United States Environmental Protection Agency

Tools for Estimating Groundwater Contaminant Flux to Surface Water

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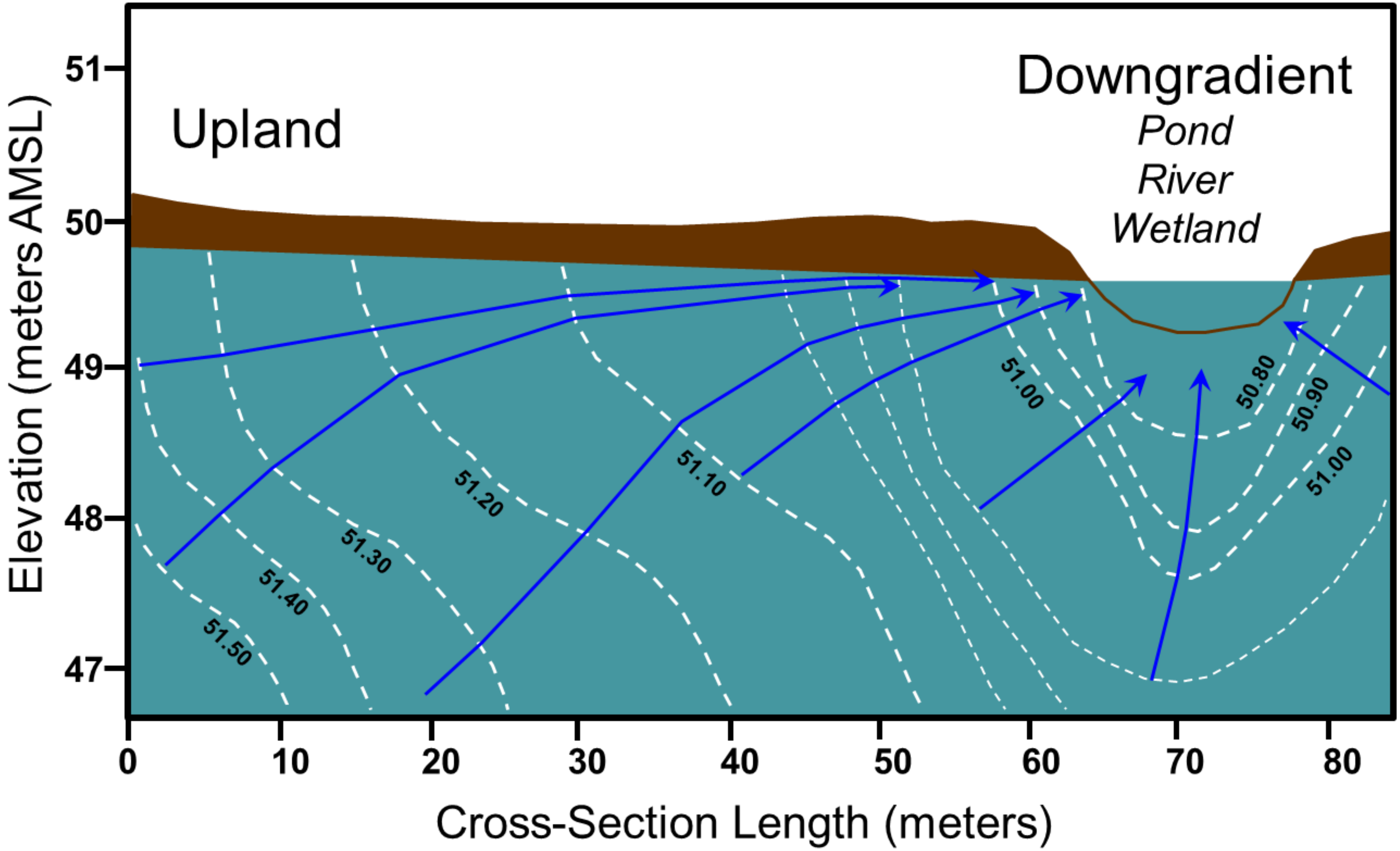
Disclaimer

The findings and conclusions in this presentation have not been formally disseminated by the U.S. EPA and should not be construed to represent any agency determination or policy.

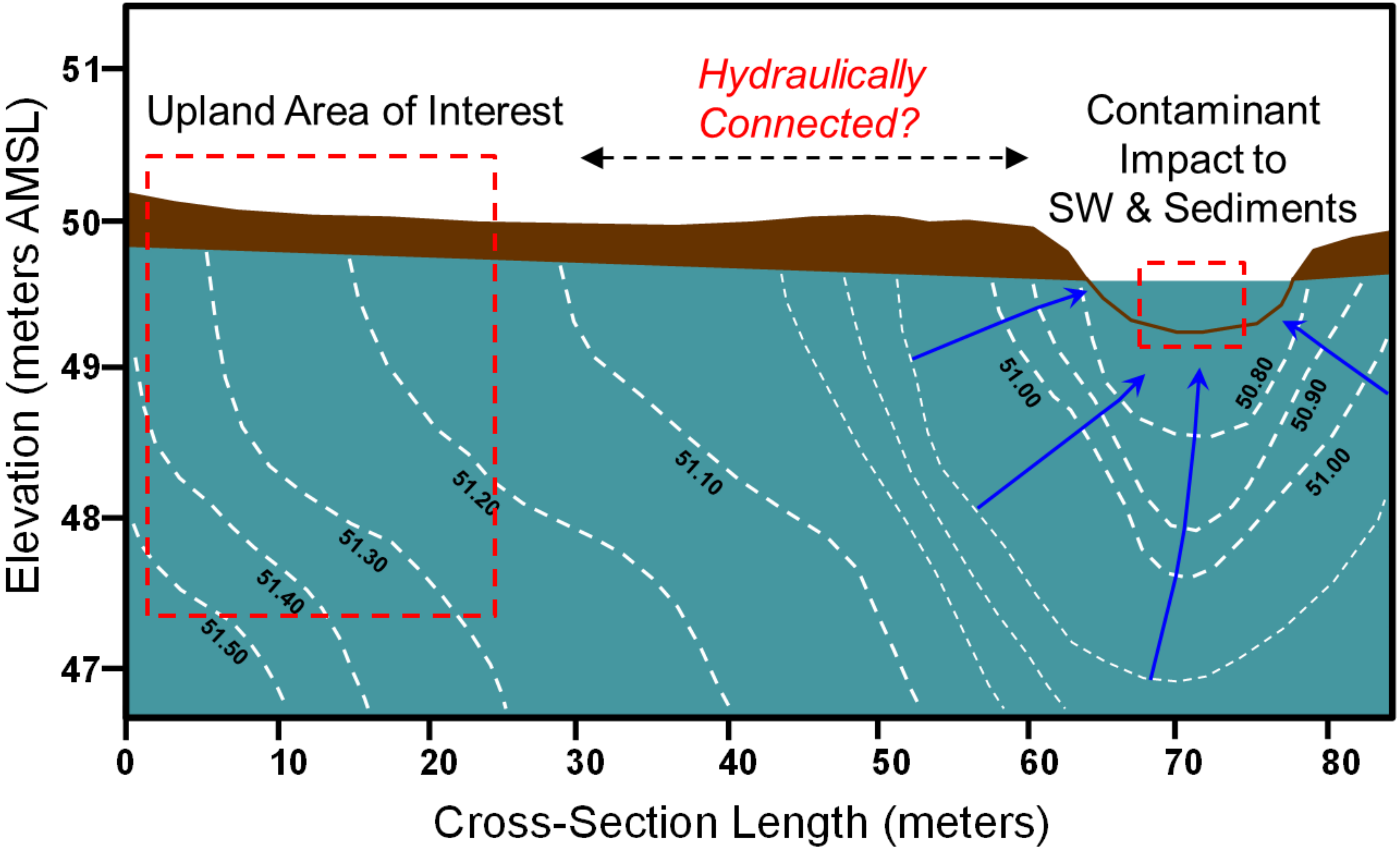
Plan for Presentation

- Context for evaluating water and contaminant flux from upland groundwater to downgradient surface water bodies
- Tools for assessing hydraulic pathway from groundwater to surface water
- Tools Implementation – Site Case Study (Arsenic)

Conceptual Site Model



Conceptual Site Model

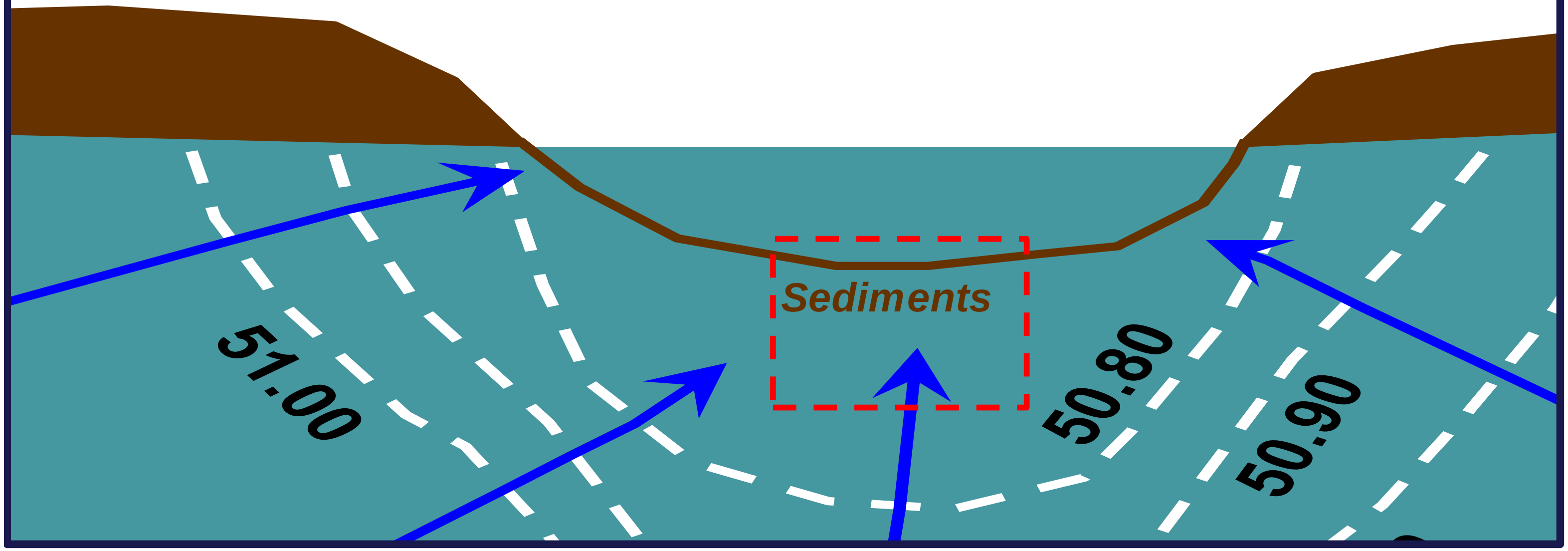


Conceptual Site Model

Questions at the GW/SW Transition Zone:

- Spatial variation of exchange flow?
- Temporal variability of exchange flow?
- Magnitude and direction of exchange flow?

