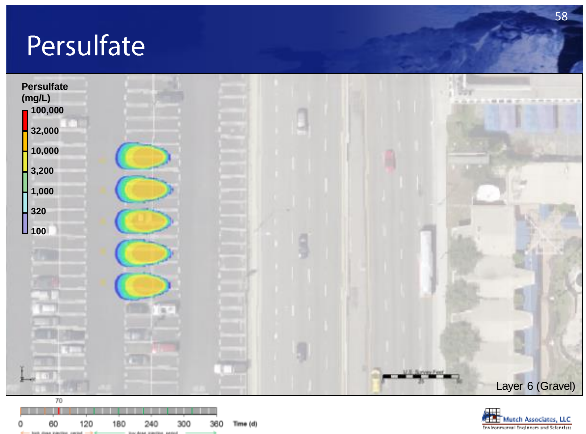
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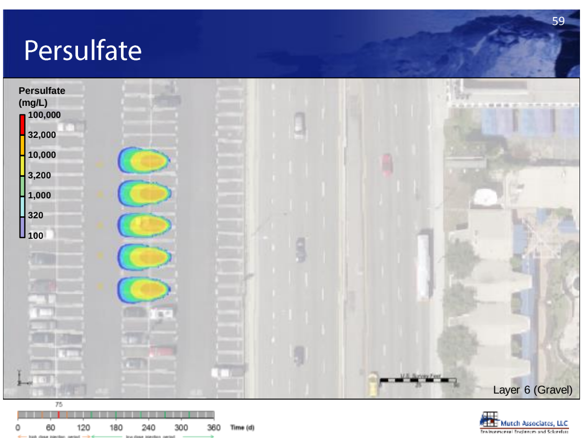
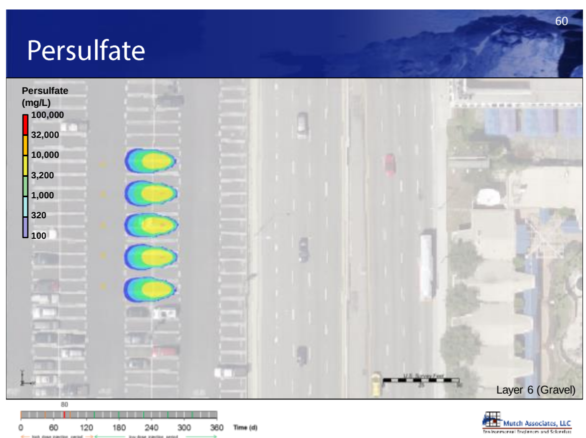
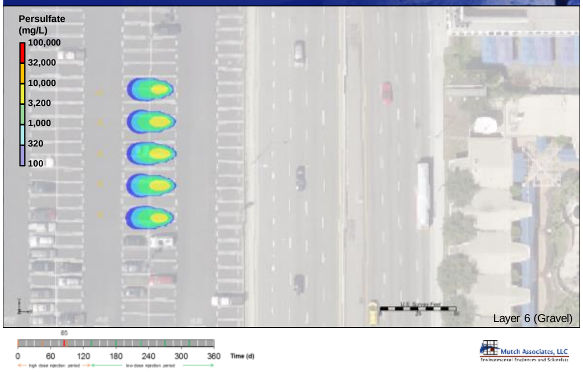
Time (d)
Mutch Associates, LLC

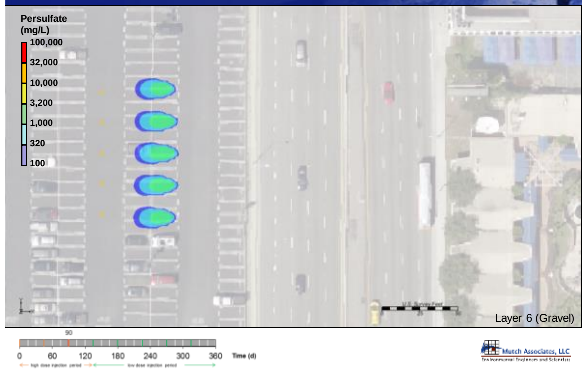

59
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
75
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


60
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
80
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

Persulfate



Persulfate



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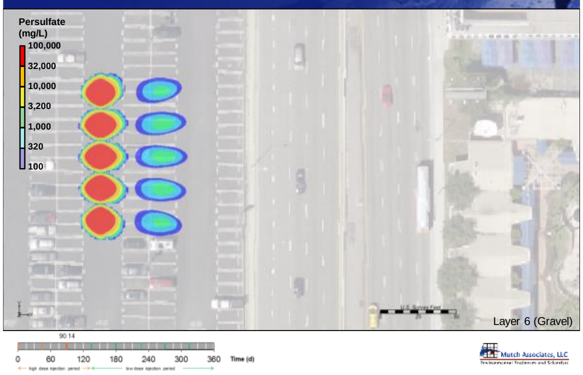

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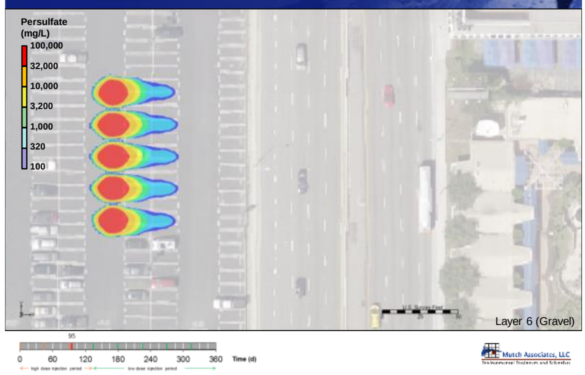

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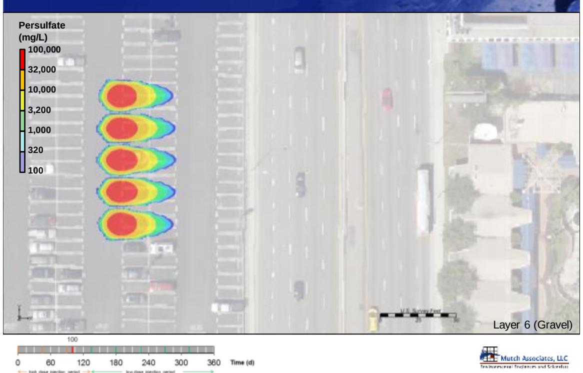
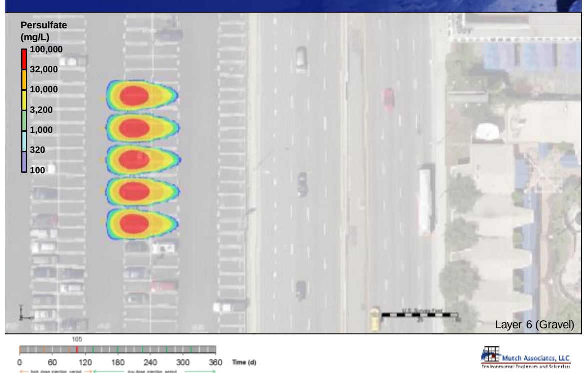
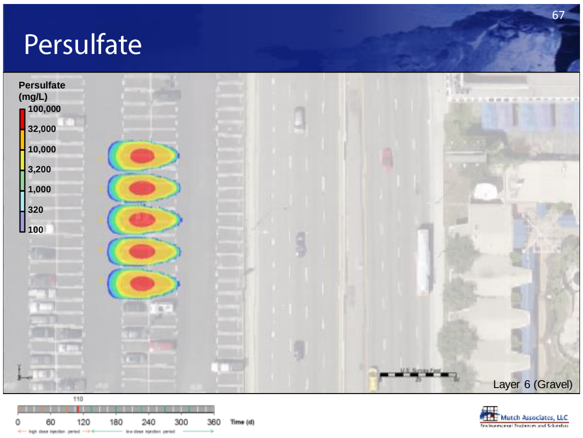
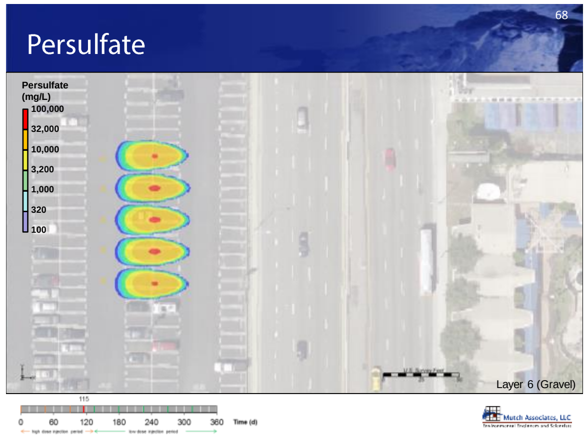
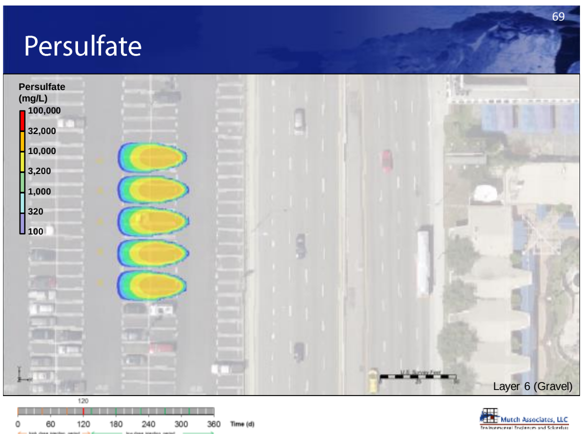


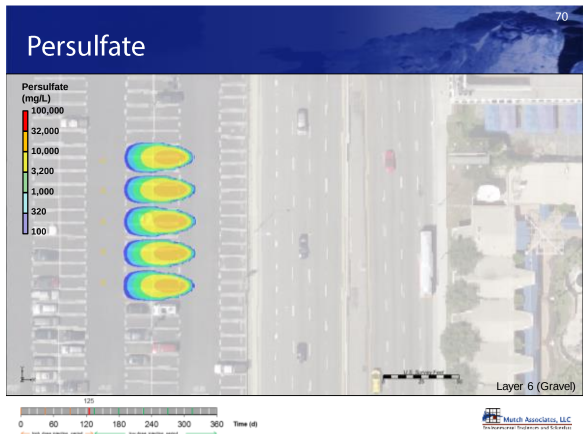
Persulfate

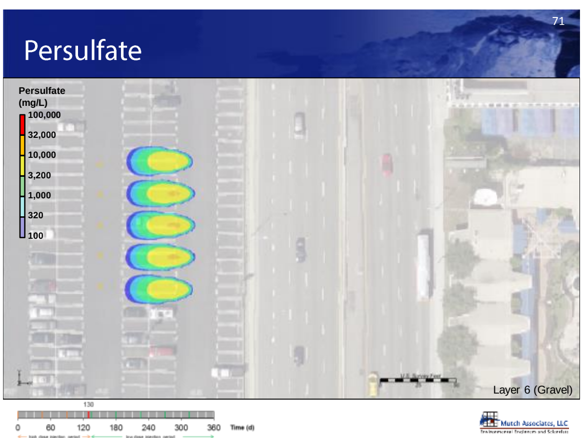



67
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
110
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


68
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
115
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


69
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
120
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


70
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
125
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


71
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
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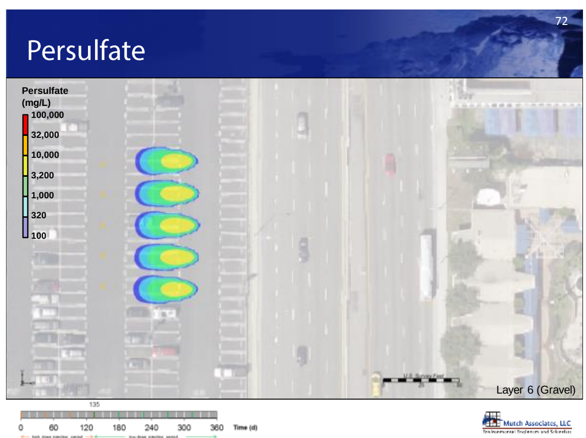
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


72
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
135
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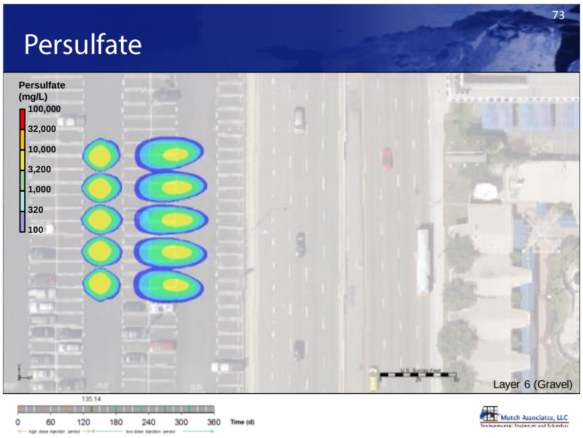
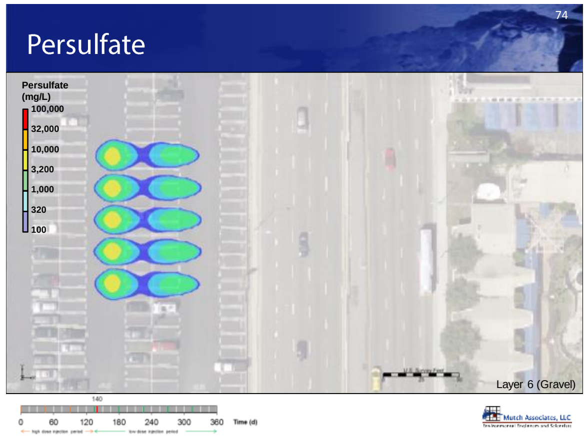
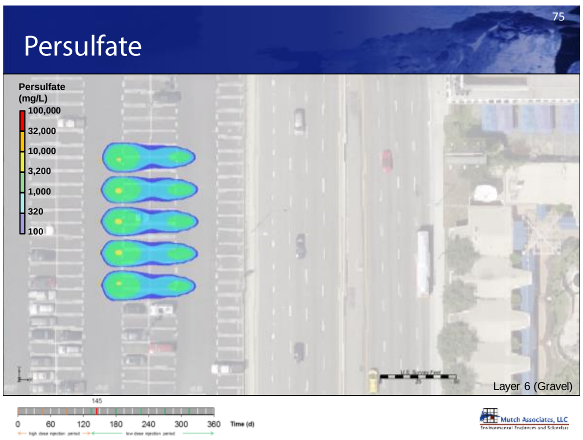
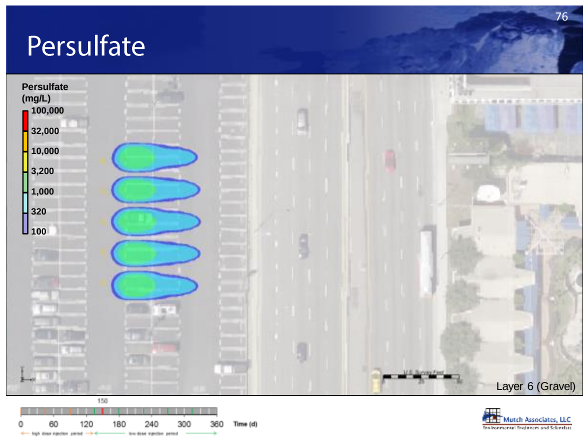
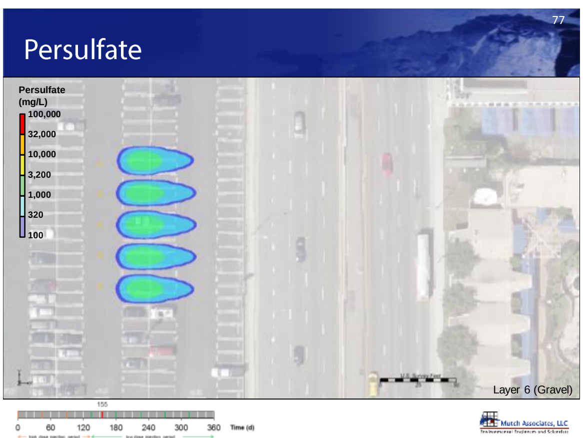
Mutch Associates, LLC