- ***Can we identify and track plume discharge?***

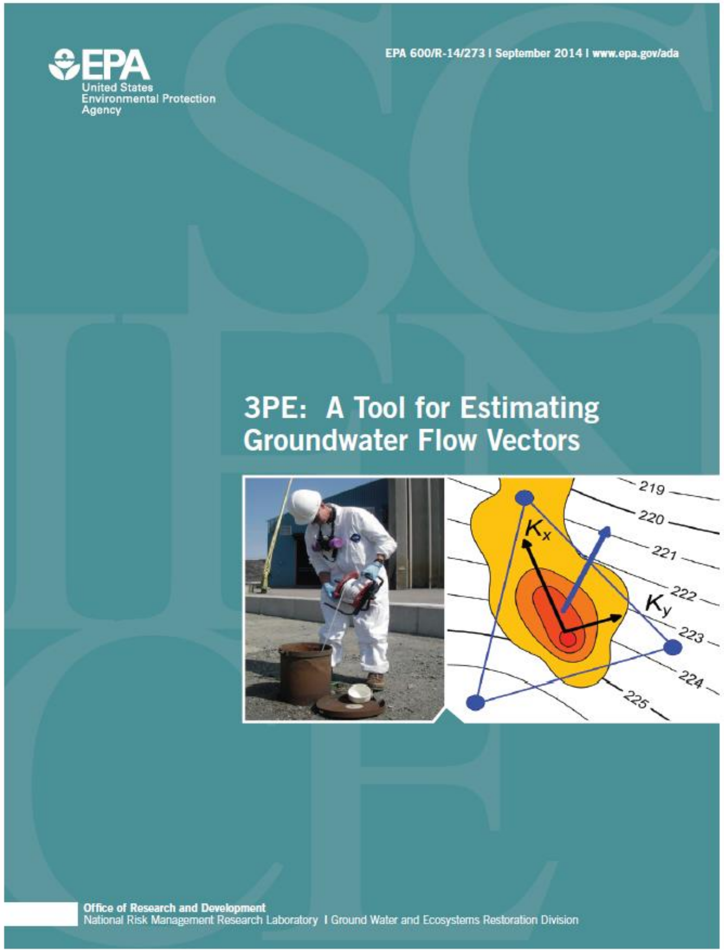


Upland Groundwater

Characterization Tools – Upland GW

- Install monitor wells or piezometers
  - Determine groundwater elevation
  - Determine aquifer properties
  - Measure groundwater chemistry
- Determine flow direction and magnitude
  - Calculate groundwater potentiometric surface from a network of wells/piezometers (sitewide)
  - Calculate flow gradient and direction for a subset of wells/piezometers (targeted)
  - **3PE: A Tool for Estimating Groundwater Flow Vectors**

Characterization Tools – Upland GW



- EPA 600/R-14/273 September 2014
- Provides background and technical guidance on appropriate application of evaluation technology
- Provides spreadsheet-based analysis tool for calculating flow gradient, velocity, and direction from measured groundwater elevations

Characterization Tools – Upland GW

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3PE – Three Point Estimator

- Implementation of a three-point mathematical solution to calculate horizontal direction and magnitude of groundwater flow
- Applicable within portions of the groundwater flow field with a planar groundwater potentiometric surface
- Groundwater seepage velocity estimated using Darcy's Law
  - hydraulic gradient from 3PE calculation
  - estimates of hydraulic conductivity and effective porosity

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Characterization Tools – Upland GW

"3 Points" monitor wells/piezometer locations

Estimated/measured aquifer properties

Project:	SITE NAME
Location:	Location or Other Information
Date:	Date Range for Data or Other Information

Well Name	X Coordinate (L)	Y Coordinate (L)	
	Well Location		
RSK12	630,520.67	3,027,093.09	1
RSK15	630,585.33	3,027,062.01	1
RedCoveSW	630,653.23	3,027,174.78	1

Principal Hydraulic Conductivity Components		
K_{max} =	65.0000	(L/T)
K_{min} =	65.0000	(L/T)
Orientation of K_{max} =	90.00	(degrees from N)
θ =	0.00	(degrees from X axis)
Effective Porosity =	0.25	(-)

User input cells are shaded green.

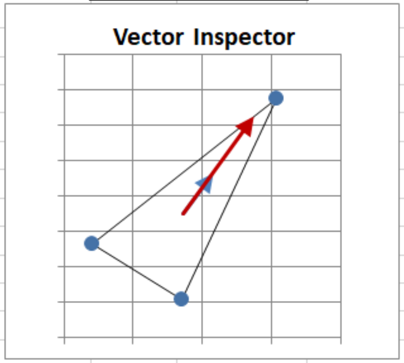
HYDRAULIC HEAD DATA SET MUST NOT CONTAIN BLANK LINES

Vector Inspector Row of Interest:	41
Must be between 22 and 66	

Statistics			
Head (L)	RSK12	RSK15	RedCoveSW
Maximum =	218.59	218.56	217.93
Minimum =	216.24	216.19	215.94
Average =	217.29	217.21	216.82
Range =	2.35	2.37	1.99

	Hyd. Grad. (L/L)	Velocity (L/T)
Maximum =	0.008335	2.167081
Minimum =	0.000558	0.144960
Average =	0.003210	0.834701

5/22/14 12:00 AM



Hydraulic Gradient Vector is BLUE

Groundwater Velocity Vector is RED

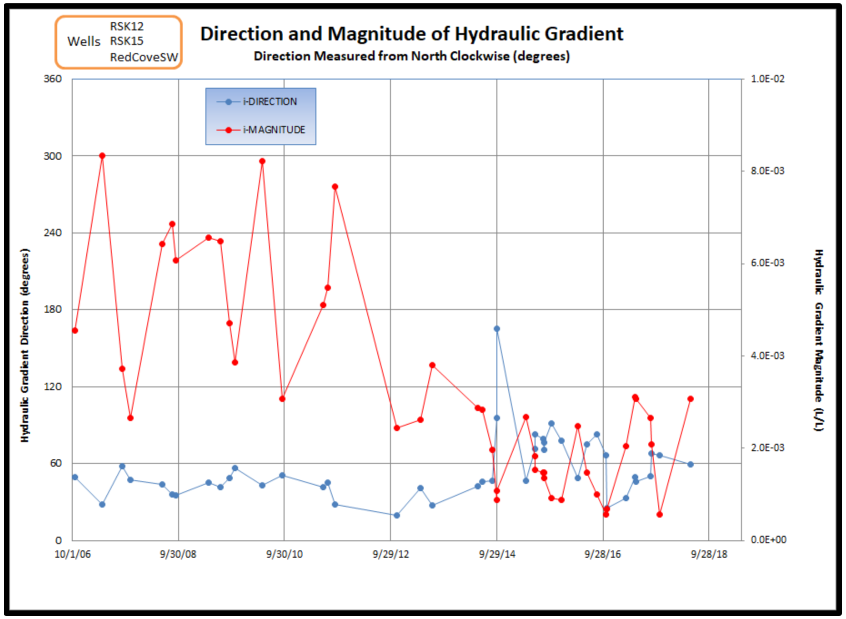
		Suggested Scaling Factors
Hyd. Grad. Scale Factor =	11,000.00	9,340.90
Velocity Scale Factor =	100.00	35.93

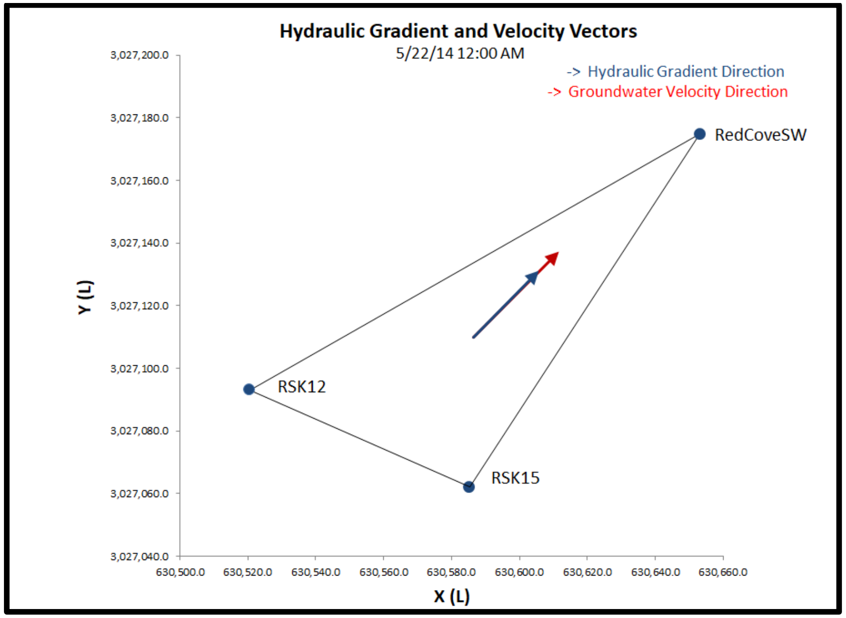
	Hydraulic Head (L)			Hydraulic Gradient		Groundwater Velocity		Angle Between Vectors	Head Drop (ft)	Planar Equation Constan	
Date/Time	RSK12	RSK15	RedCoveSW	Magnitude (L/L)	Direction (deg)	Magnitude (L/T)	Direction (deg)	(deg)		A	B
10/19/2006	218.03	217.90	217.33	0.004556	49.56	1.184458	49.56	0.00	0.70	-0.003467089	-0.00295514
4/26/2007	218.59	218.56	217.46	0.008335	28.48	2.167081	28.48	0.00	1.13	-0.003974909	-0.007326058
9/10/2007	217.77	217.63	217.19	0.003726	58.21	0.968636	58.21	0.00	0.58	-0.003166636	-0.001962636

"3 Points" – measured groundwater elevations

Characterization Tools – Upland GW

- 3PE Output for each round of synoptic measurements
  - Magnitude and direction of hydraulic gradient
  - Magnitude and direction of groundwater velocity





Characterization Tools

GW/SW Transition Zone (Surface Water Body)

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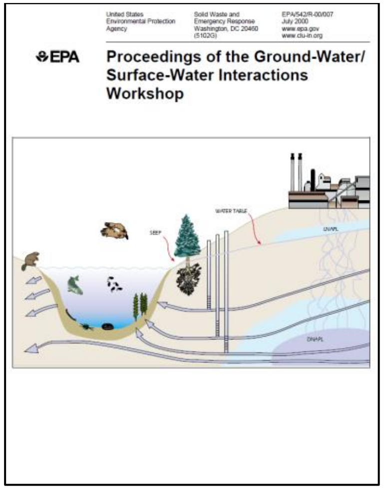
Characterization Tools – Transition Zone

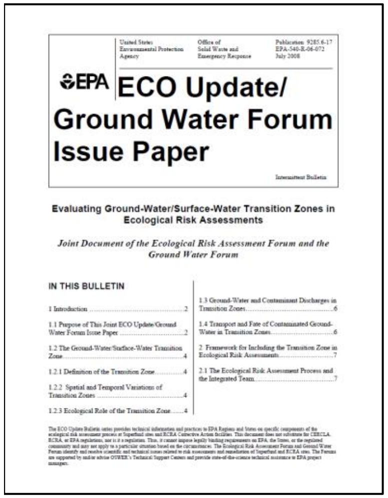
- **Qualitative Tools or Approaches (Where)**
  - Visual observations in surface water body (discolorations, sheens)
  - Detailed spatial chemistry sampling for contaminants or plume indicators
  - Detailed spatial geophysical measurements (resistivity, electromagnetic surveys)
  - Detailed spatial temperature contrast measurements (indirect or direct)
- **Critical first step to defining CSM and devising a site characterization network**

Characterization Tools – Transition Zone



United States Environmental Protection Agency | Solid Waste and Emergency Response Washington, DC 20460 (5102G) | EPA/542/R-00/007 July 2000 www.epa.gov www.clu-in.org

EPA Proceedings of the Ground-Water/ Surface-Water Interactions Workshop



United States Environmental Protection Agency | Office of Solid Waste and Emergency Response | Publication 9285.6-17 EPA-540-R-06-072 July 2006

EPA ECO Update/ Ground Water Forum Issue Paper

Intermittent Bulletin

Evaluating Ground-Water/Surface-Water Transition Zones in Ecological Risk Assessments

Joint Document of the Ecological Risk Assessment Forum and the Ground Water Forum

IN THIS BULLETIN

- Sources of Information
  - EPA-542-R-00-007, Proceedings of the Ground-Water/Surface-Water Interactions Workshop (Part 3 – Case Studies)
  - EPA-540-R-06-072, ECO Update/Ground Water Forum Issue Paper
  - EPA-600-R-10-015, Evaluating Potential Exposures to Ecological Receptors Due to Transport of Hydrophobic Organic Contaminants in Subsurface Systems

Characterization Tools – Transition Zone

- **Quantitative Tools (How Much & Direction)**
  - Flow balance calculations to estimate GW contribution to baseflow (quantity)
  - Piezometer-Stilling Well installations in surface water body (direction, quantity estimate)
  - Seepage meter measurements: snap-shots or continuous (quantity and direction)
  - 1D-2D-3D Groundwater-Surface Water flow models (major undertaking; data intensive)
  - **Quantify Seepage Flux using Sediment Temperatures**

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Characterization Tools – Transition Zone

- EPA 600/R-15/454 December 2014
- Provides background and technical guidance on appropriate application of technology
- Illustrates use of spreadsheet-based analysis tools for calculating seepage flux magnitude and direction from sediment temperature profile data

Modeling Seepage Flux

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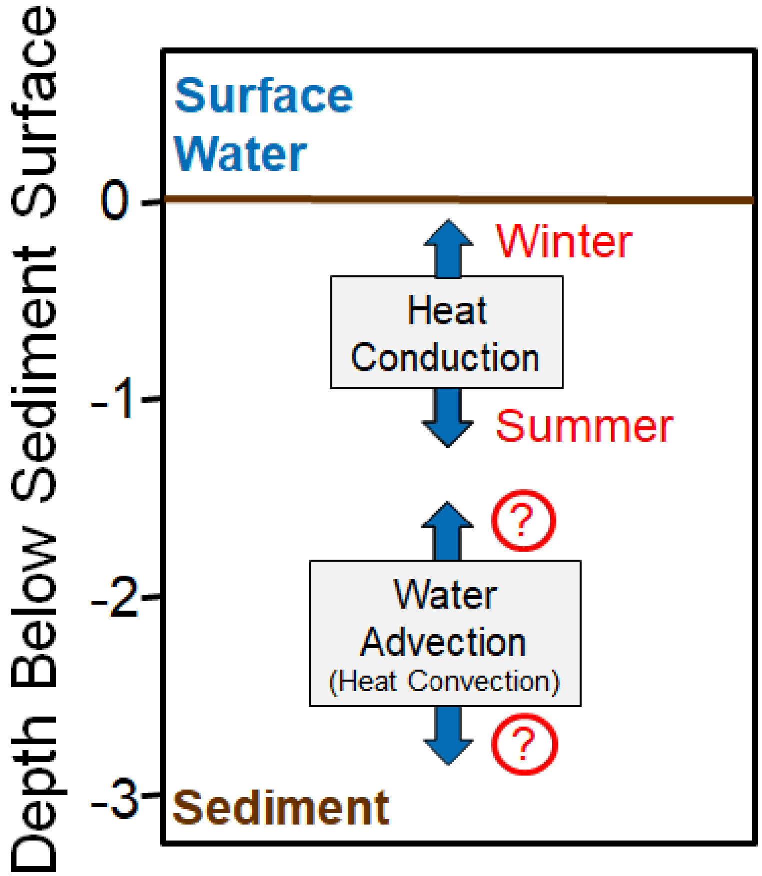
Seepage Flux Calculations

- Theoretical basis for heat flux modeling has been around for decades
- Several modeling programs have been developed in either freeware format or free plugins for commercial software programs
- Wide variety of commercial devices available to measure temperature and other sediment properties (model input parameters)
  - Range of accuracy and resolution for temperature (price range)
  - Snap-shot versus continuous logging capabilities

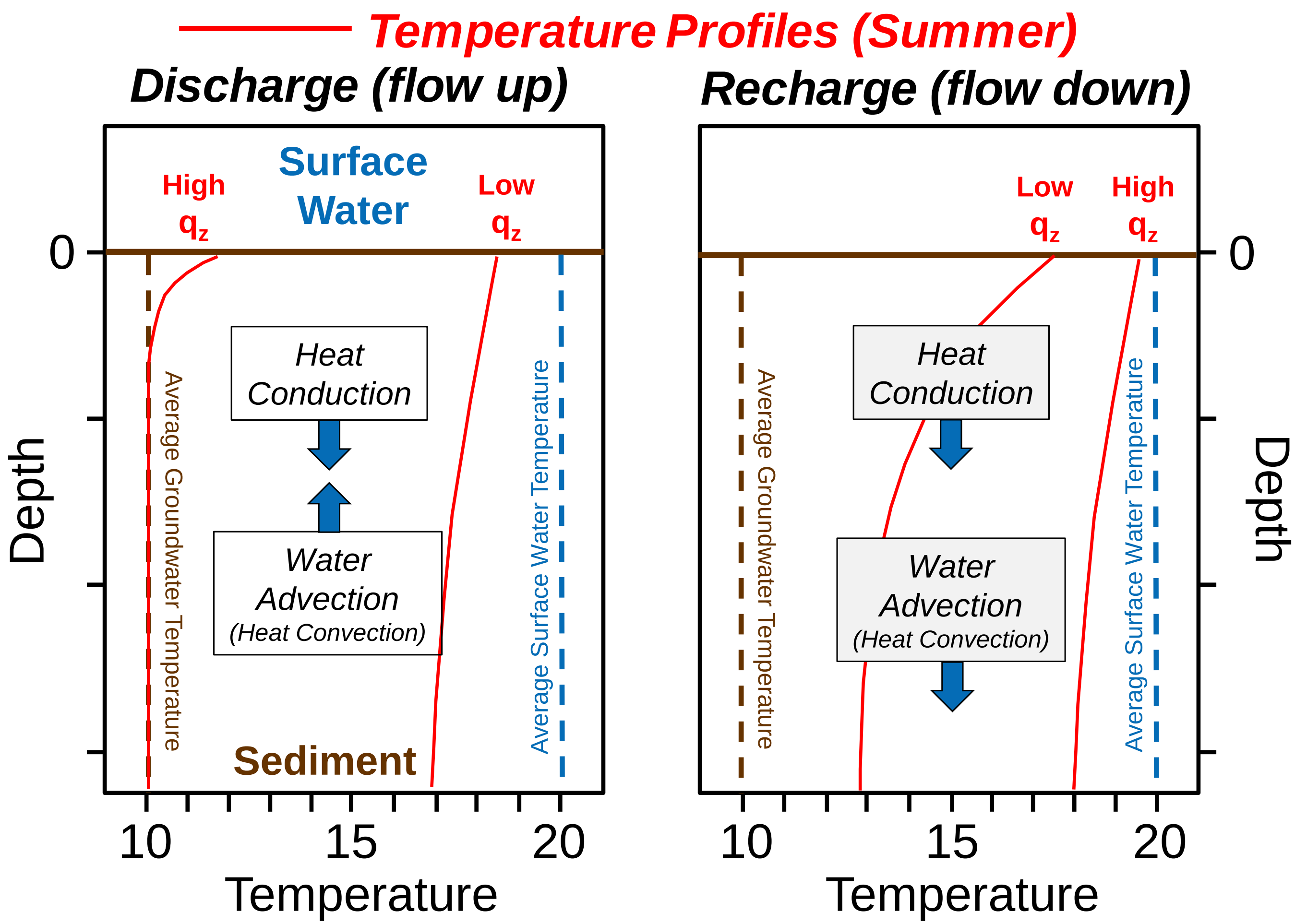
Modeling Seepage Flux



- Heat conduction influenced by GW-SW temperature gradient
- Heat convection influenced by flow up (discharge) or flow down (recharge)
- Shape of temperature profile influenced by magnitude and direction of GW flow

Adapted from: Conant (2004) Ground Water, 42:243-257

Modeling Seepage Flux



Adapted from: Conant (2004) Ground Water, 42:243-257

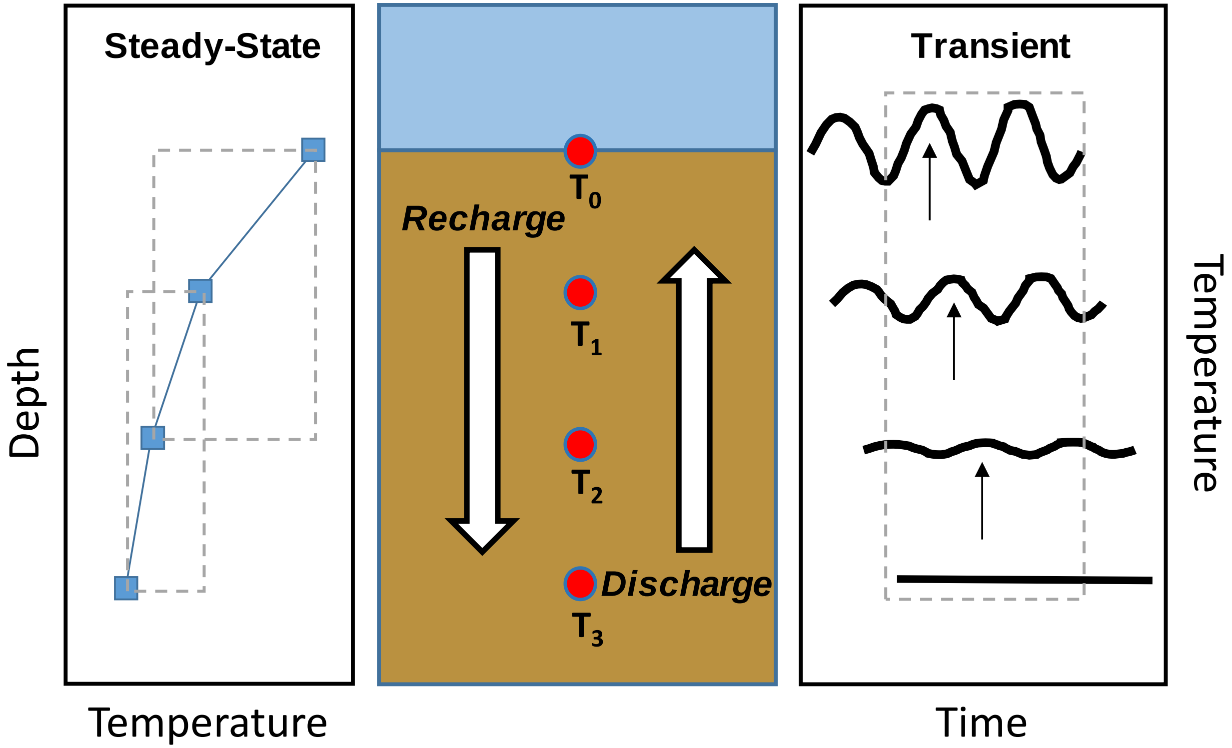
Modeling Seepage Flux

Seepage Flux Calculations: Two principal modeling approaches

- Steady-State Models based on temperature gradient
  - Contrast between SW and GW temperature
  - Temperature at minimum of 3 depths
- Transient Models based on propagation of daily (diurnal) temperature cycle down sediment profile
  - Dependent on usable diurnal temperature signal from two depths
  - Change in amplitude and timing for diurnal signal across depth interval