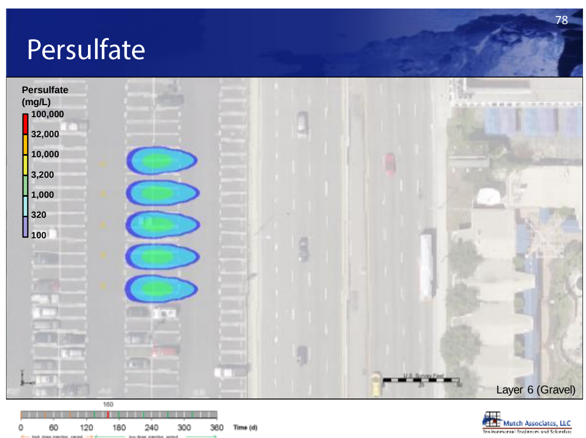

73
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
135.14
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


74
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
140
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

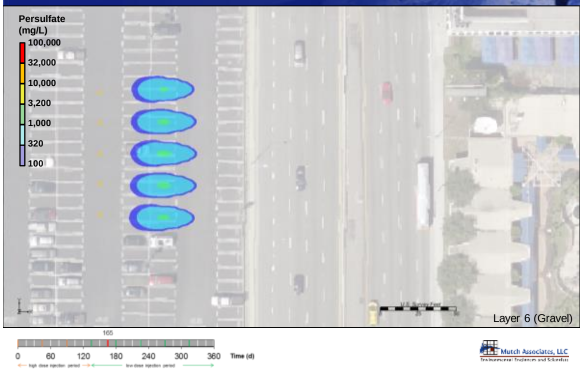

75
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
145
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


76
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
150
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

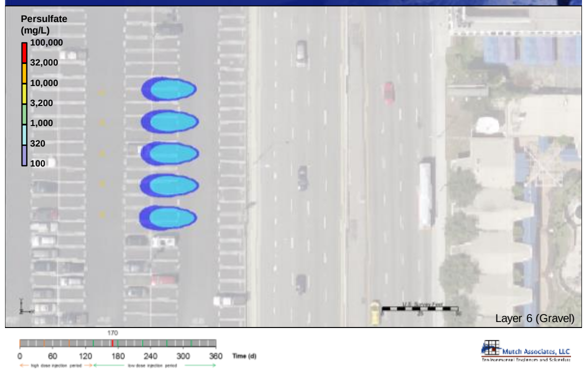

77
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
155
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


78
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
160
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

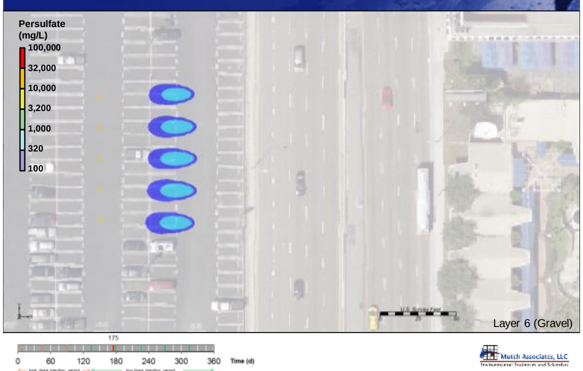
Persulfate
79



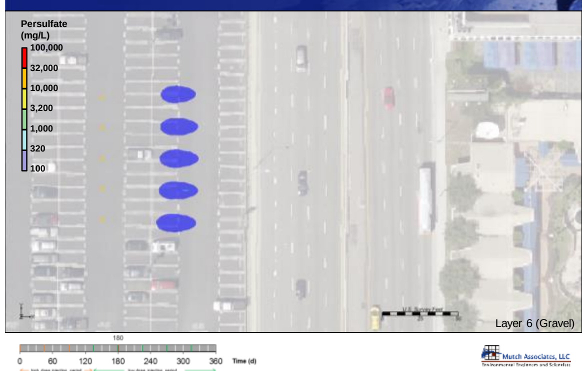
Persulfate
80



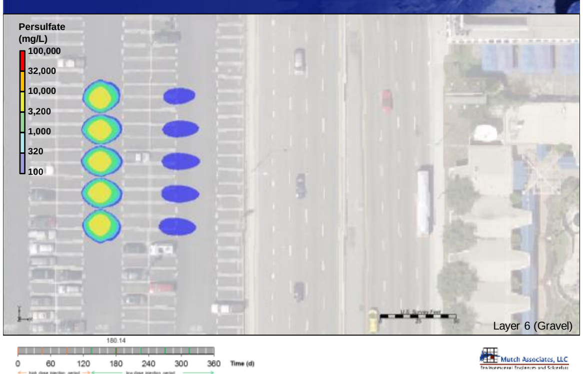
Persulfate
81



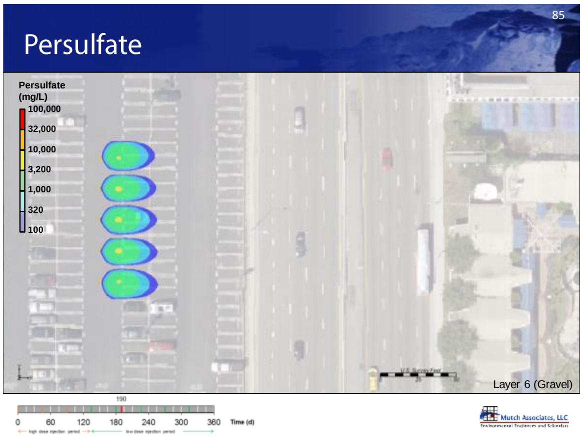
Persulfate
82

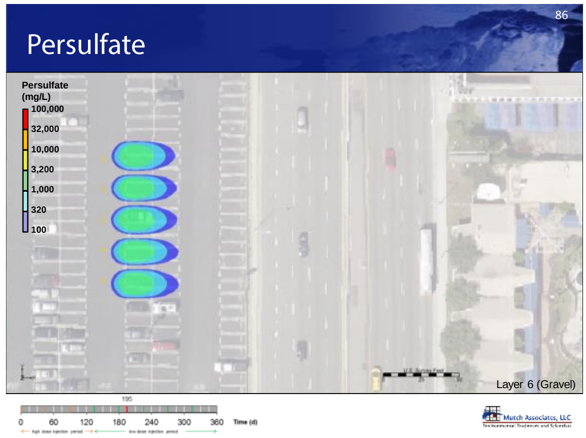


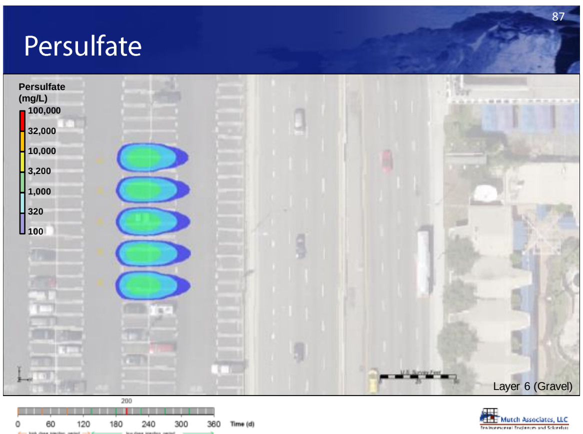
Persulfate
83

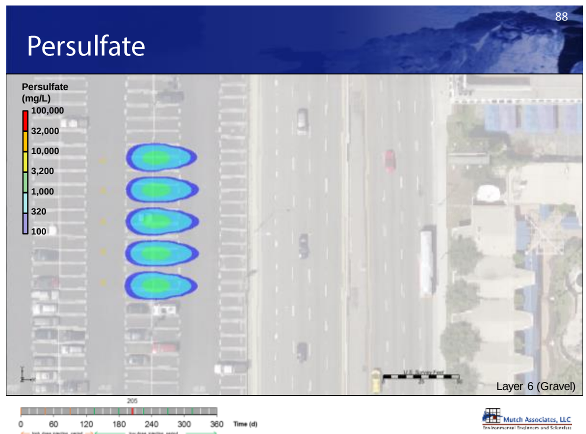


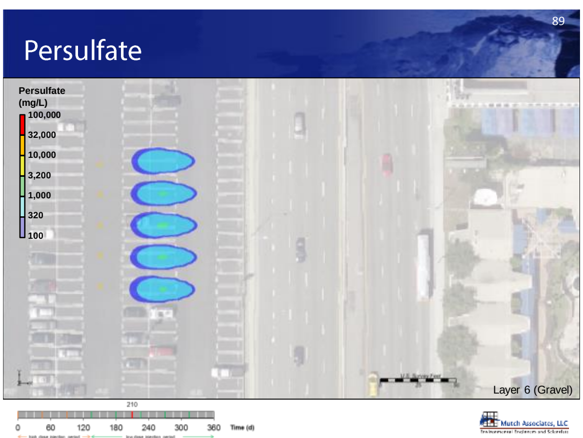
Persulfate
84

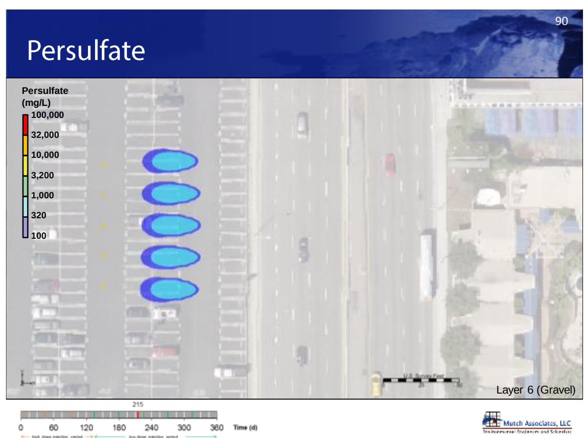

85
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
190
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

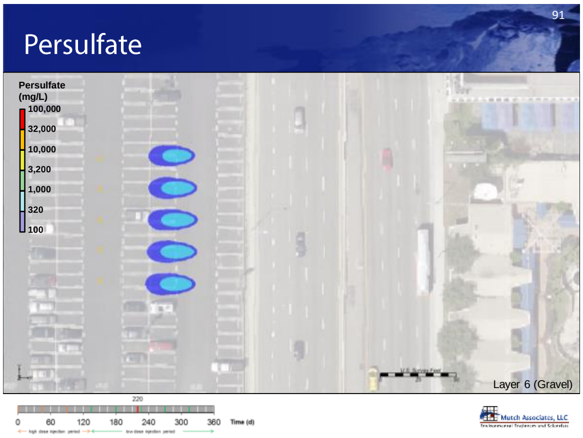

86
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
195
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

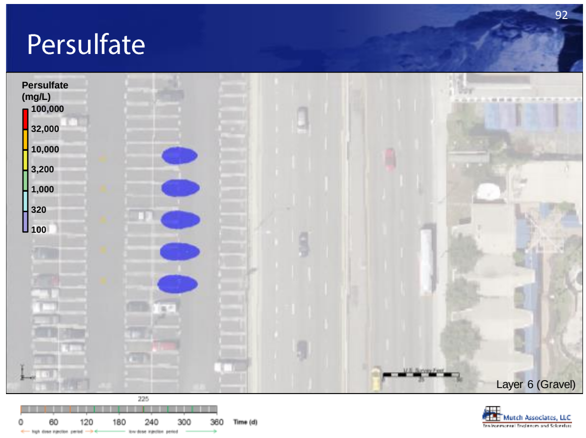

87
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
200
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

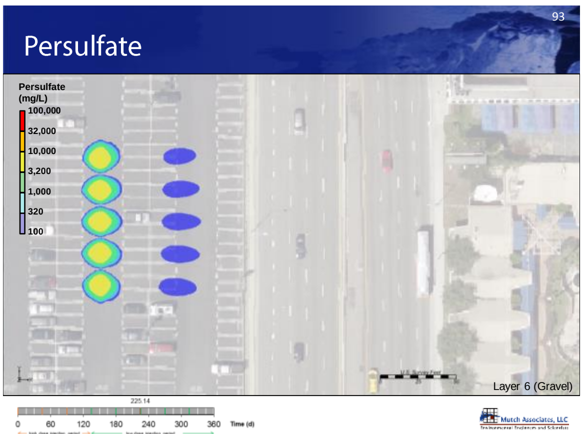

88
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
205
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

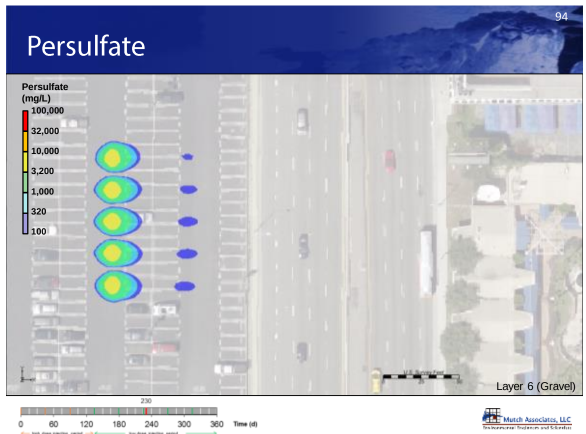

89
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
210
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

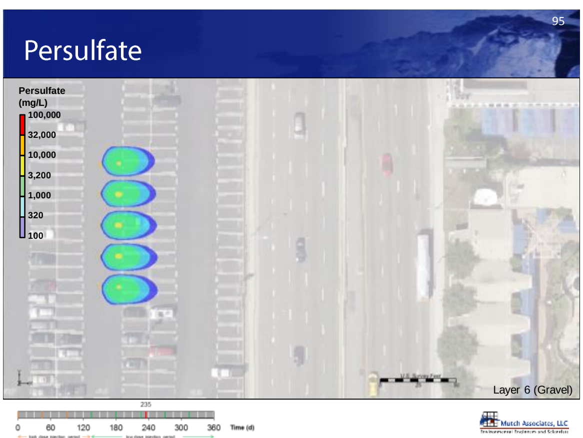

90
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
215
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

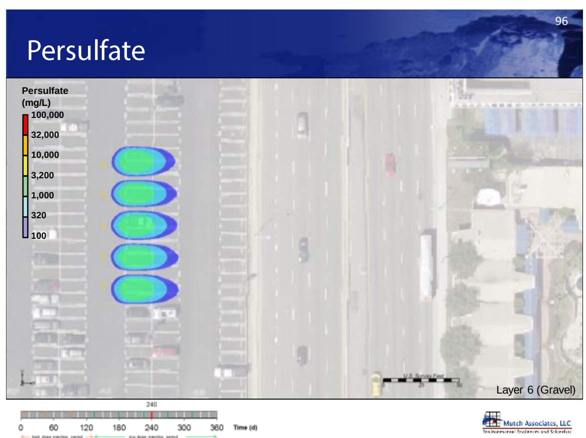

91
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
220
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


92
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
225
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

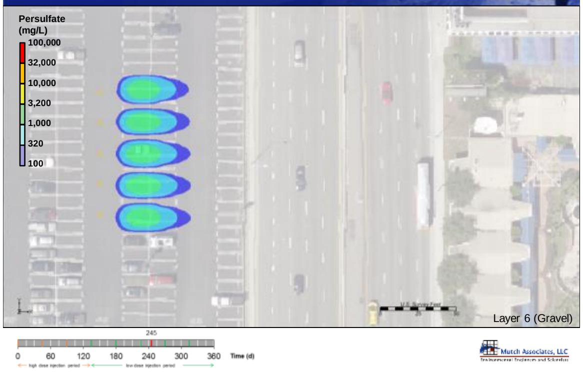

93
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
225.14
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


94
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
230
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

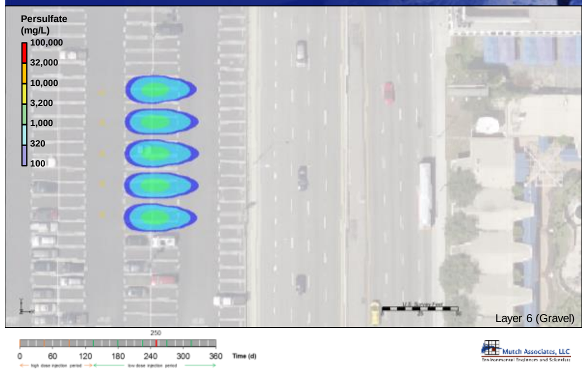

95
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
235
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


96
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
240
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