Modeling Seepage Flux

- Steady-State and Transient Model Systems
  - temperature contrast across vertical boundaries
  - sediment properties (heat transport, transmissivity)
  - direction and magnitude of seepage flow

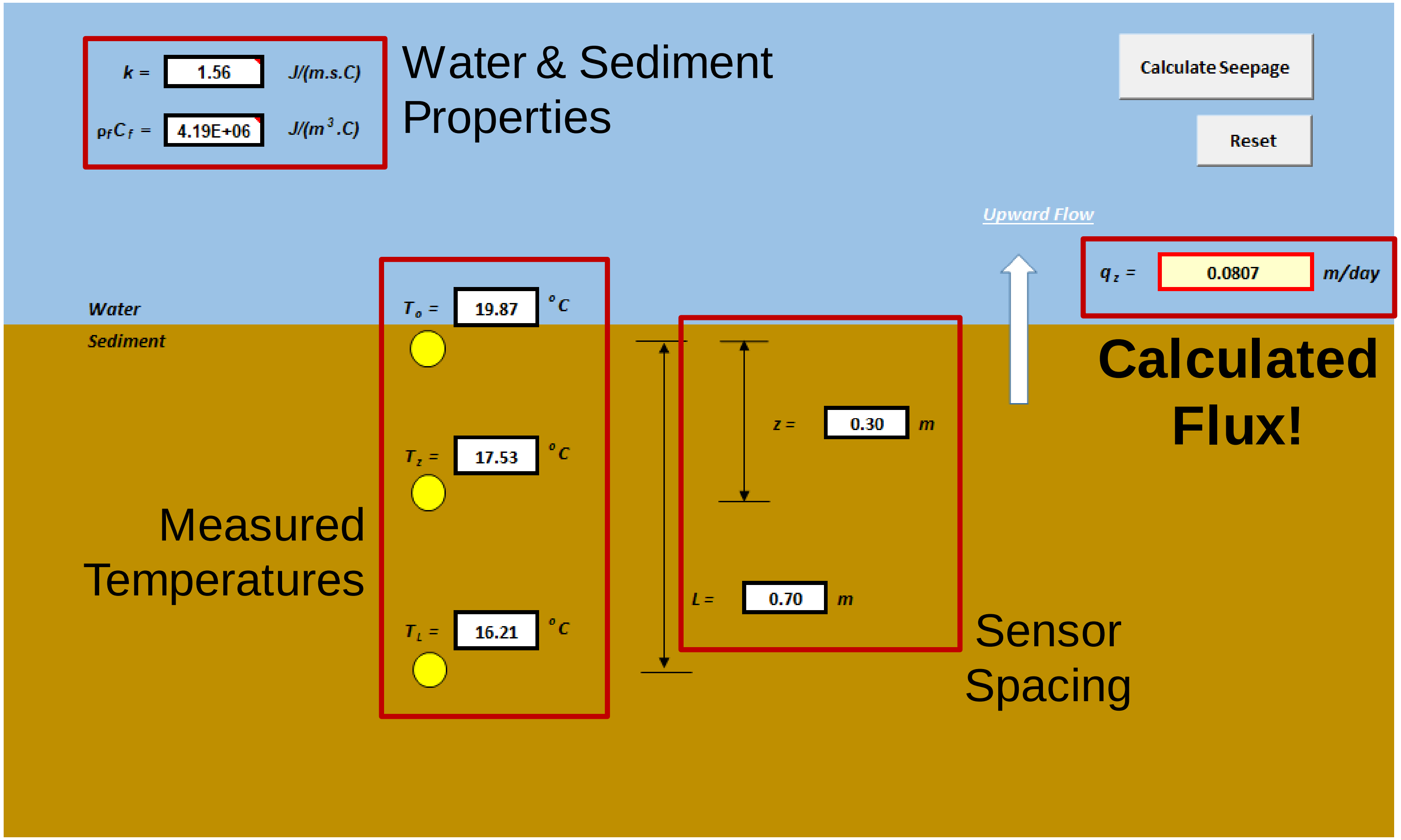


Modeling Seepage Flux

- Spreadsheet-based models that implement calculations using several derived analytical solutions
- Steady-State Models
  - Schmidt et al (2007) 2 sediment depths + regional GW temperature
  - Bredehoeft and Papadopulos (1965) 3 sediment depths
- Transient Models
  - McCallum et al (2012) 2 sediment depths, diurnal amplitude ratio and phase shift
  - Hatch et al (2006) 2 sediment depths, only diurnal amplitude ratio
- Output from models is equivalent to Darcy Flux (specific discharge)

Modeling Seepage Flux

- Steady-State Workbook - Spreadsheet-based calculation tool



Modeling Seepage Flux

- Transient Workbook - Spreadsheet-based calculation tool

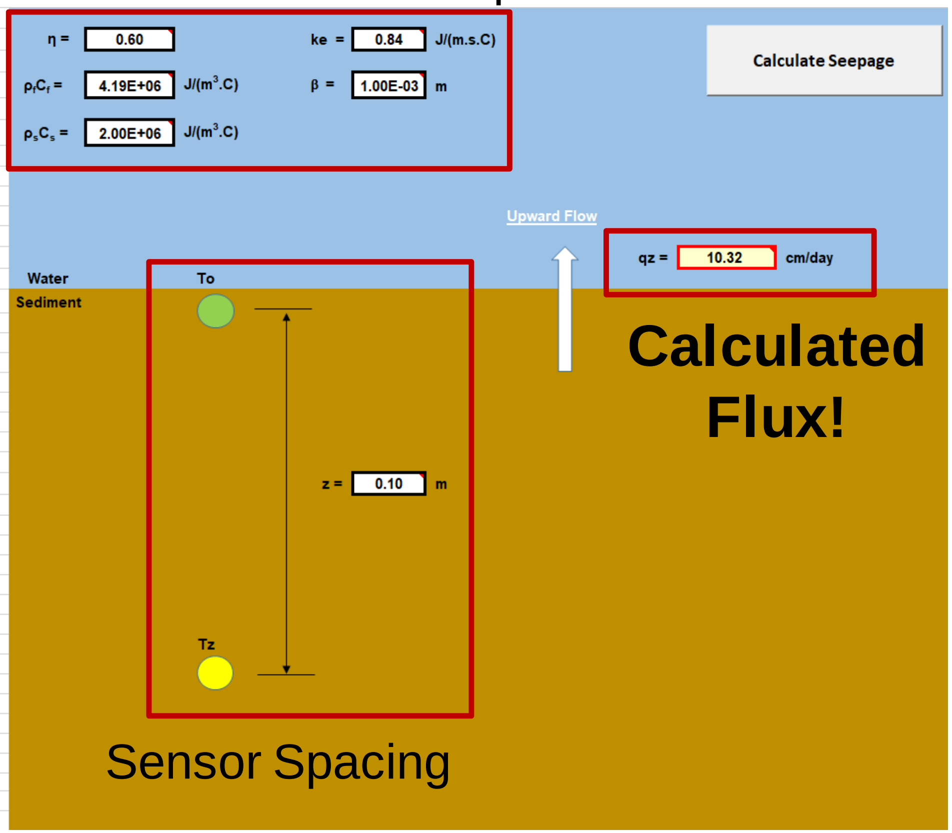
Water & Sediment Properties

SITE NAME:
LOCATION ID:
DESCRIPTION:

NOTE: This Model requires a temperature time-series of 24-hour duration & a minimal of 12 samples per 24-hour-period.

Clear Time-Series Data

Temperature Time-Series of To		Temperature Time-Series of Tz	
Date/Time	To	Date/Time	Tz
m/d/yyyy h:mm	°C	m/d/yyyy h:mm	°C
7/12/2014 0:00	24.51	7/12/2014 0:00	21.07
7/12/2014 1:00	24.38	7/12/2014 1:00	21.07
7/12/2014 2:00	24.20	7/12/2014 2:00	21.07
7/12/2014 3:00	24.07	7/12/2014 3:00	21.07
7/12/2014 4:00	23.88	7/12/2014 4:00	21.01
7/12/2014 5:00	23.70	7/12/2014 5:00	21.01
7/12/2014 6:00	23.51	7/12/2014 6:00	20.94
7/12/2014 7:00	23.45	7/12/2014 7:00	20.94
7/12/2014 8:00	23.45	7/12/2014 8:00	20.88
7/12/2014 9:00	23.63	7/12/2014 9:00	20.82
7/12/2014 10:00	23.95	7/12/2014 10:00	20.82
7/12/2014 11:00	24.26	7/12/2014 11:00	20.82
7/12/2014 12:00	24.51	7/12/2014 12:00	20.82
7/12/2014 13:00	24.70	7/12/2014 13:00	20.82
7/12/2014 14:00	24.82	7/12/2014 14:00	20.88
7/12/2014 15:00	24.88	7/12/2014 15:00	20.88
7/12/2014 16:00	24.88	7/12/2014 16:00	20.94
7/12/2014 17:00	24.88	7/12/2014 17:00	20.94
7/12/2014 18:00	24.76	7/12/2014 18:00	21.01
7/12/2014 19:00	24.63	7/12/2014 19:00	21.01
7/12/2014 20:00	24.51	7/12/2014 20:00	21.07
7/12/2014 21:00	24.45	7/12/2014 21:00	21.07
7/12/2014 22:00	24.32	7/12/2014 22:00	21.07
7/12/2014 23:00	24.20	7/12/2014 23:00	21.07
7/13/2014 0:00	24.13	7/13/2014 0:00	21.01



Measured Temperatures (24-hour period)