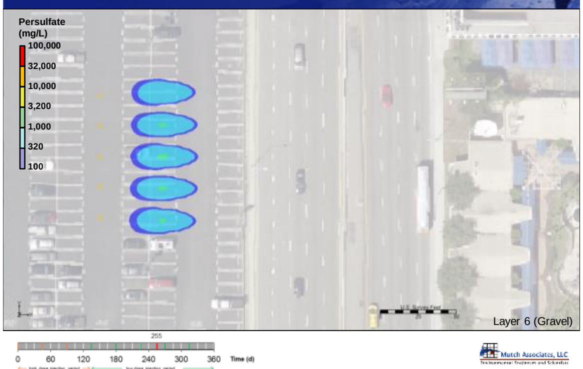
Persulfate



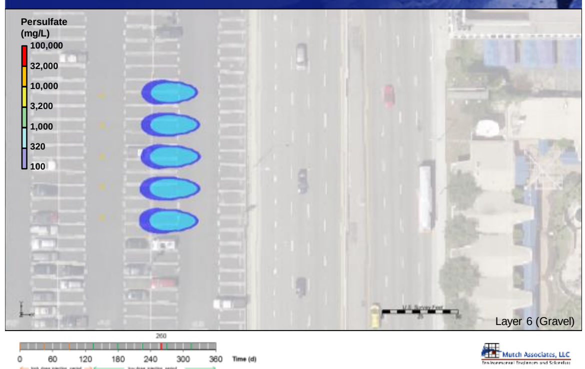
Persulfate



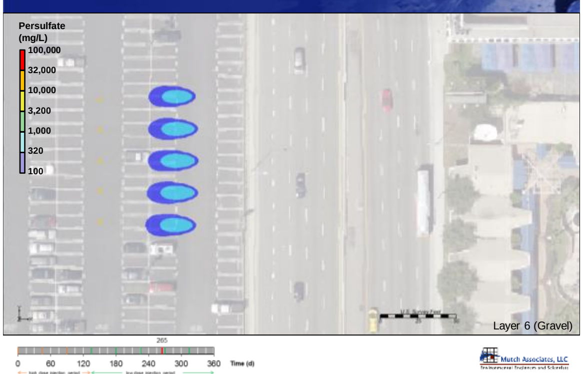
Persulfate



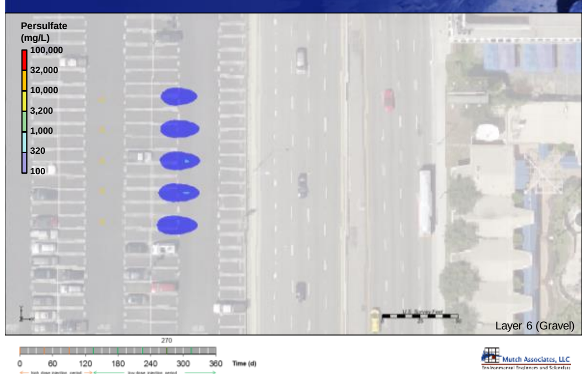
Persulfate

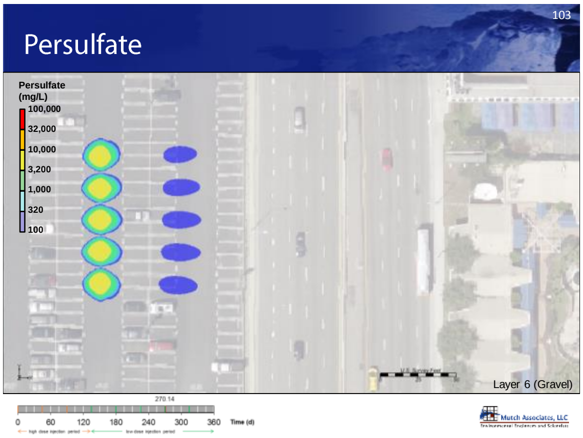


Persulfate

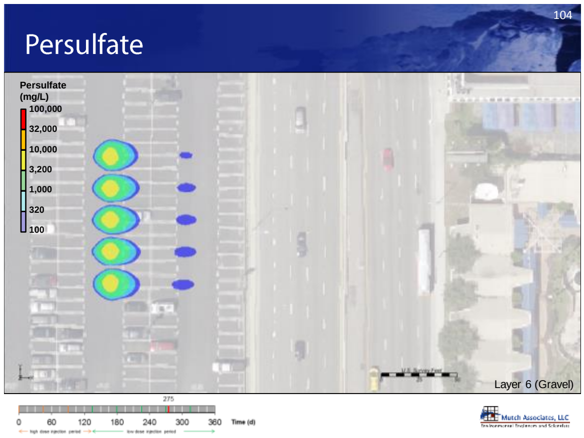


Persulfate

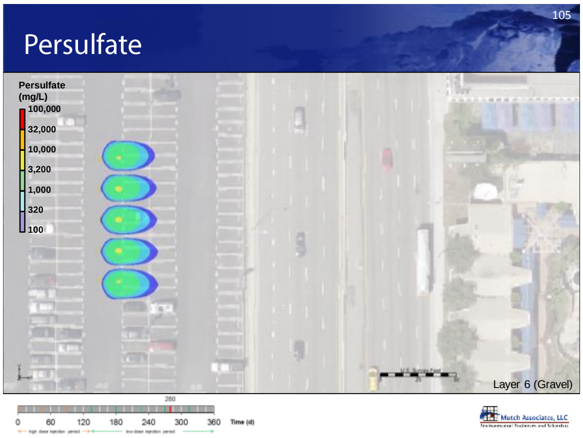




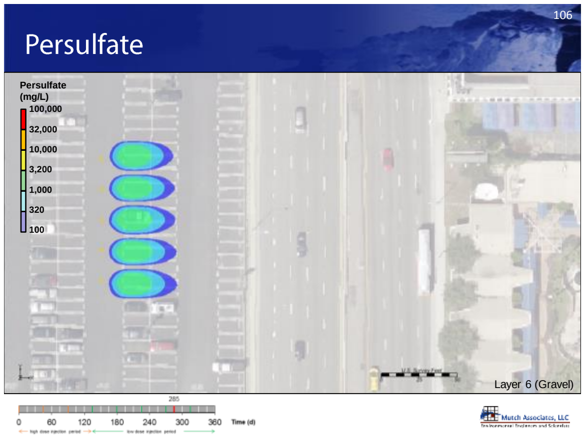
103
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
270.14
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC



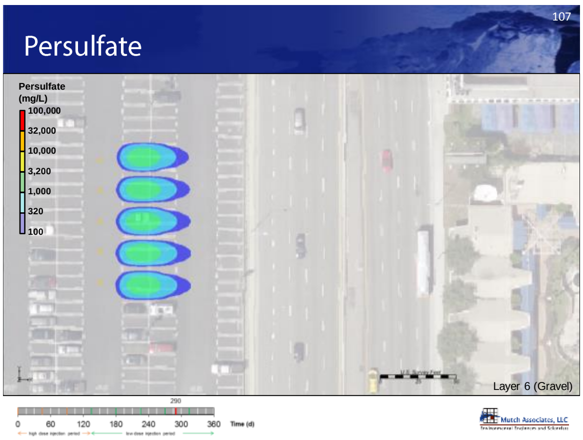
104
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
275
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC



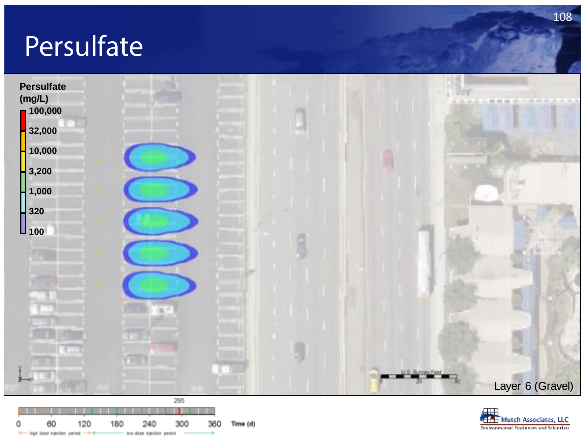
105
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
280
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC



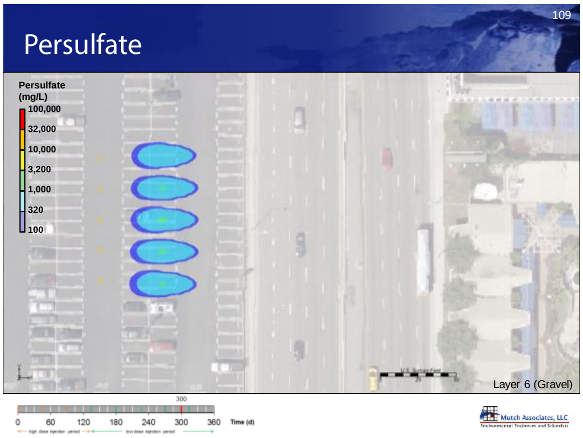
106
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
285
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

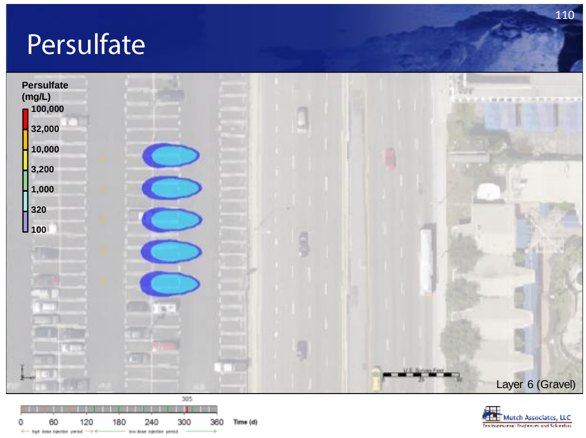


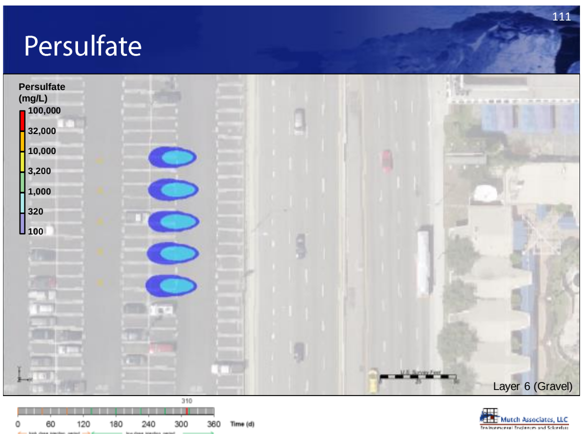
107
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
290
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

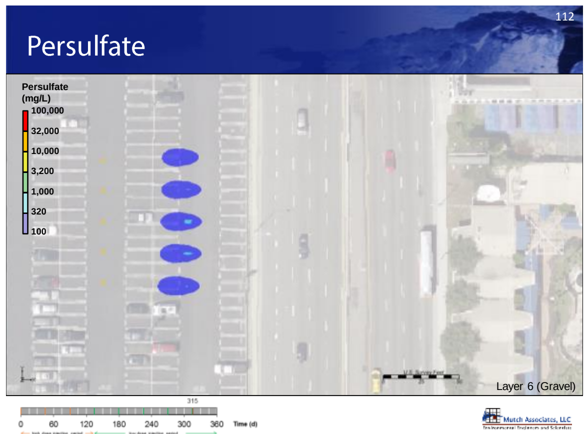


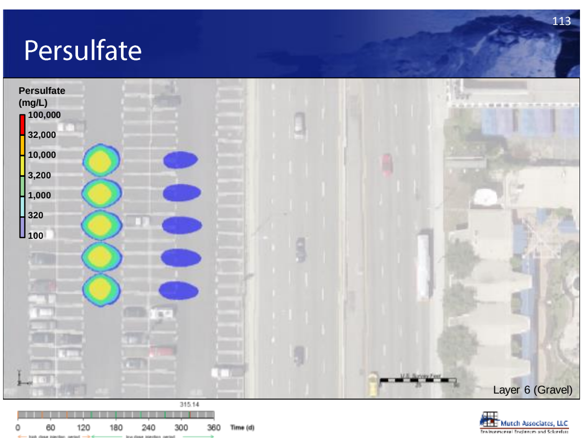
108
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
295
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

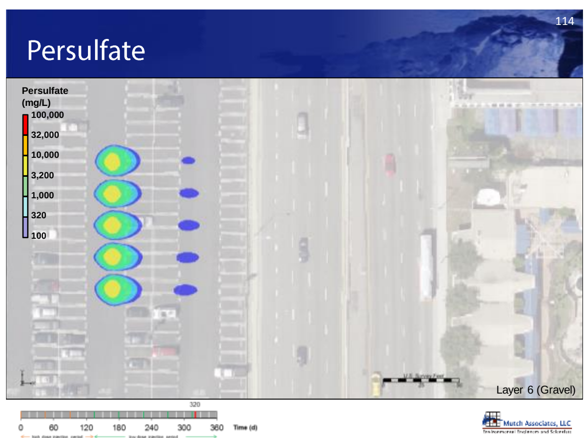

109
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
300
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


110
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
305
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


111
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
310
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

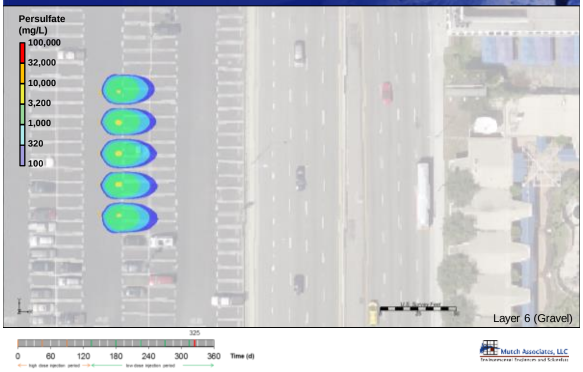

112
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
315
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


113
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


114
Persulfate
Persulfate (mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
320
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

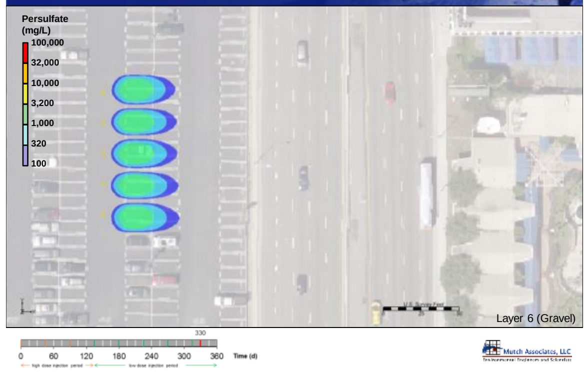
115

Persulfate



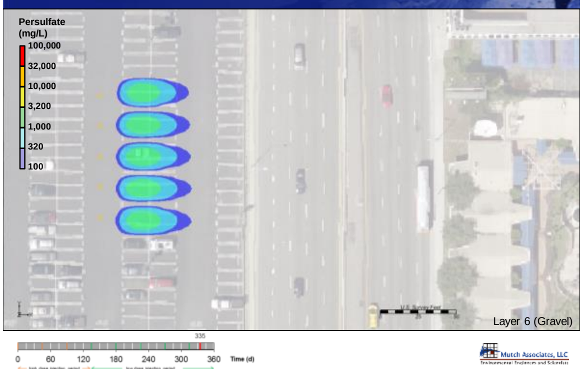
116

Persulfate



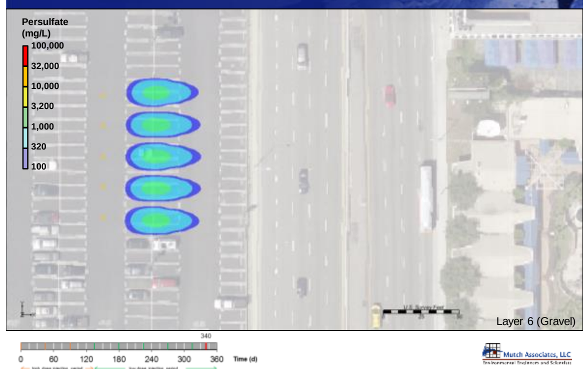
117

Persulfate



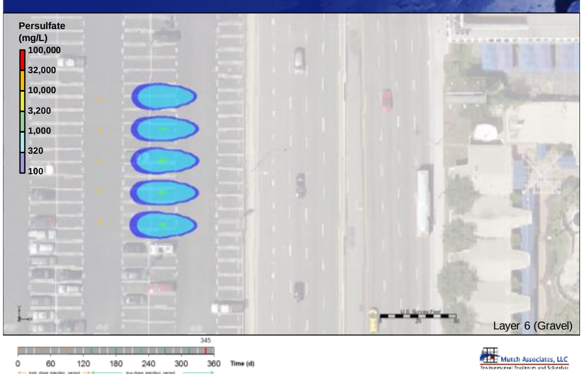
118

Persulfate



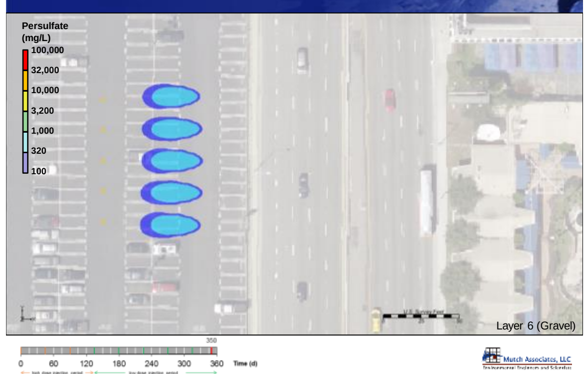
119

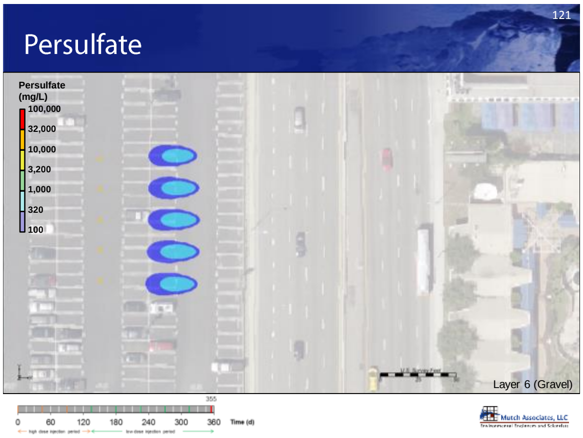
Persulfate

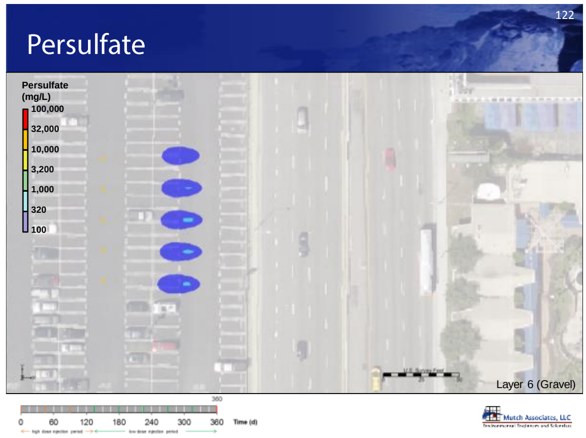


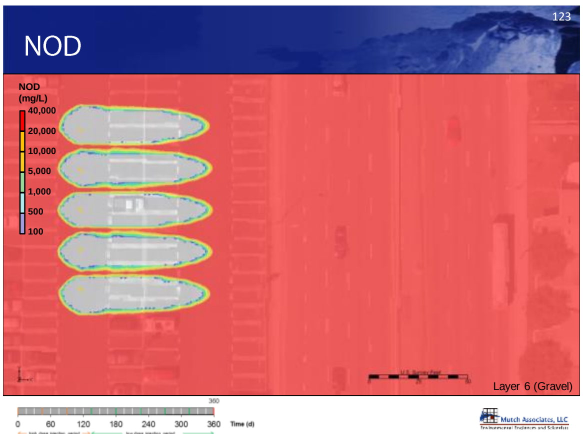
120

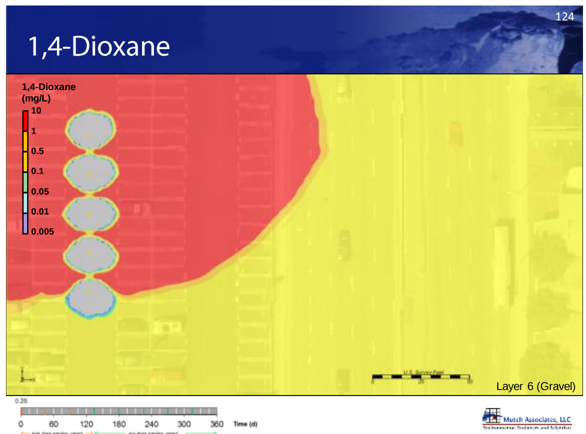
Persulfate

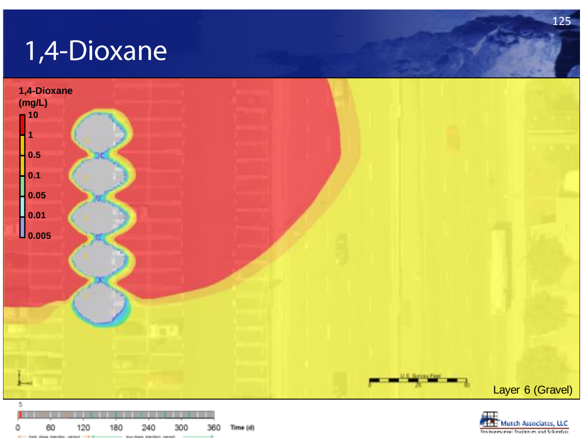


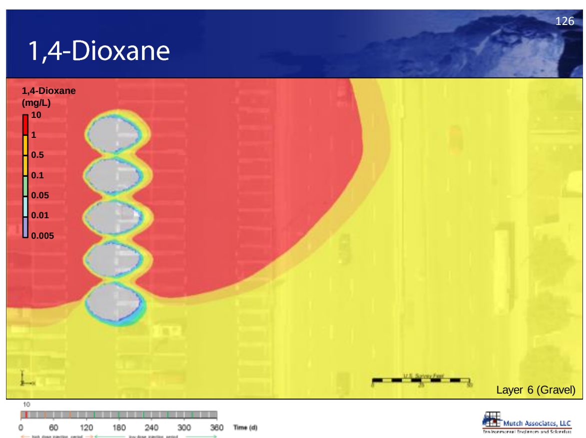

121
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


122
Persulfate
Persulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
320
100
Layer 6 (Gravel)
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


123
NOD
NOD
(mg/L)
40,000
20,000
10,000
5,000
1,000
500
100
Layer 6 (Gravel)
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

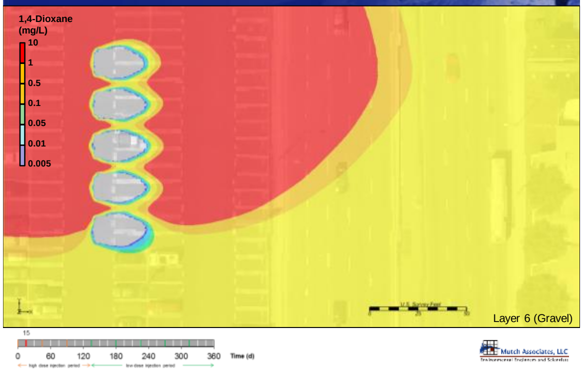

124
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


125
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


126
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

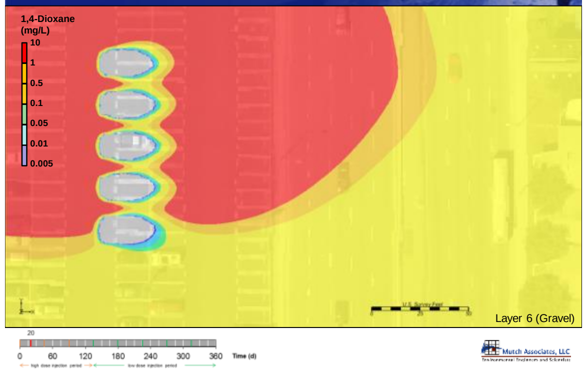
127

1,4-Dioxane



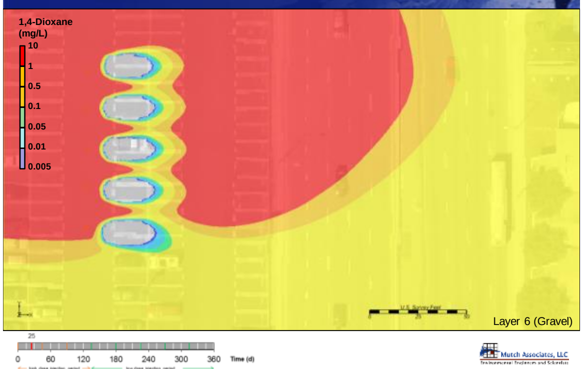
128

1,4-Dioxane



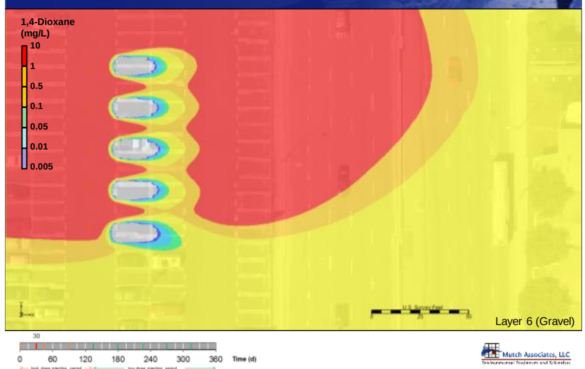
129

1,4-Dioxane



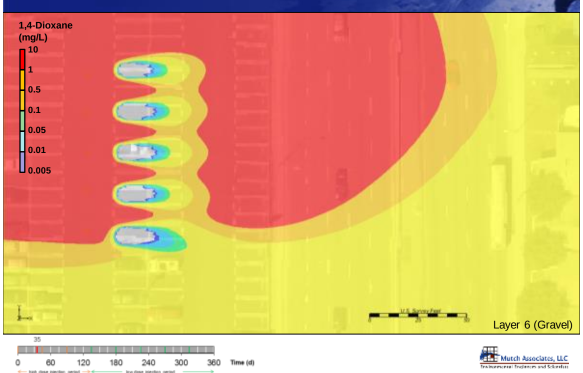
130

1,4-Dioxane



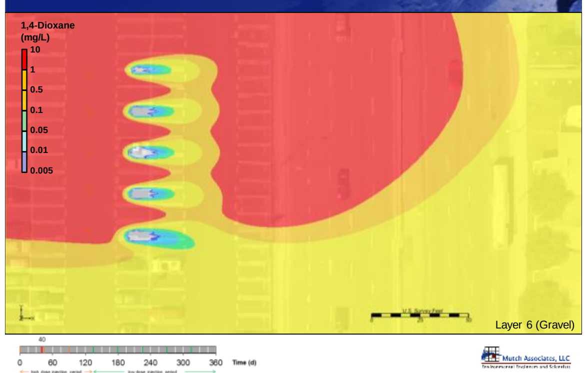
131

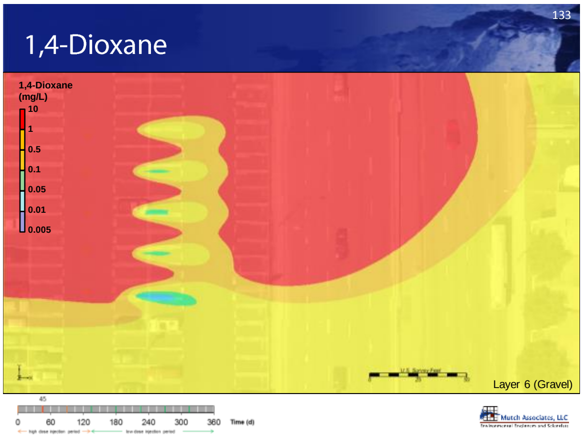
1,4-Dioxane

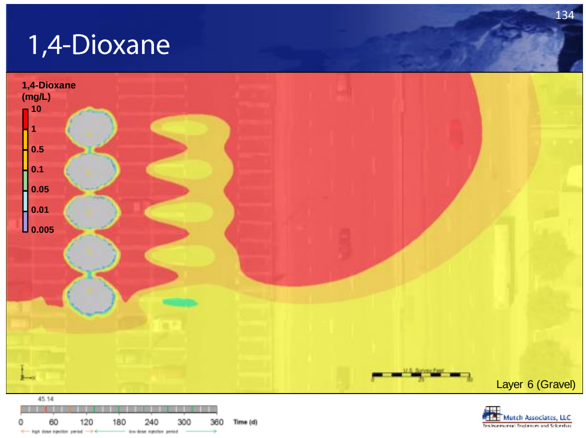


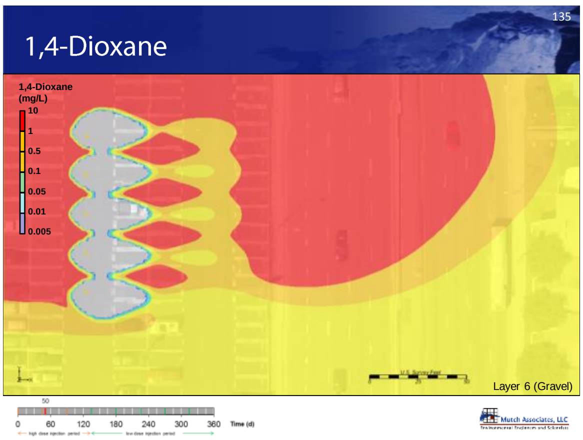
132

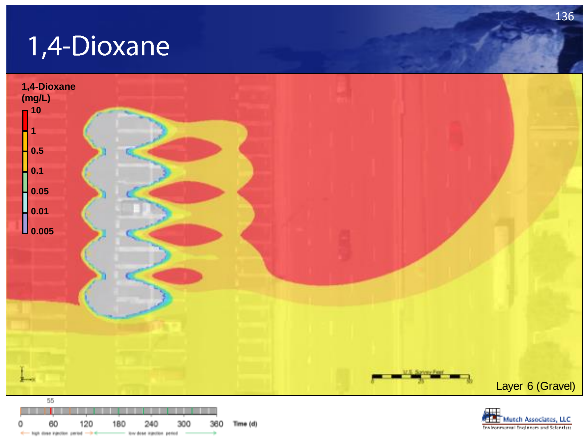
1,4-Dioxane

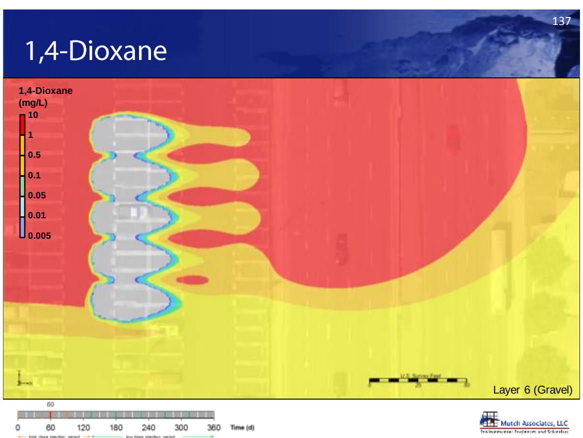


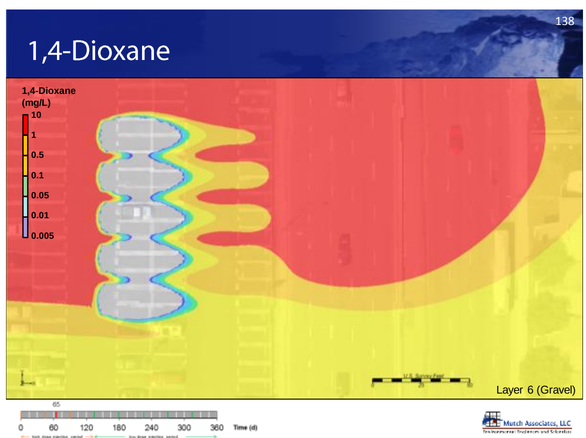

133
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
45
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

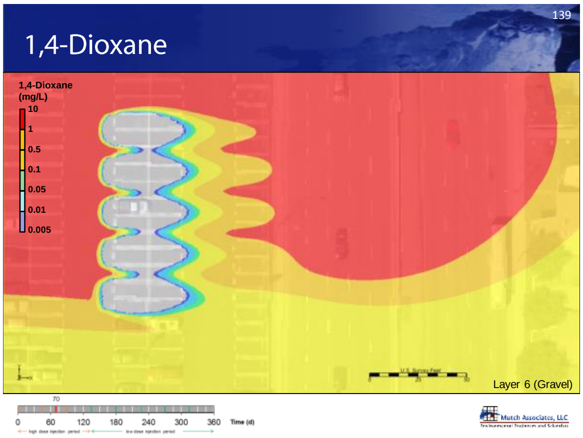

134
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

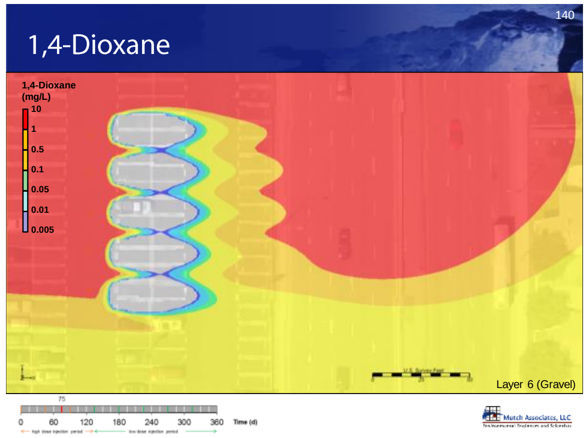

135
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
50
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