Modeling Seepage Flux

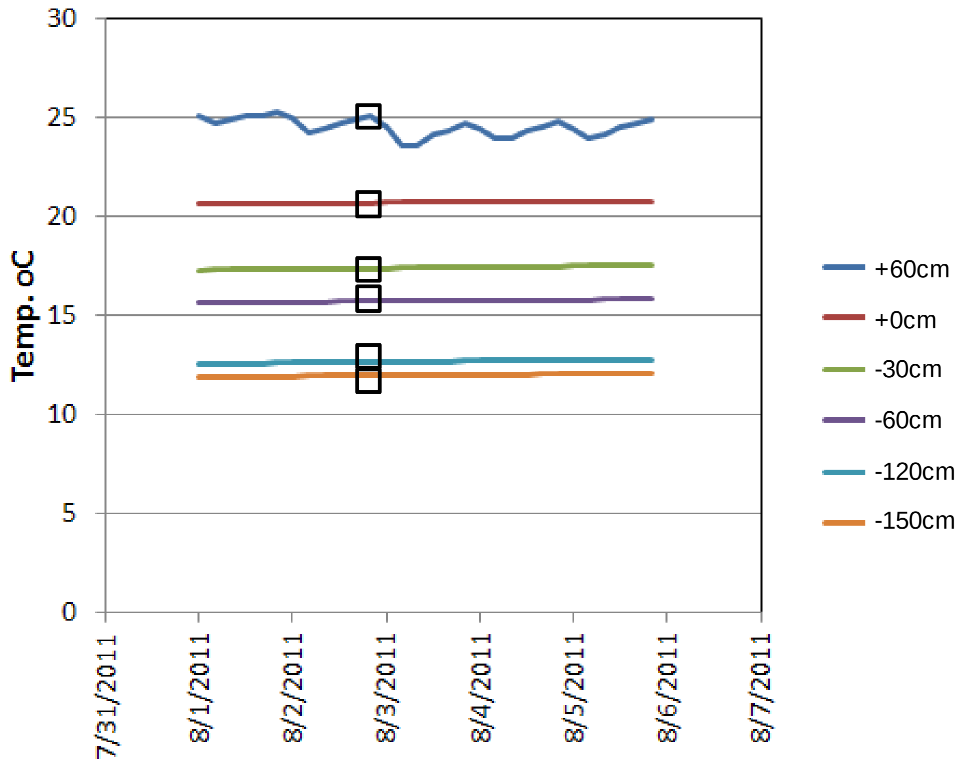
Temperature Profile Data

- Sensors have non-volatile memory & programmed for unattended data acquisition
- Temperature monitoring network installed in 1-2 days
- Deployed for 2-3 months & retrieved in 1 day – data downloaded and analyzed using Workbook Tool

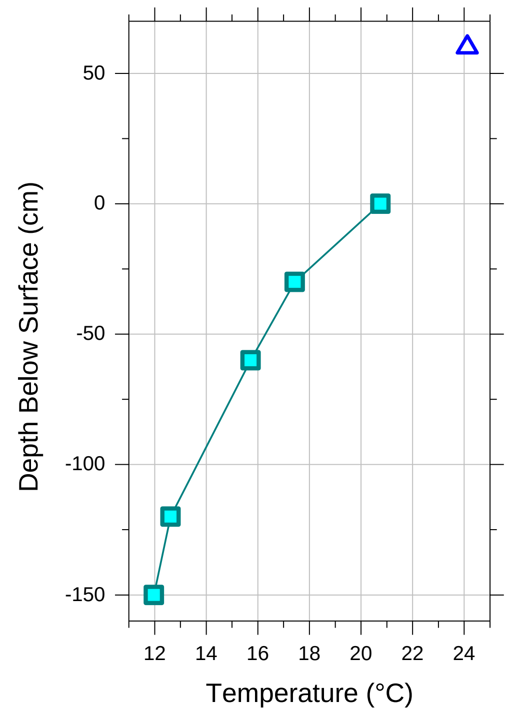
Modeling Seepage Flux

- Data collection can be configured to allow potential use of both model types

Continuous temperature logs…



Give daily temperature profiles



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Tools Development & Implementation

Steven Acree

Methods and best practices for measuring groundwater hydraulics; 3PE Workbook (with Milovan Beljin)

Robert Ford

Methods and best practices for measuring seepage flux in surface water bodies

Bob Lien

Seepage Flux Workbooks

Randall Ross

Equipment development for sediment temperature profile data acquisition; 3PE Workbook (with Milovan Beljin)

Tools Development & Implementation

Standard Operating Procedures (Internal EPA/ORD)

- Upland Groundwater
  - Elevation Surveys (very critical in low gradient areas)
  - Slug Tests (manual, pneumatic) to assess hydraulic conductivity of screened aquifer interval
  - Manual Water Level measurements
  - Use of Automated Pressure Transducers/Data Loggers for continuous records of water level measurements

- These measurements all present potential sources of error that need to be controlled as much as possible

- Presumes that the well/piezometer was properly constructed and developed to insure representative of aquifer condition

Tools Development & Implementation

Standard Operating Procedures (Internal EPA/ORD)

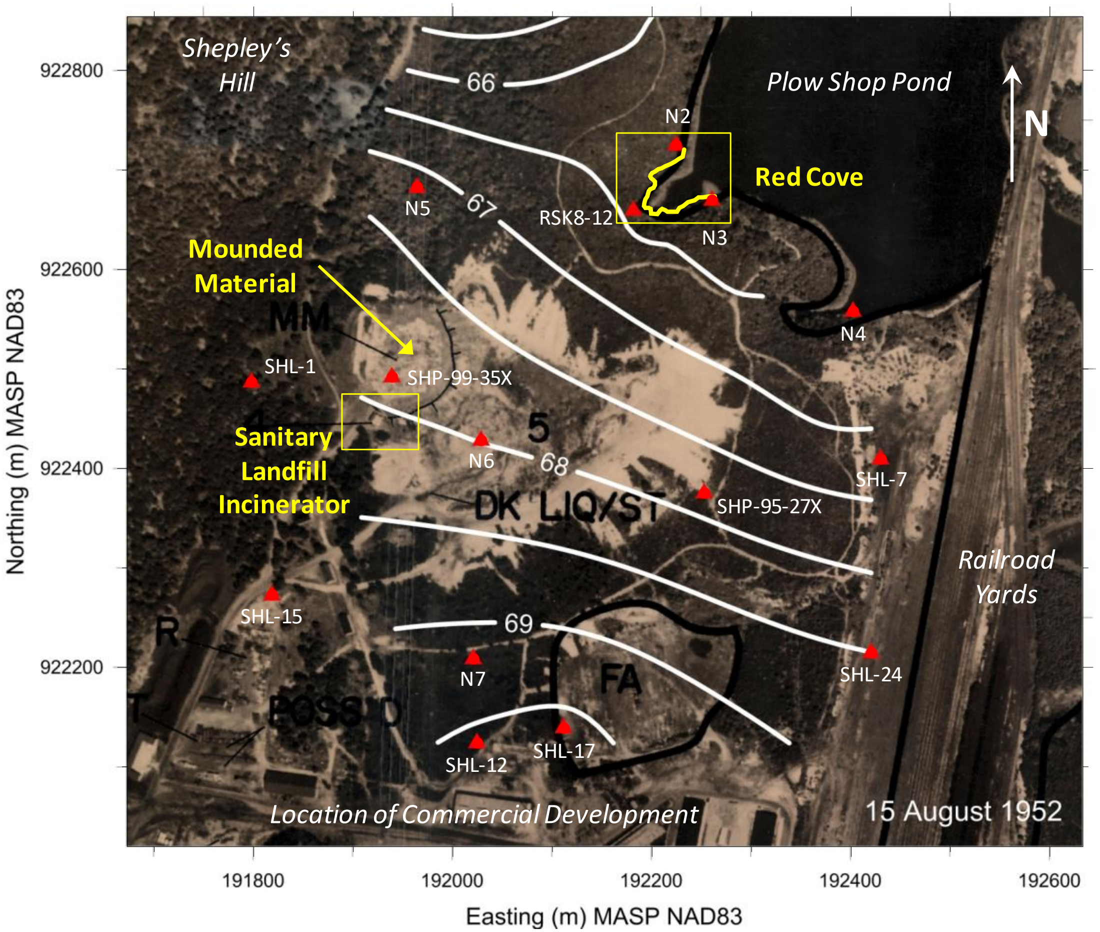
- Seepage Flux (Surface Water Body)
  - Installation of Temporary Piezometers with Stilling Wells to assess vertical gradient
  - Thermal Conductivity measurement for saturated sediments (important model input parameter)
  - Snap-Shot Temperature Profile measurement for submerged sediments (still a work in progress; issues with thermal conduction)
  - Sediment Temperature Profile Logging using commercial temperature logging devices (range of options; deployment configuration is important to insure usable data)
- Current EPA/ORD recommendation is to always try to collect an independent measure of vertical gradient

Application Illustration

- *Initial Site Characterization to Inform Remediation Design*
- *Monitoring Remedy Performance*

Application Illustration

(Former) Fort Devens Superfund Site

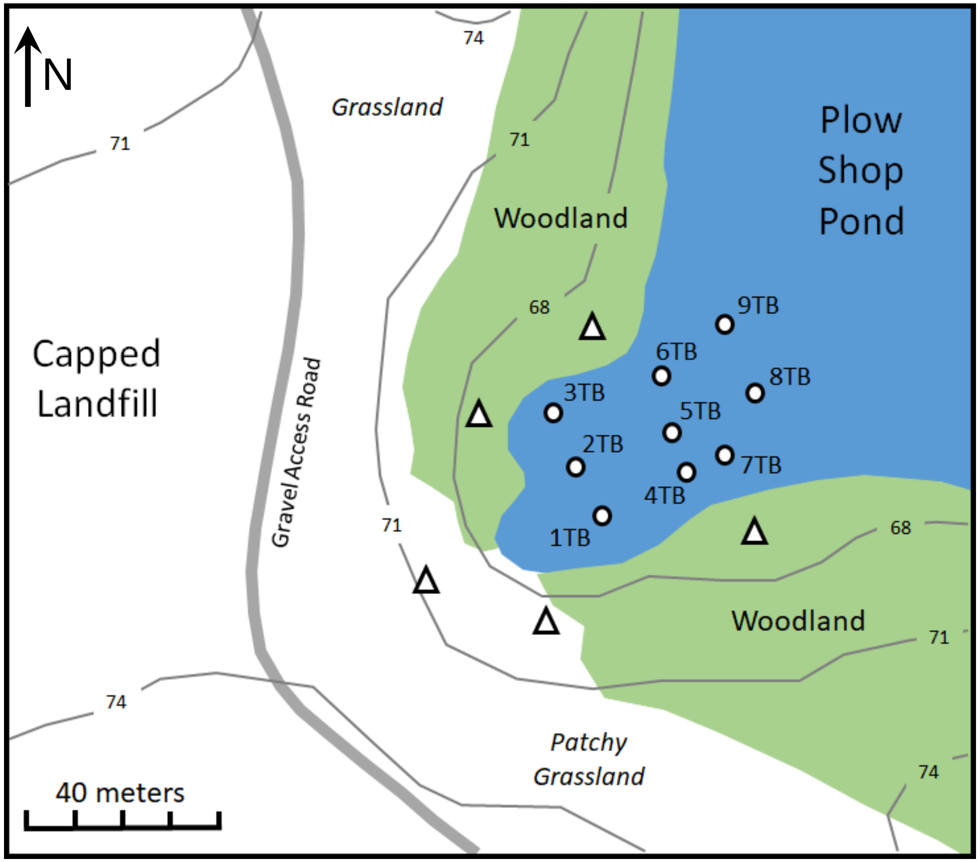


- Historical, un-lined landfill
- Arsenic contamination in GW derived from waste and natural sources
- Contaminated groundwater discharging to part of adjacent recreational lake