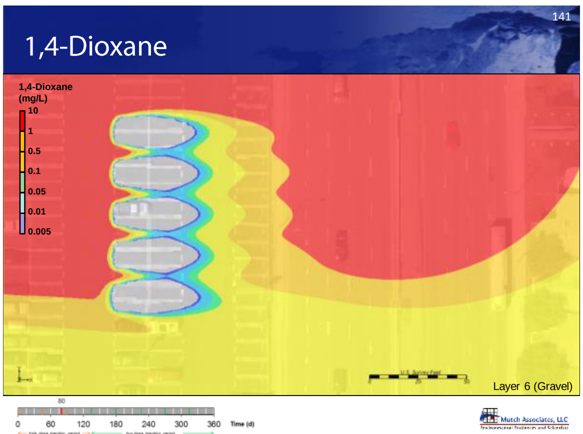

136
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
55
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

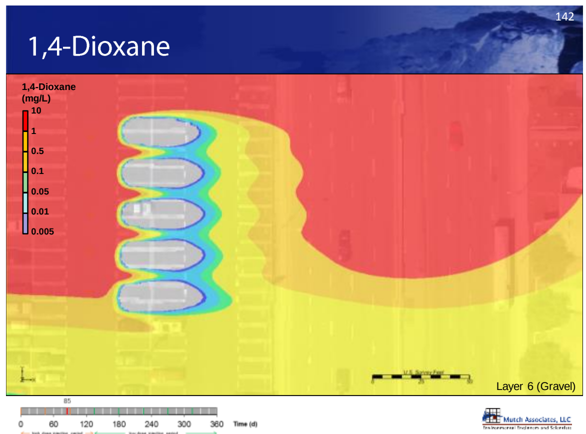

137
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
60
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

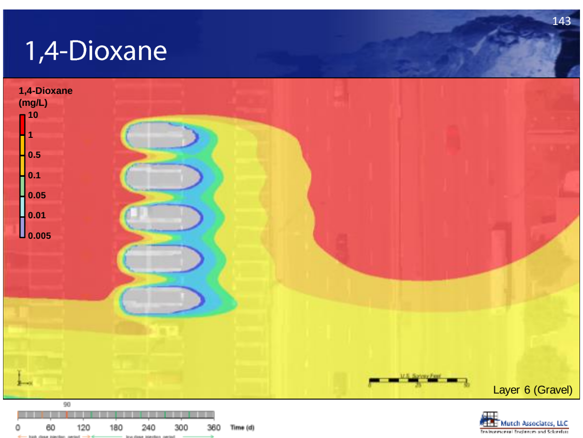

138
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
65
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

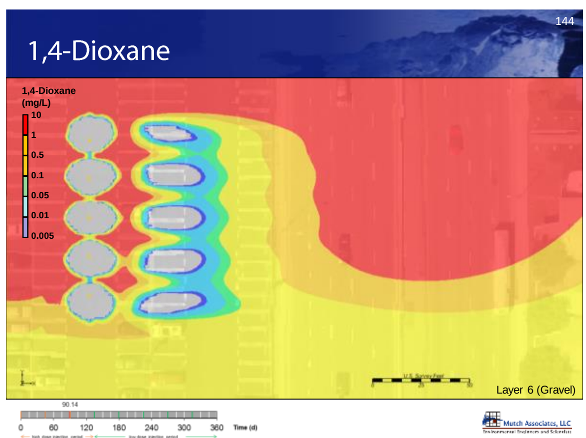

139
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
70
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


140
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
75
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


141
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
80
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

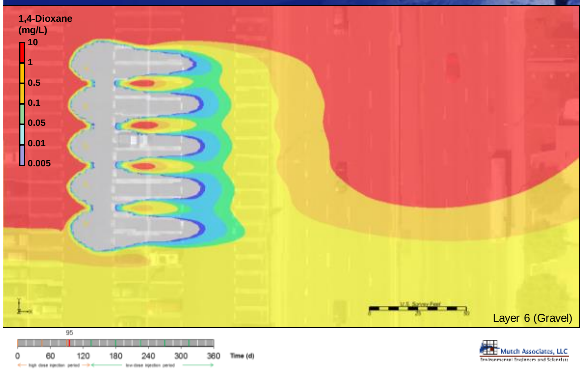

142
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
85
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


143
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
90
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


144
1,4-Dioxane
1,4-Dioxane (mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
90.14
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

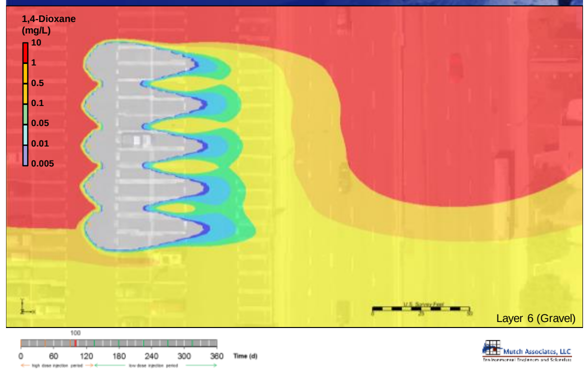
1,4-Dioxane

145



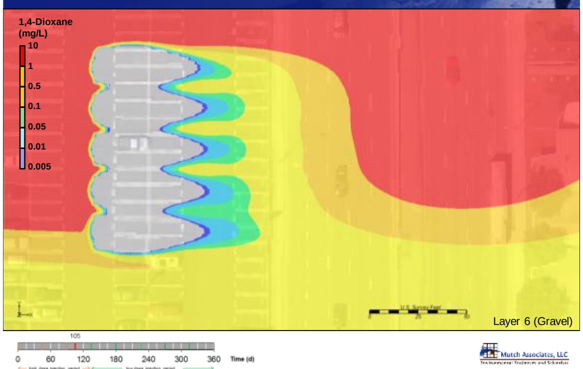
1,4-Dioxane

146



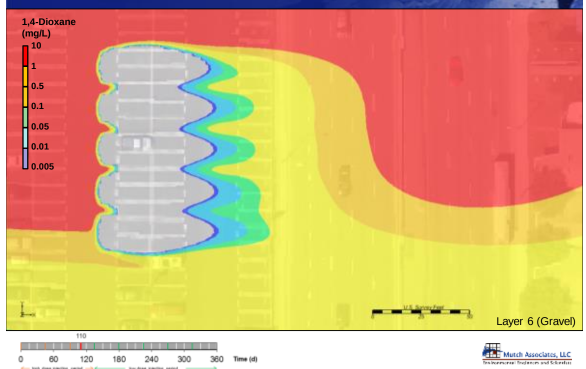
1,4-Dioxane

147



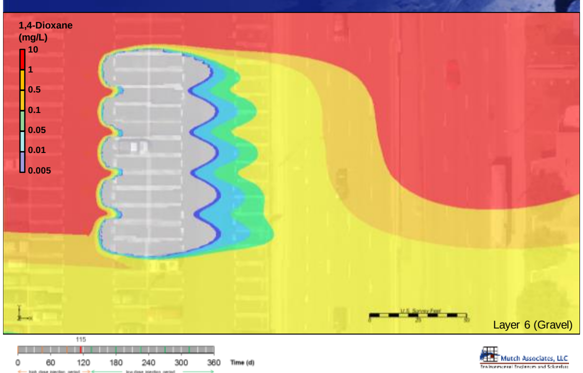
1,4-Dioxane

148



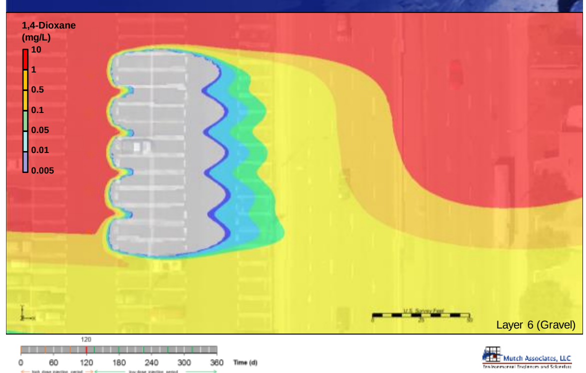
1,4-Dioxane

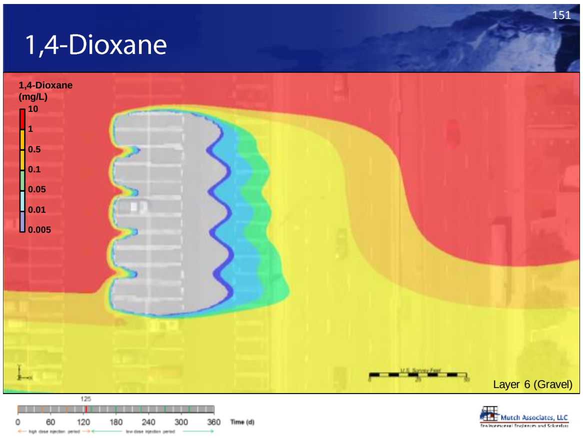
149

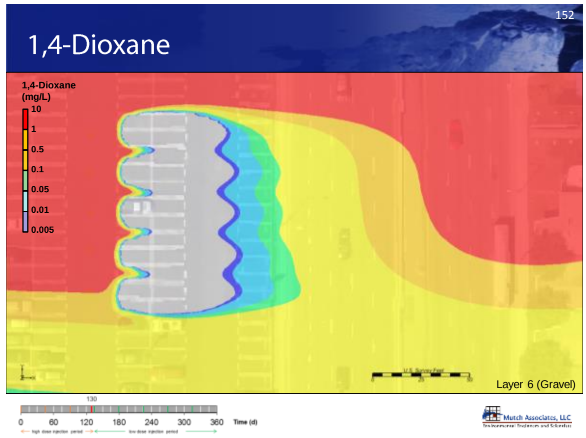


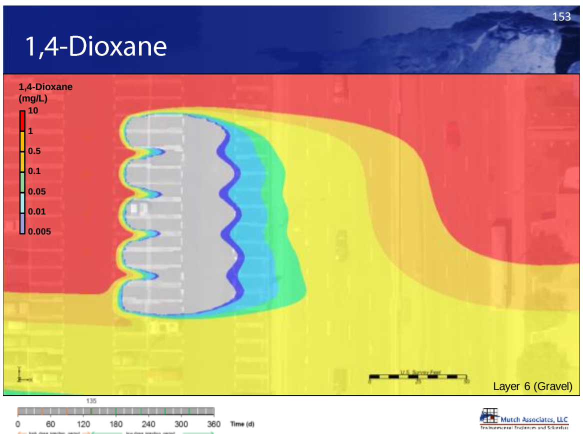
1,4-Dioxane

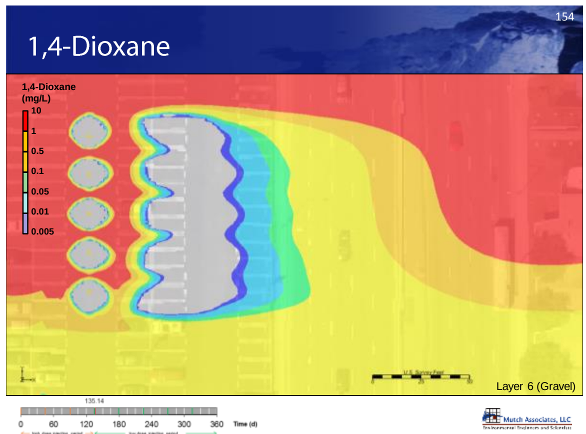
150

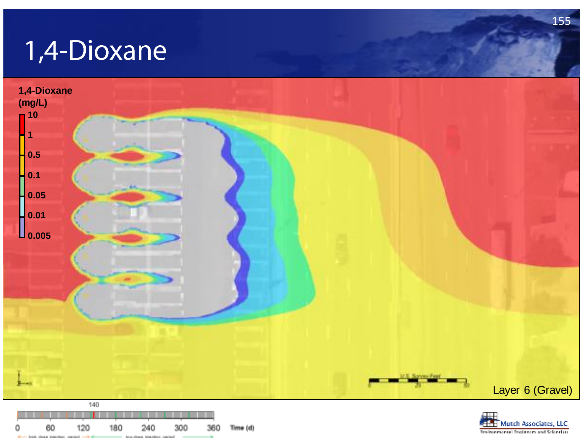


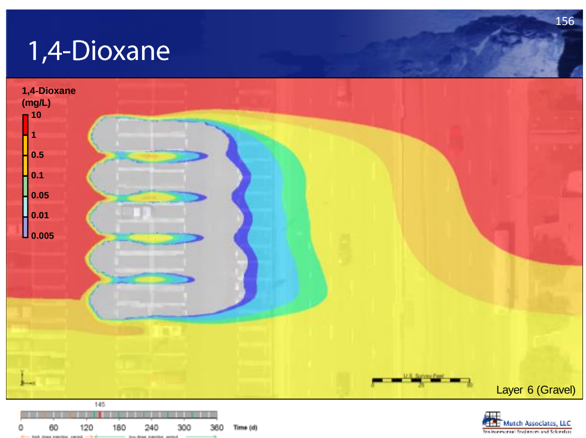

151
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


152
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


153
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

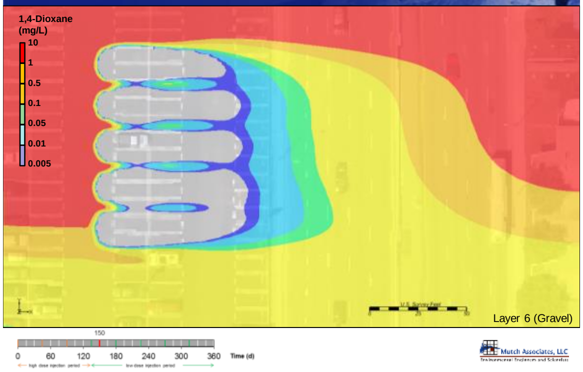

154
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


155
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


156
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

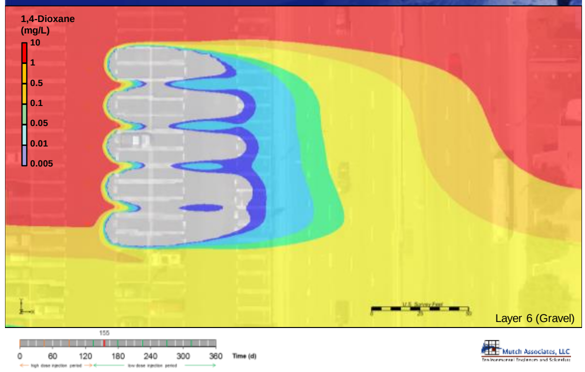
157

1,4-Dioxane



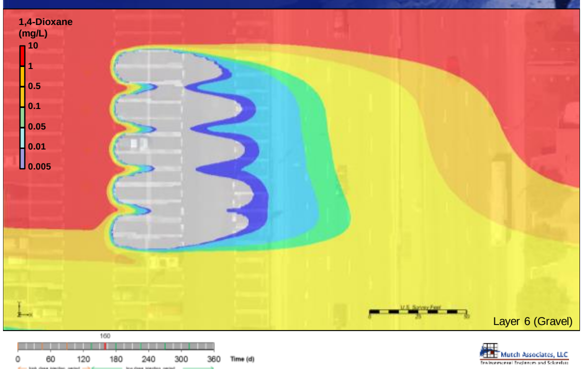
158

1,4-Dioxane



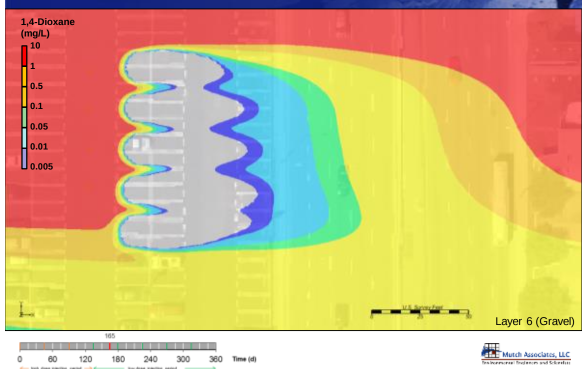
159

1,4-Dioxane



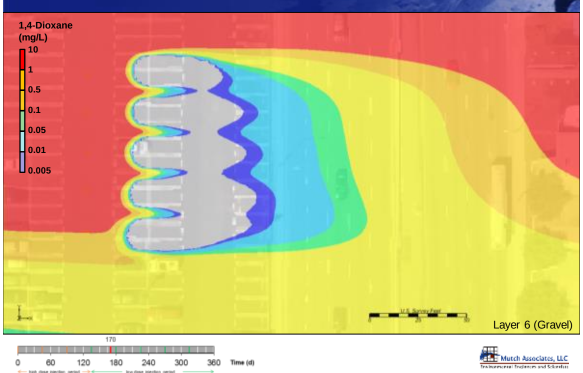
160

1,4-Dioxane



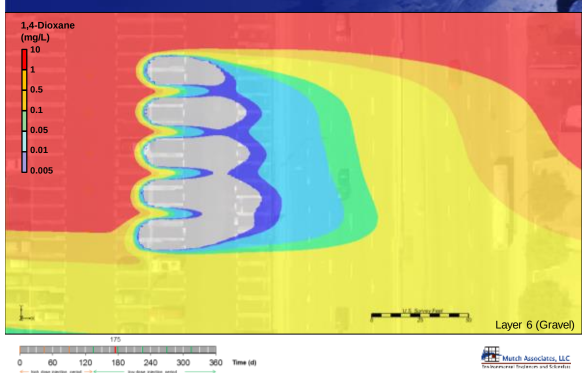
161

1,4-Dioxane



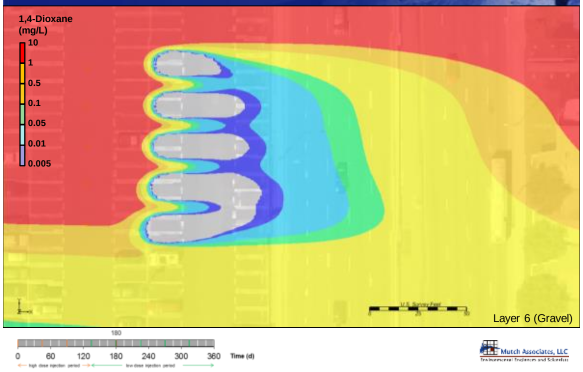
162

1,4-Dioxane



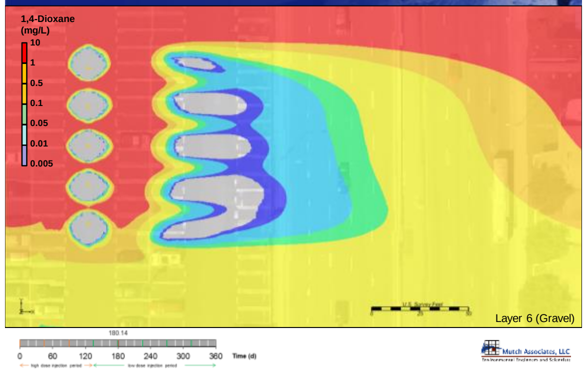
163

1,4-Dioxane



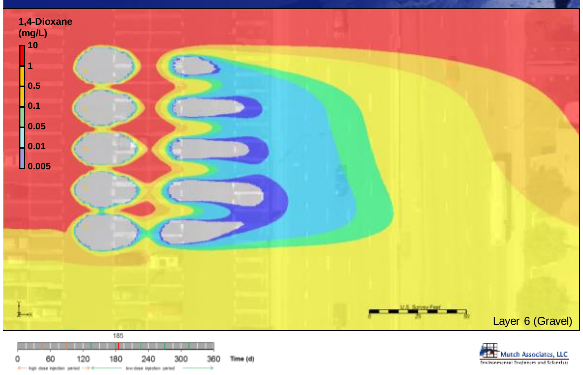
164

1,4-Dioxane



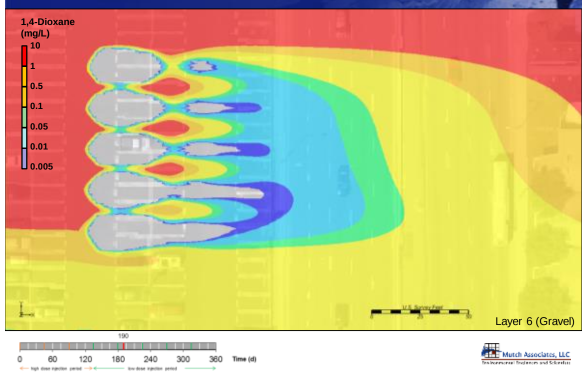
165

1,4-Dioxane



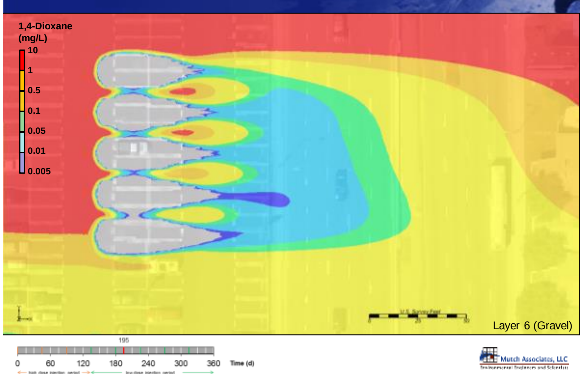
166

1,4-Dioxane



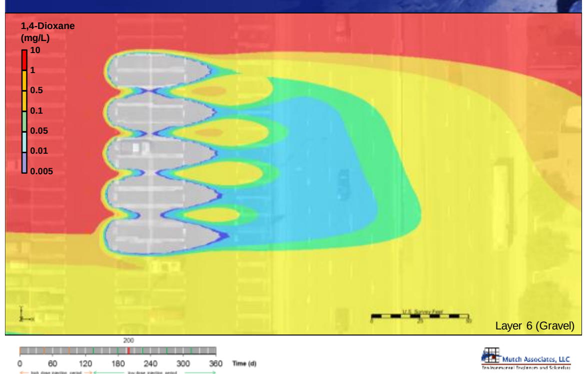
167

1,4-Dioxane



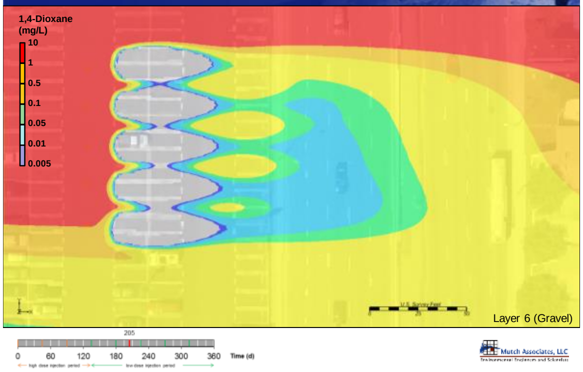
168

1,4-Dioxane



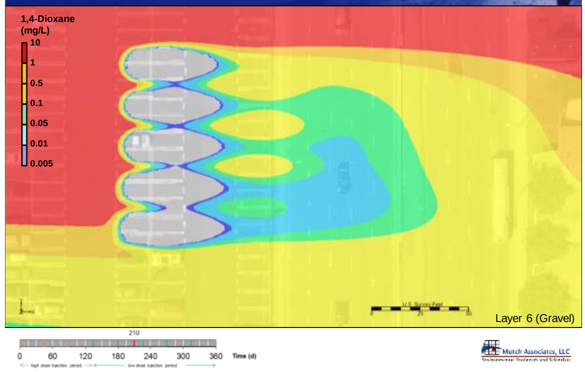
169

1,4-Dioxane



170

1,4-Dioxane



171

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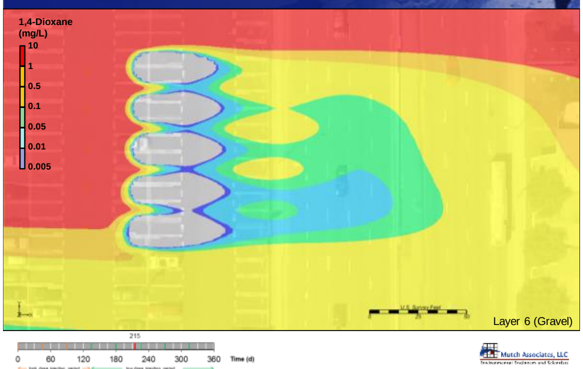
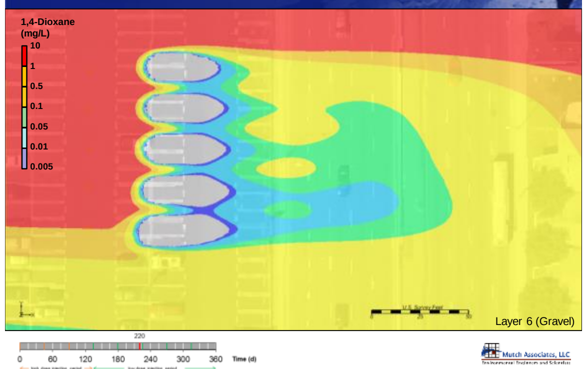


172

1,4-Dioxane



173

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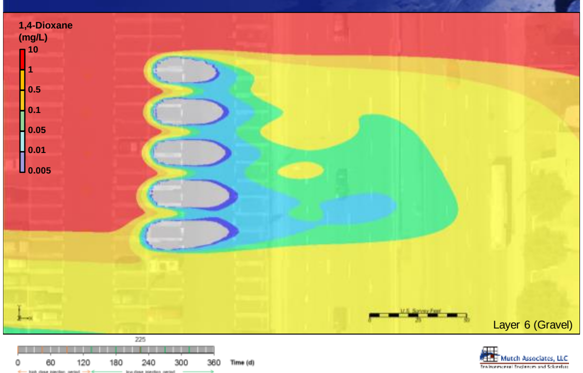

174

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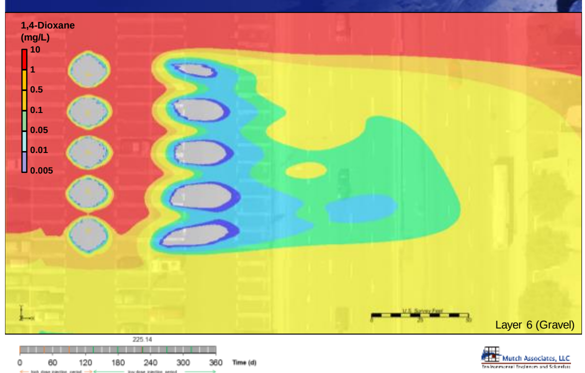

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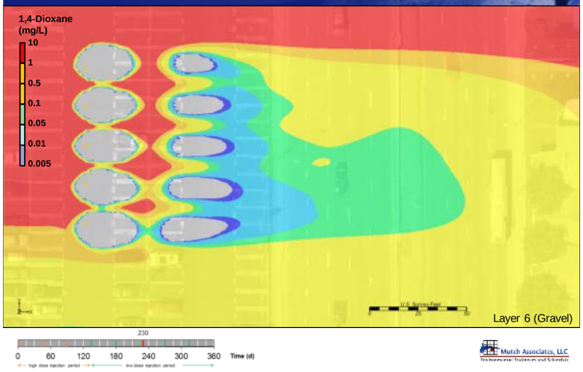

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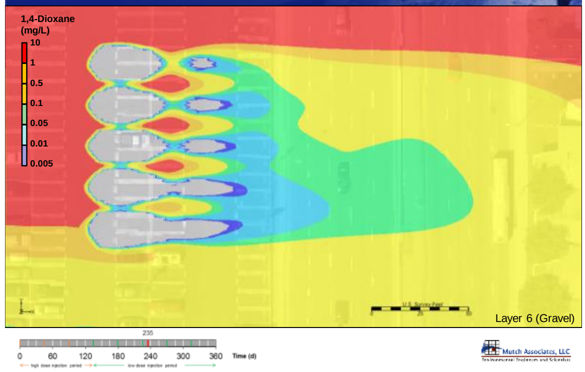

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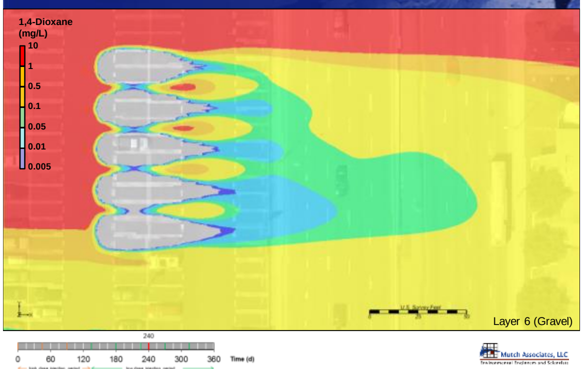

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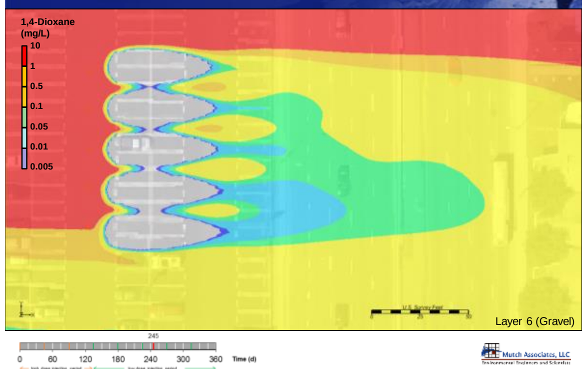

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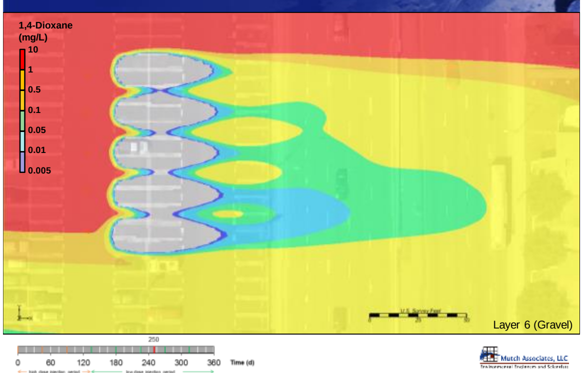

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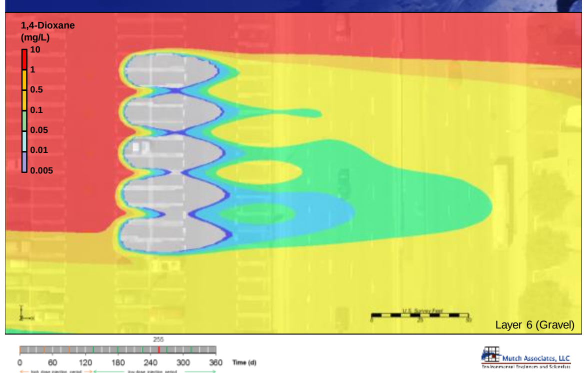

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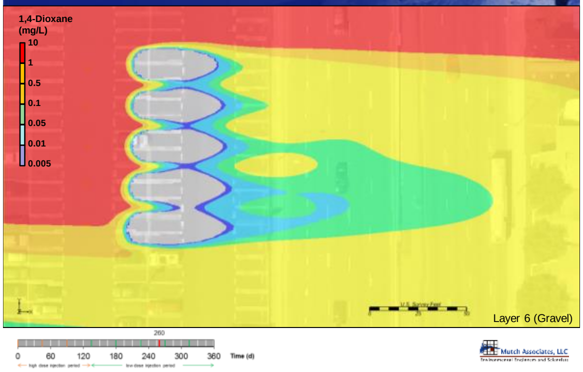

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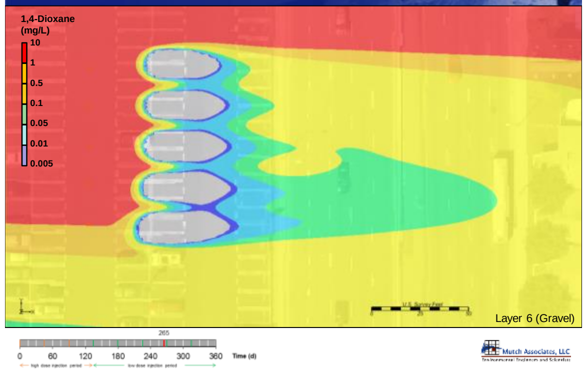