Ford et al (2011) Chemosphere, 85: 1525-1537

Application Illustration

△ Nested Piezometers, Cove Piezometers
○ Seepage Flux, Chemistry (Water & Sediment)

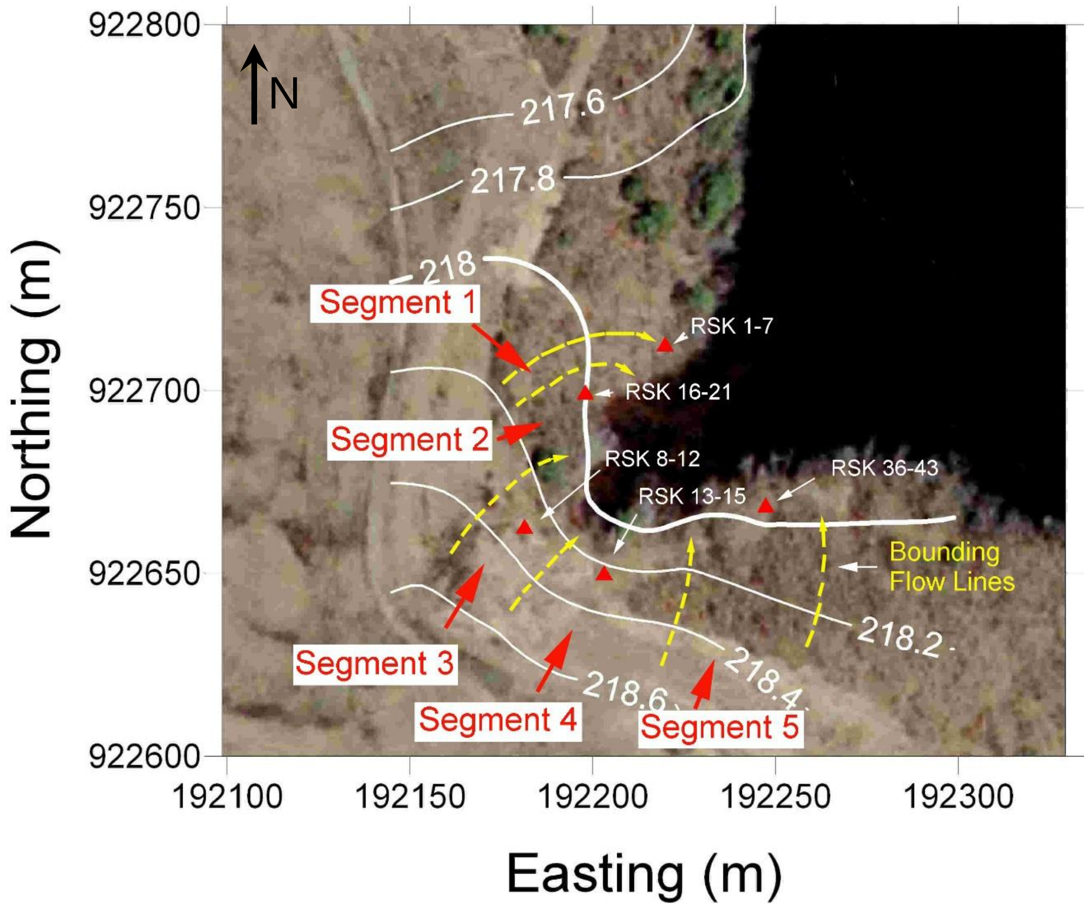


Monitoring Approach

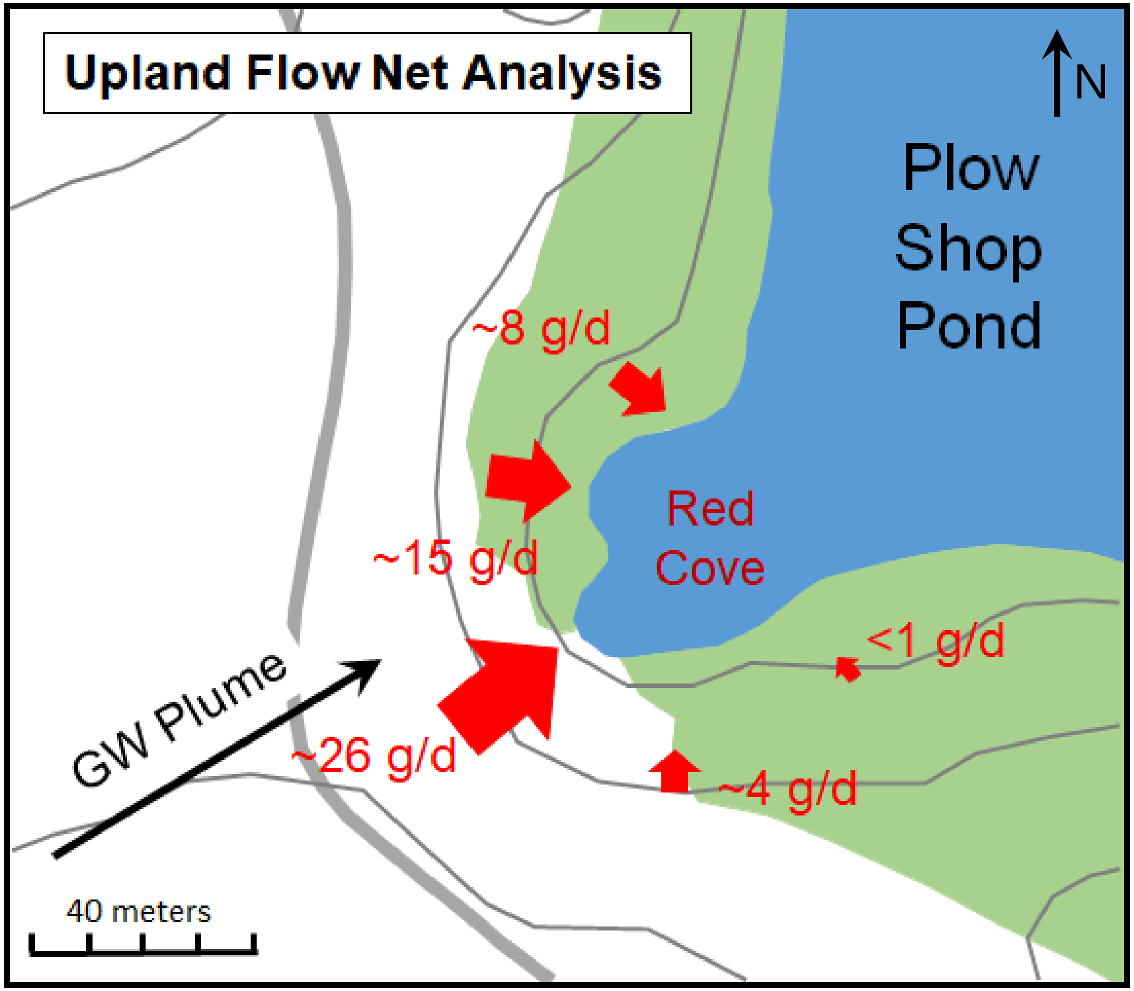
- GW hydrology and chemistry
- Flow gradient and seepage flux in cove
- SW chemistry
- Sediment chemistry

Application Illustration

Flow Net Analysis – GW Table from Site Wells



Application Illustration



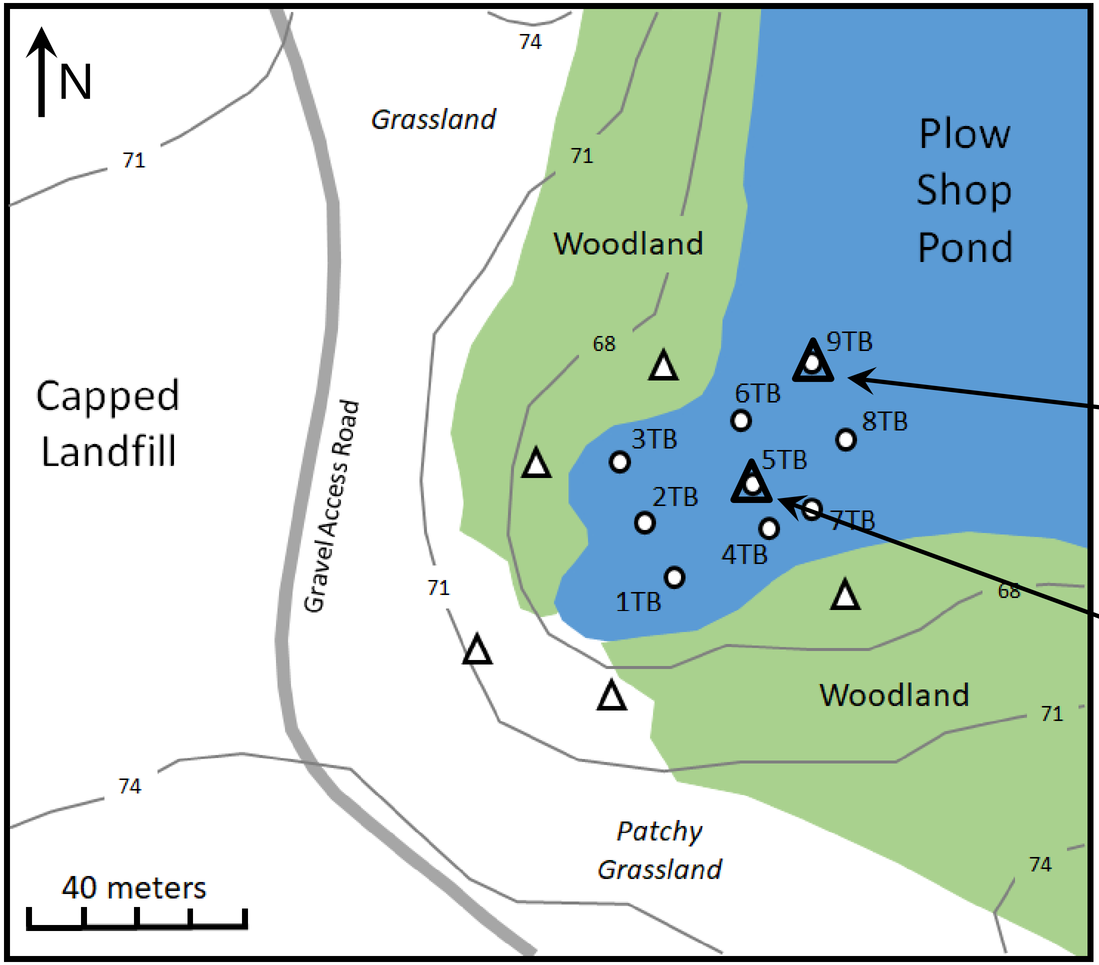
- Arsenic plume flowing from landfill toward cove
- Nested piezometers used to evaluate magnitude & distribution of arsenic flux