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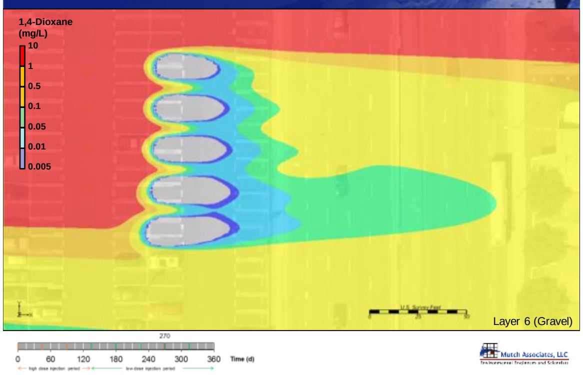

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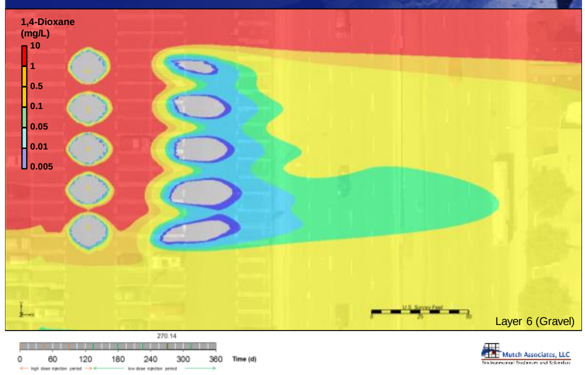
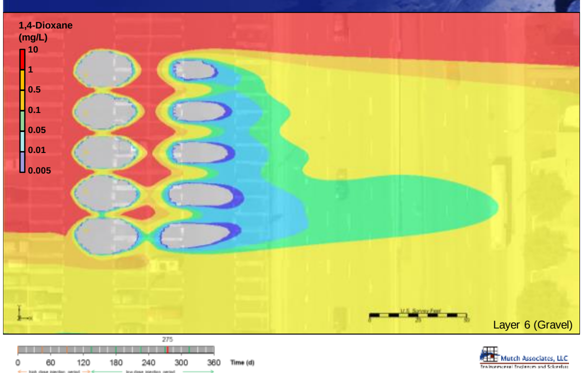
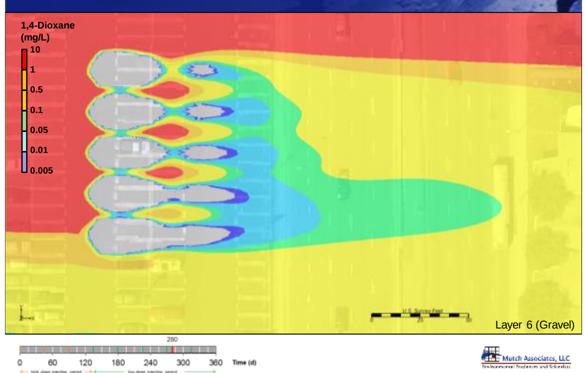


1,4-Dioxane



1,4-Dioxane



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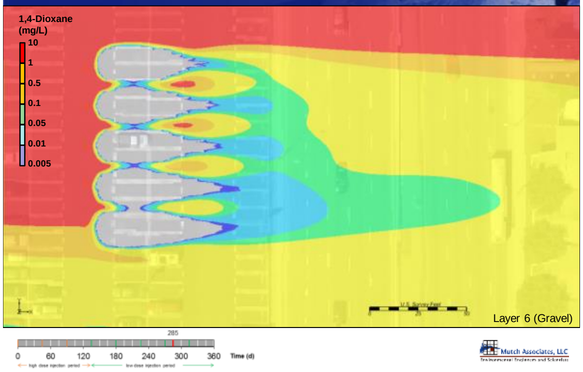
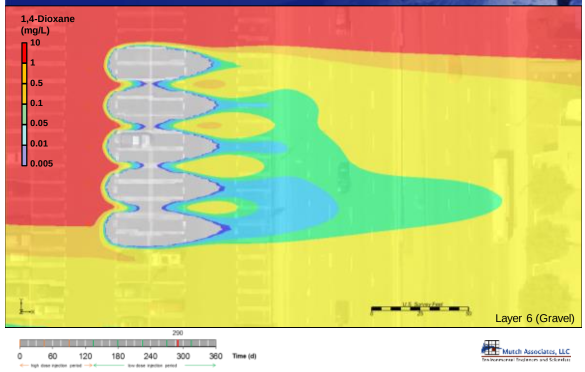
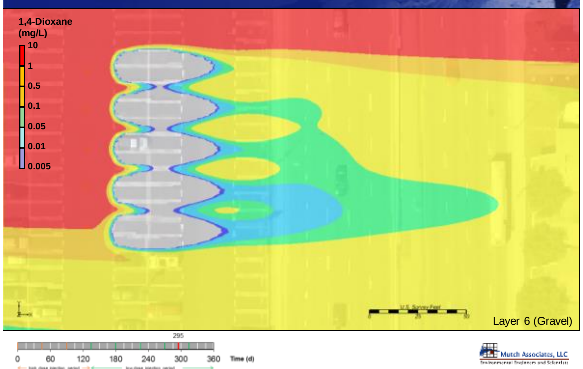


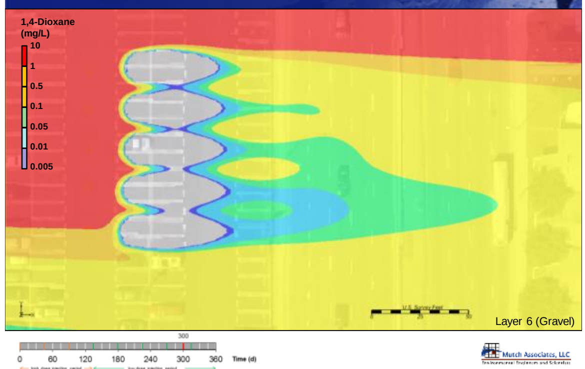
1,4-Dioxane



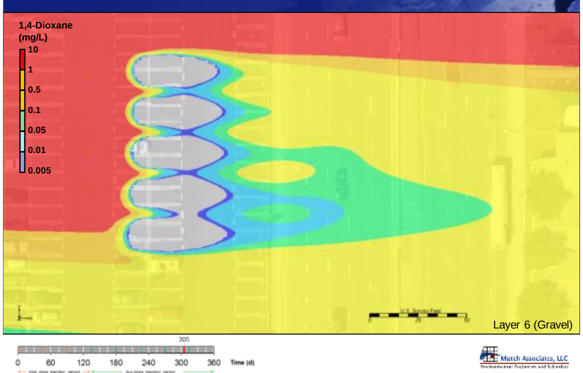
1,4-Dioxane



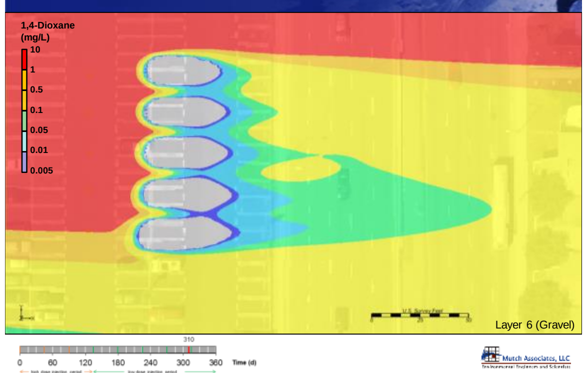
1,4-Dioxane

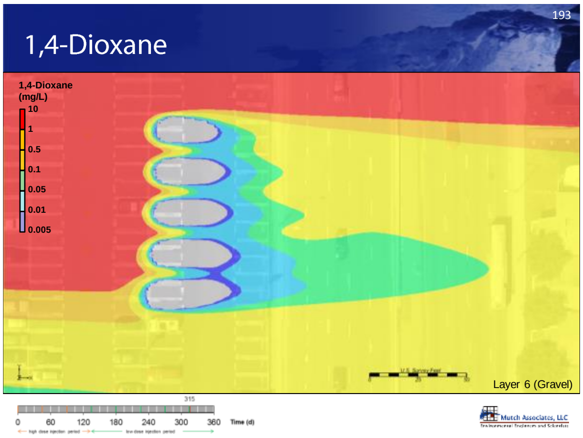


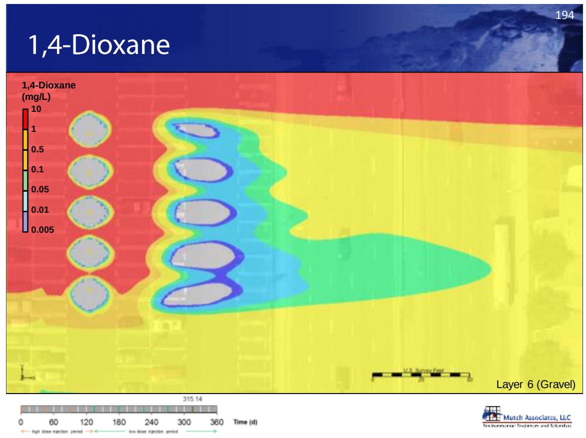
1,4-Dioxane

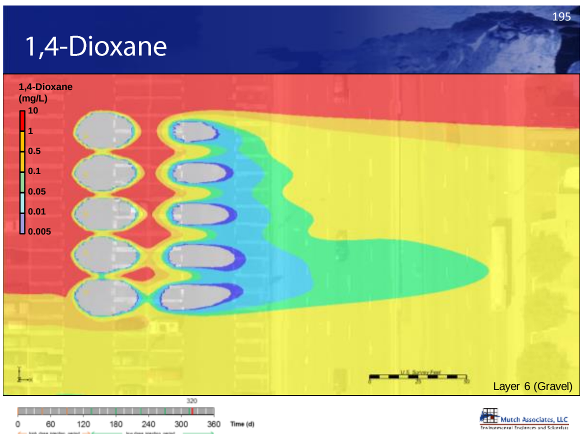


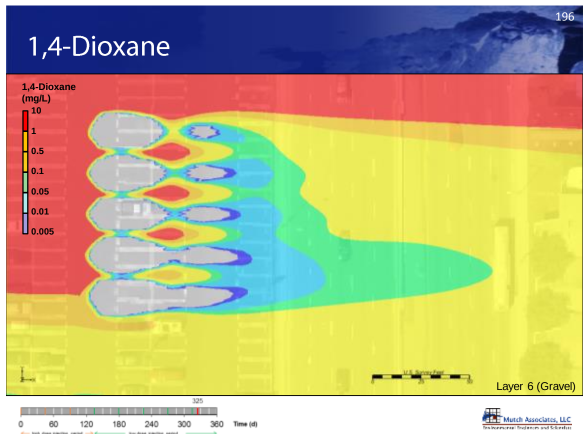
1,4-Dioxane

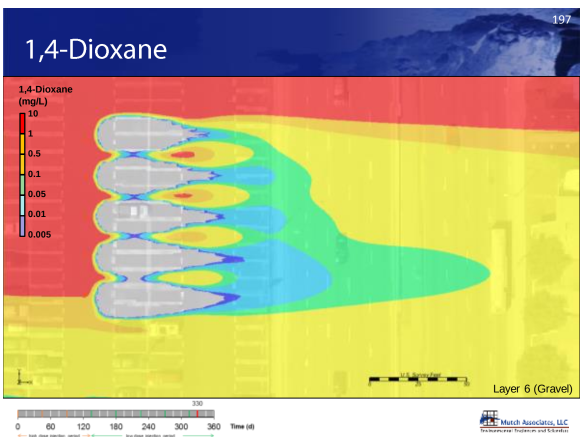


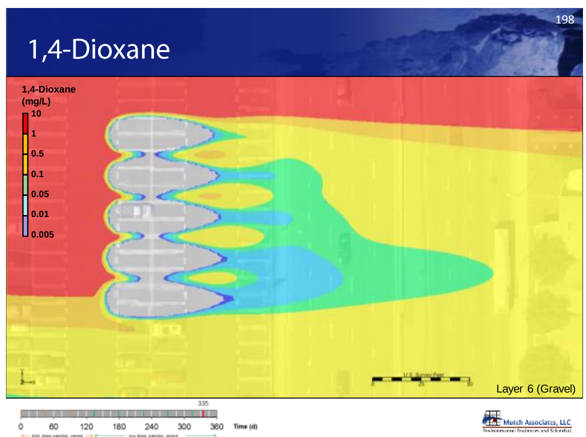

193
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
315
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


194
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
315.14
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


195
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
320
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

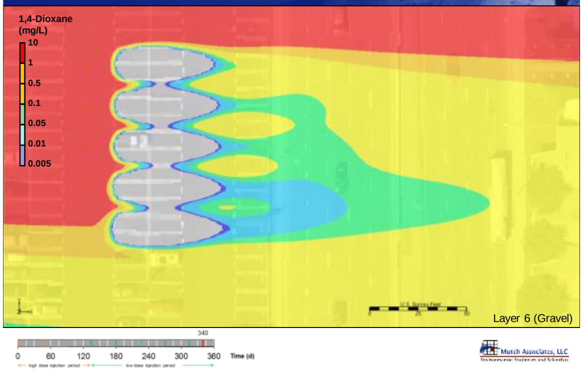

196
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
325
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


197
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
330
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC


198
1,4-Dioxane
1,4-Dioxane
(mg/L)
10
1
0.5
0.1
0.05
0.01
0.005
Layer 6 (Gravel)
335
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

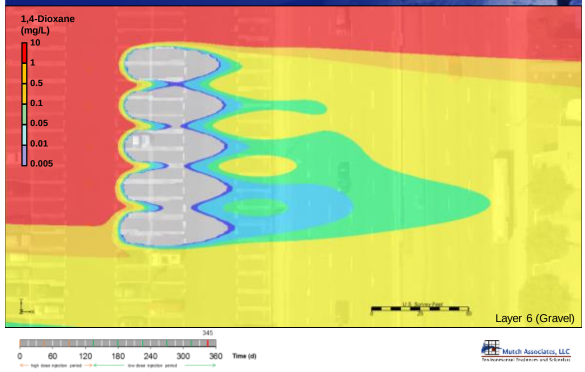
199

1,4-Dioxane



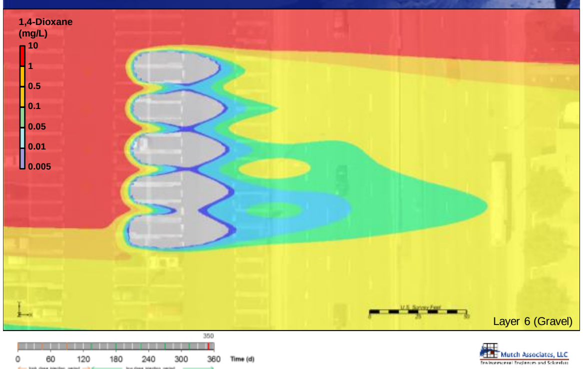
200

1,4-Dioxane



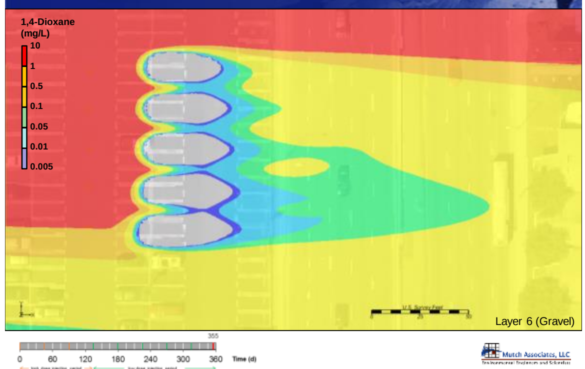
201

1,4-Dioxane



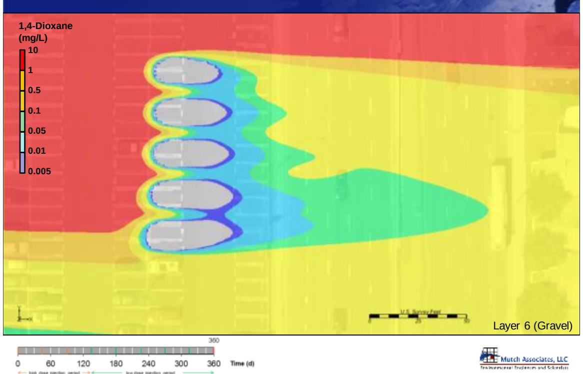
202

1,4-Dioxane



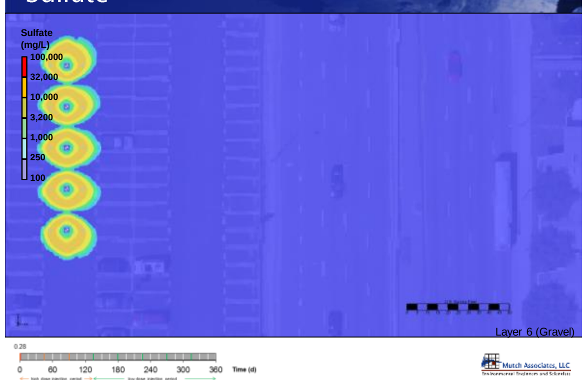
203

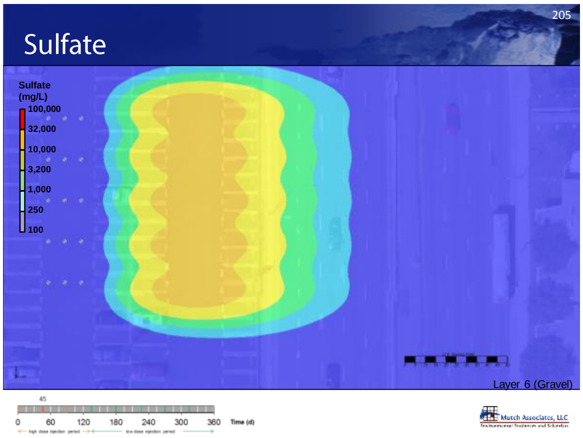
1,4-Dioxane

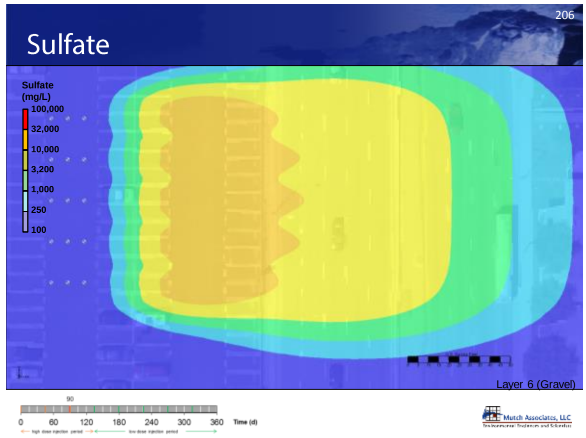


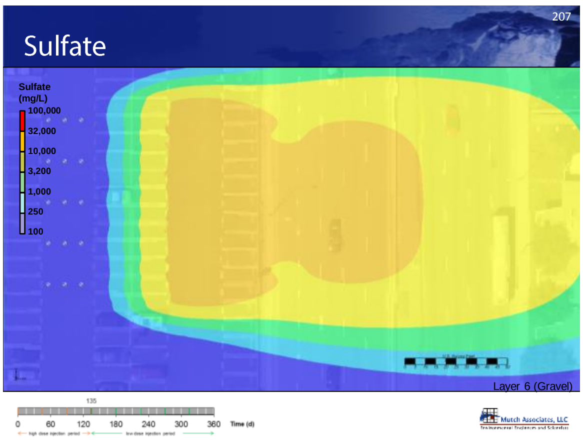
204

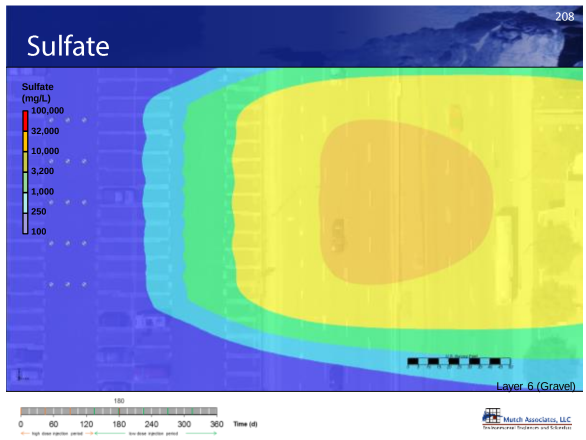
Sulfate

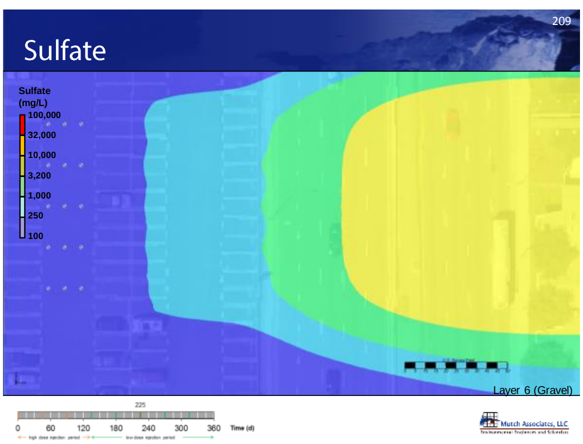


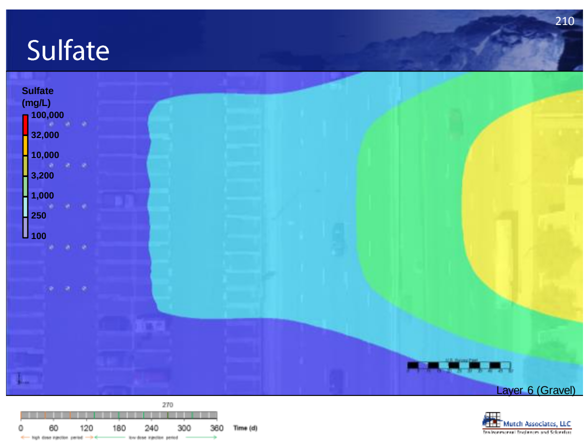

205
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
45
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

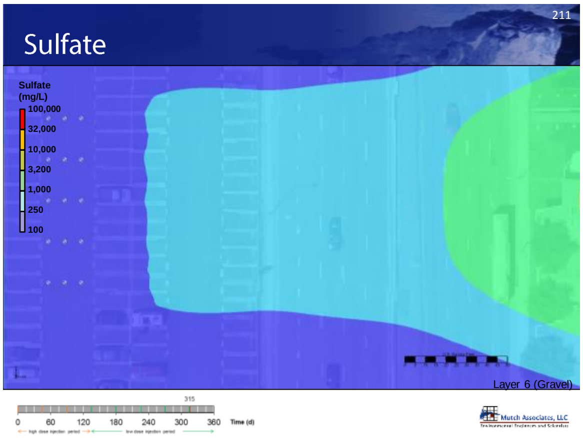

206
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
90
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

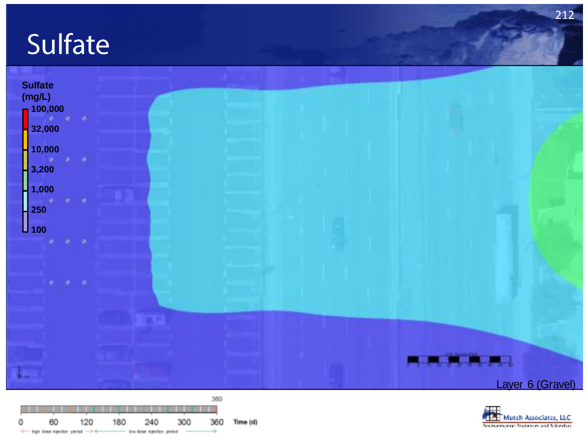

207
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
135
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

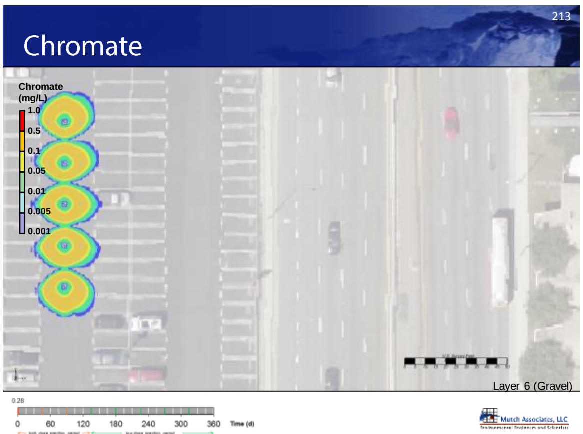

208
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
180
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

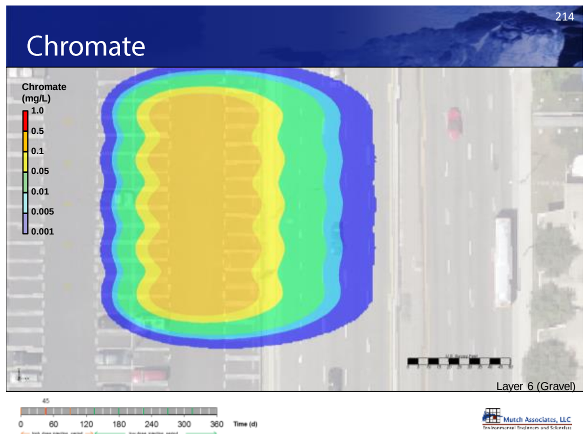

209
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
225
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

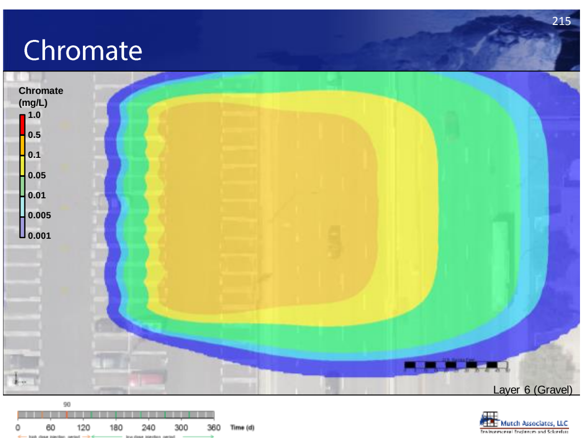

210
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
270
0 60 120 180 240 300 360 Time (d)
Mutch Associates, LLC

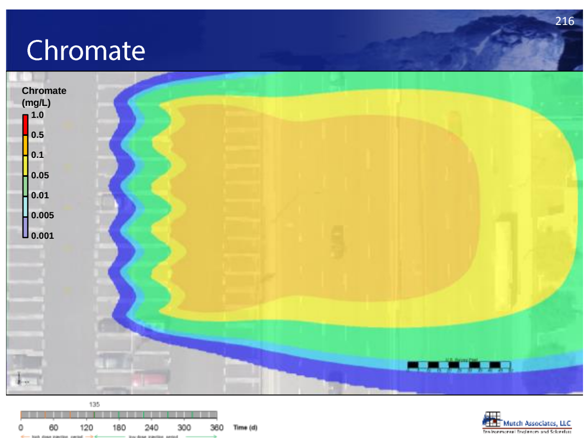

211
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
315
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


212
Sulfate
Sulfate
(mg/L)
100,000
32,000
10,000
3,200
1,000
250
100
Layer 6 (Gravel)
360
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


213
Chromate
Chromate
(mg/L)
1.0
0.5
0.1
0.05
0.01
0.005
0.001
Layer 6 (Gravel)
0.28
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

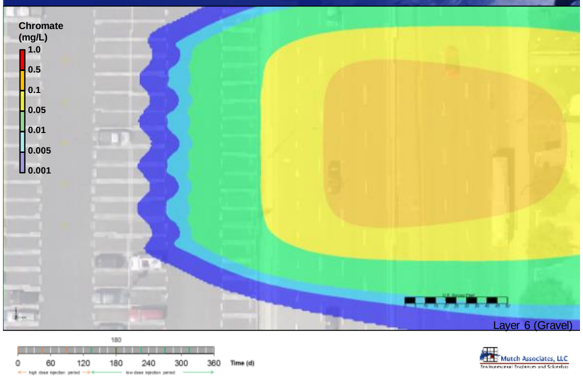

214
Chromate
Chromate
(mg/L)
1.0
0.5
0.1
0.05
0.01
0.005
0.001
Layer 6 (Gravel)
45
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


215
Chromate
Chromate
(mg/L)
1.0
0.5
0.1
0.05
0.01
0.005
0.001
Layer 6 (Gravel)
90
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC


216
Chromate
Chromate
(mg/L)
1.0
0.5
0.1
0.05
0.01
0.005
0.001
135
0
60
120
180
240
300
360
Time (d)
Mutch Associates, LLC

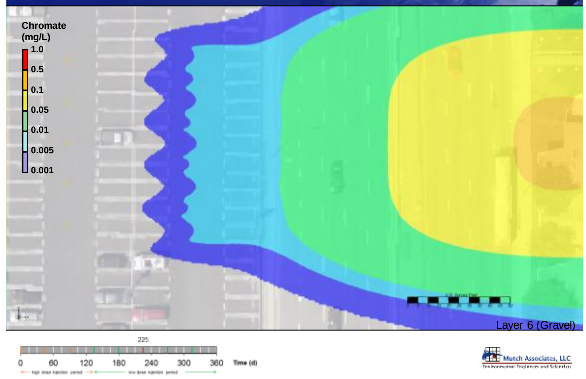
217

Chromate



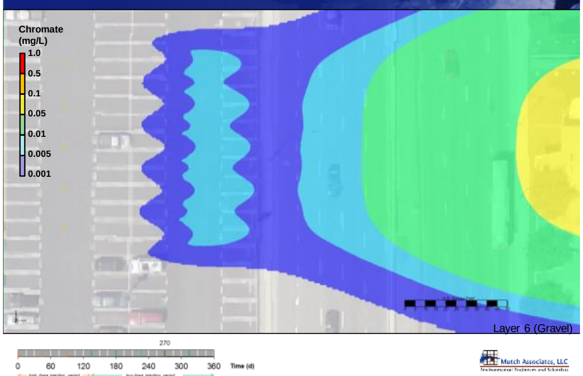
218

Chromate



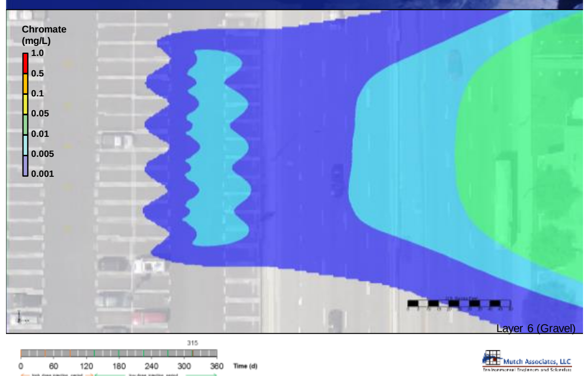
219

Chromate



220

Chromate



221

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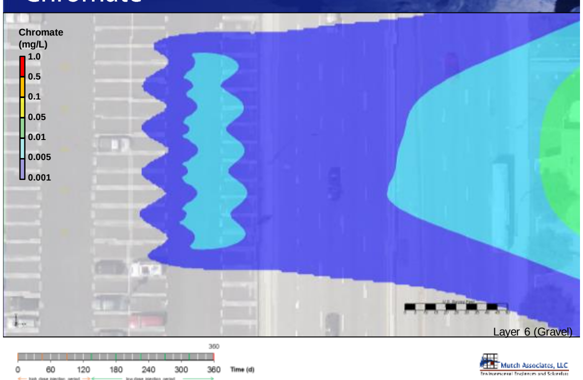
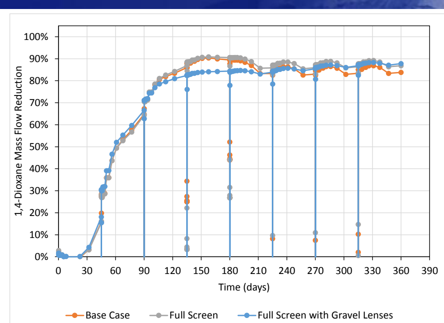


222

Summary of Mass Flow Reduction Results



Summary and Conclusions

- 3-D reactive transport modeling is revolutionizing the design of in situ treatment systems
  - Offers unparalleled insights into what is happening in the subsurface
  - Helps avoid ISTs falling short of performance objectives or failing altogether
  - Saves time and money
  - Applicable to most permutations of ISCO, ISCR, and in situ bioremediation