Application Illustration

Picture of cove from north shore

Picture at central cove from boat next to contaminated seepage area

Application Illustration



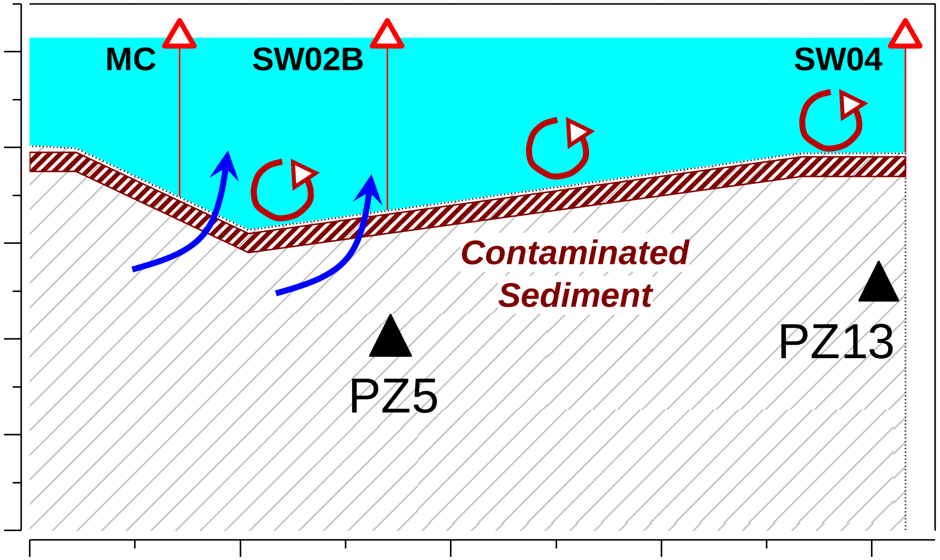
Seepage Flux Aug-Sep 2011

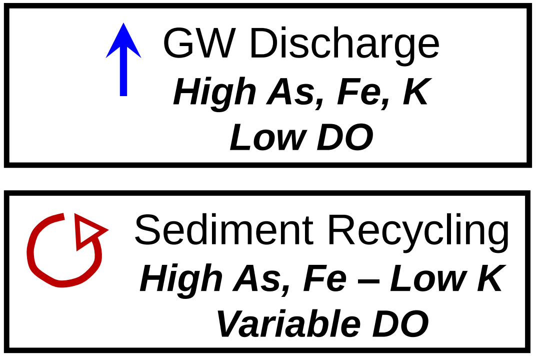
9TB (PZ13)
2.0 ± 0.9 cm/d

5TB (PZ5)
14.3 ± 1.0 cm/d

Application Illustration

What influences SW concentrations?





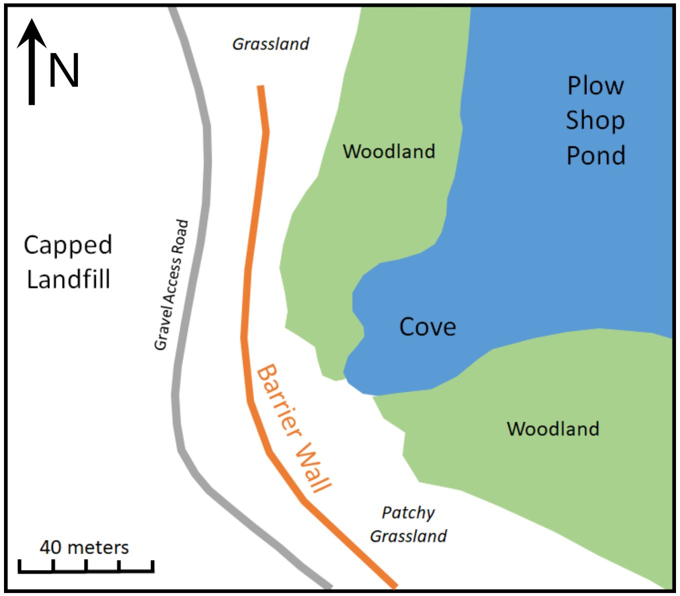
- Sediment arsenic concentrations variable within cove – correlate with iron
- PZ5 location shows sustained discharge with plume chemistry signature in deep SW
- PZ13 location shows variable discharge-recharge & no plume chemistry signature in deep SW

Application Illustration

- **Initial Site Characterization**
  - Does plume discharge to cove? [Yes]
  - Are sediments and surface water impaired by plume discharge? [Yes]
  - Unacceptable Human Health and Ecological Exposure Potential
- **Non-Time Critical Removal Action**
  - Cut off on-going contaminated GW discharge to the cove in Plow Shop Pond
  - Remove existing contaminated sediments derived from historical contaminated GW discharge

Application Illustration

Hydraulic Barrier Wall (2012)

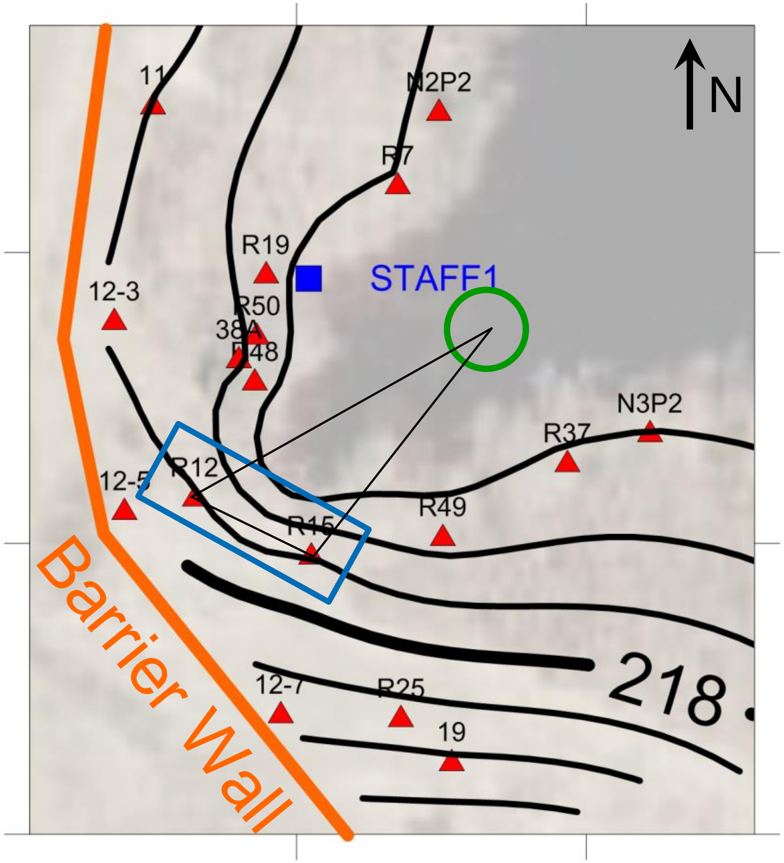


Sediment Removal in Cove (2013)

- **Monitoring Remedy Performance**
  - Does remedy influence GW-SW hydraulics?
  - Does groundwater show recovery trend?
  - Does surface water show recovery trend?

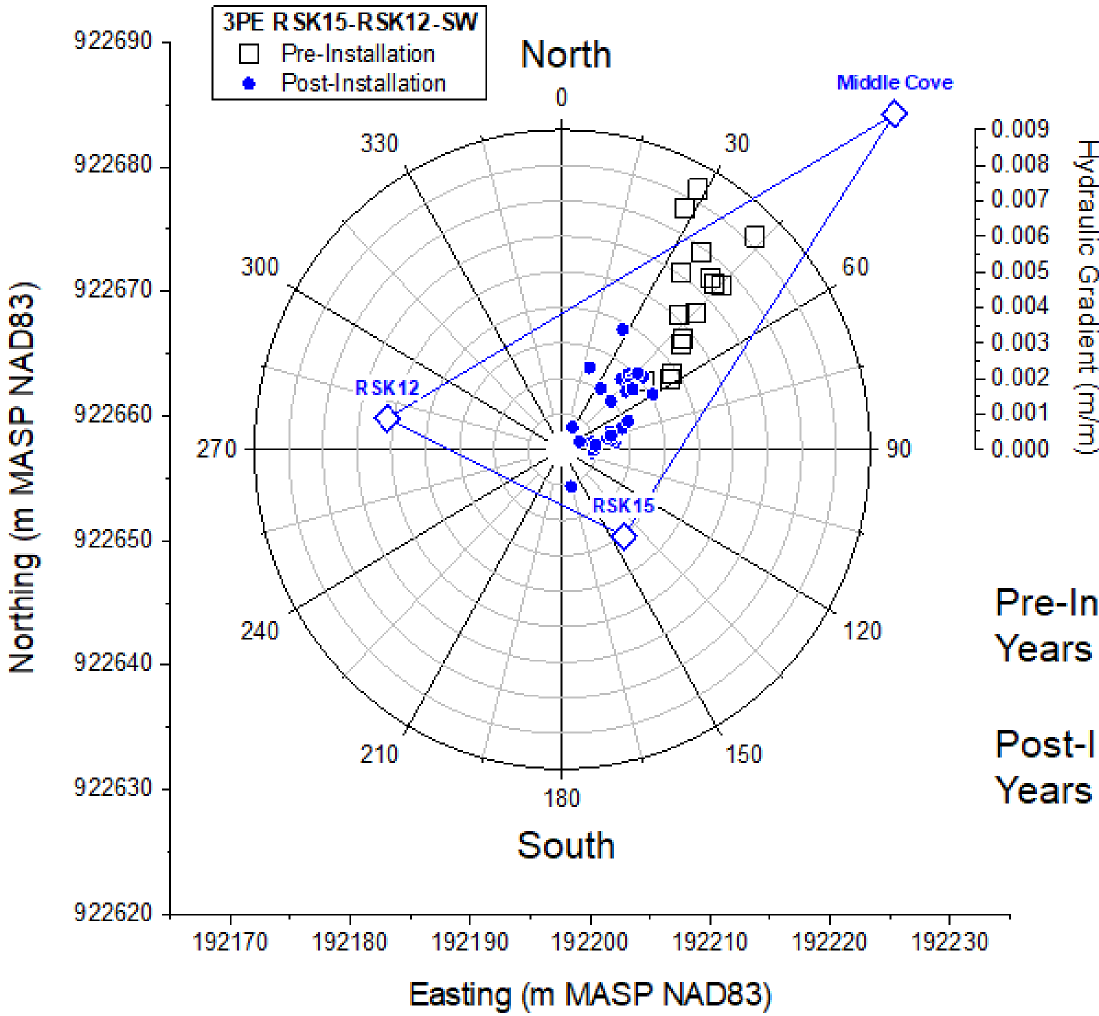
Application Illustration

GW Potentiometric Surface
9-10 July 2013 (0.2-ft contour)



- Limited monitoring during 2012-2013 due to remedy construction activities
- Upland GW monitoring recommenced 2012 (RSK12, RSK15, SW)
- Cove monitoring recommenced 2014 (green circle)

Application Illustration

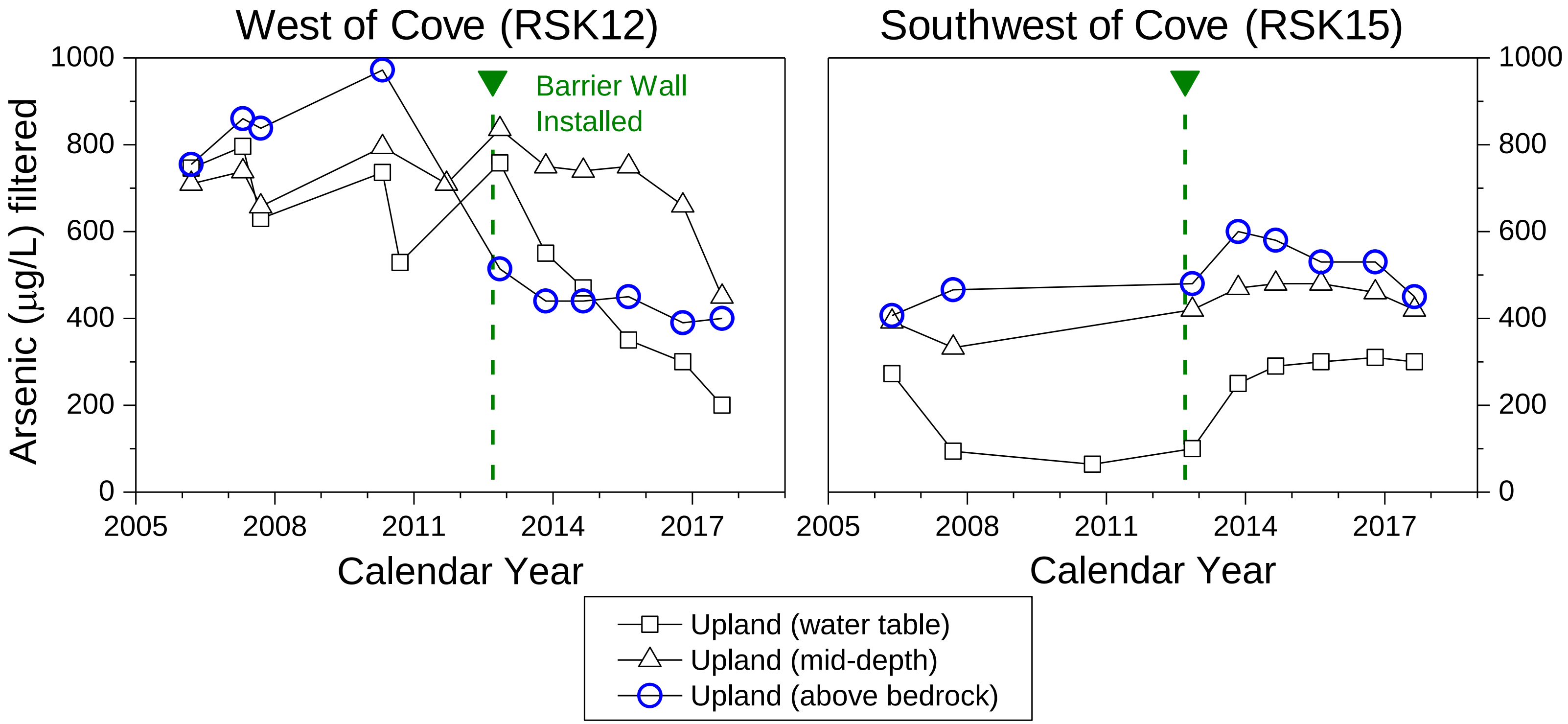


Pre-Installation
Years 2006-2011

Post-Installation
Years 2012-2018

Application Illustration

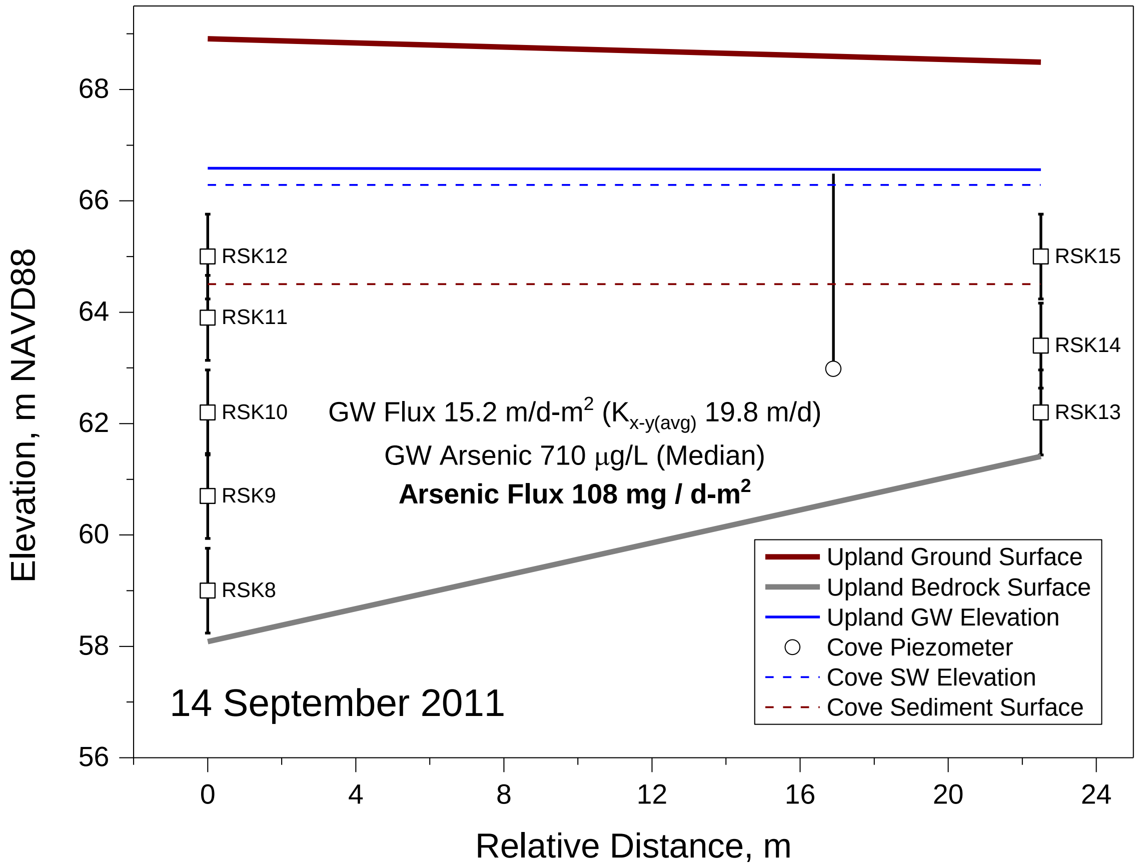
- GW arsenic concentrations decreasing in aquifer at primary area of contaminant flux (RSK12)
- Arsenic concentrations less changed southwest of cove (RSK15)



Application Illustration

- GW Flux = (3PE Seepage Velocity) x (Porosity)
- Arsenic Flux = (GW Flux) x (GW Concentration)

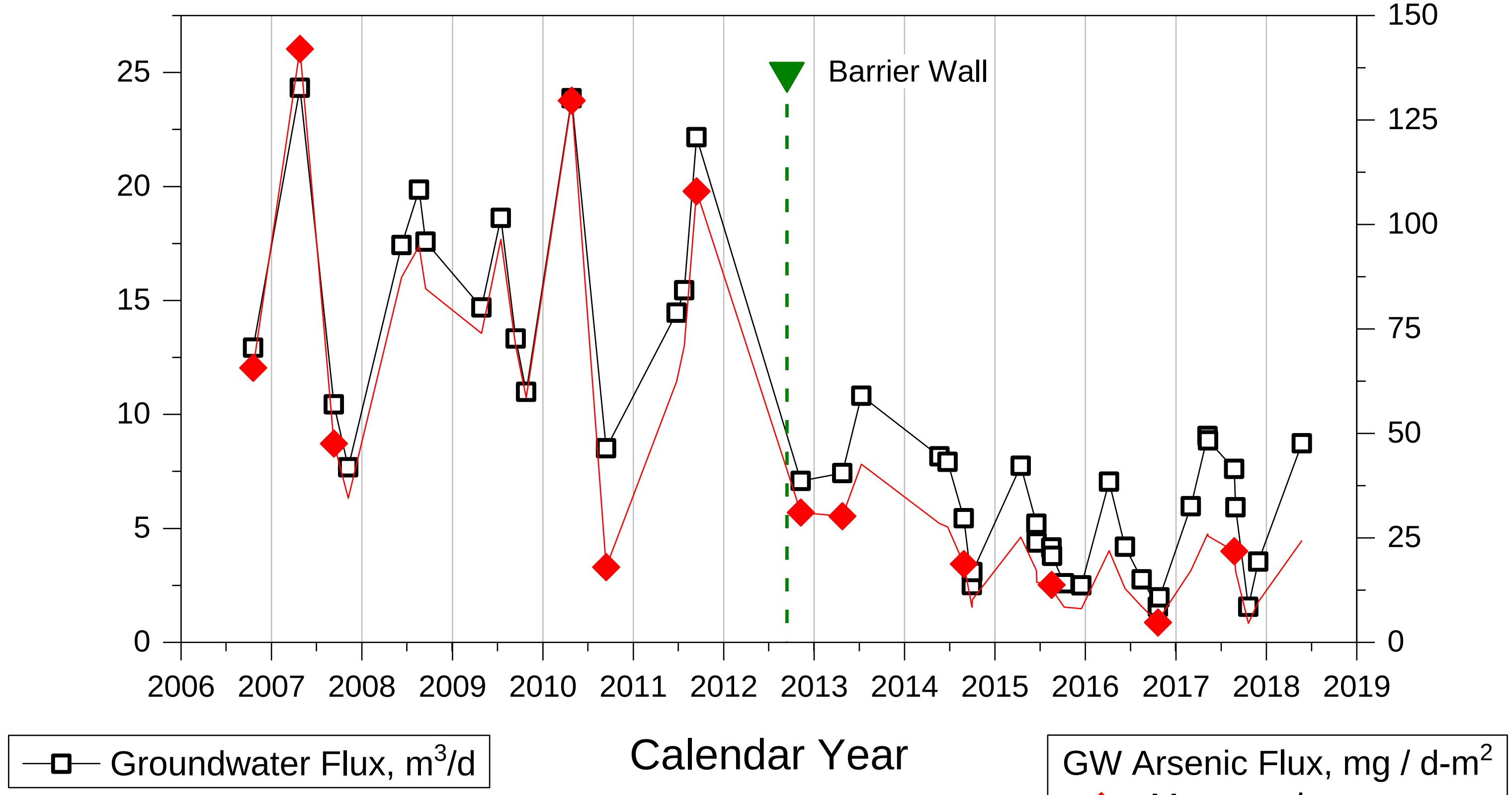
View from upland out to cove



Application Illustration

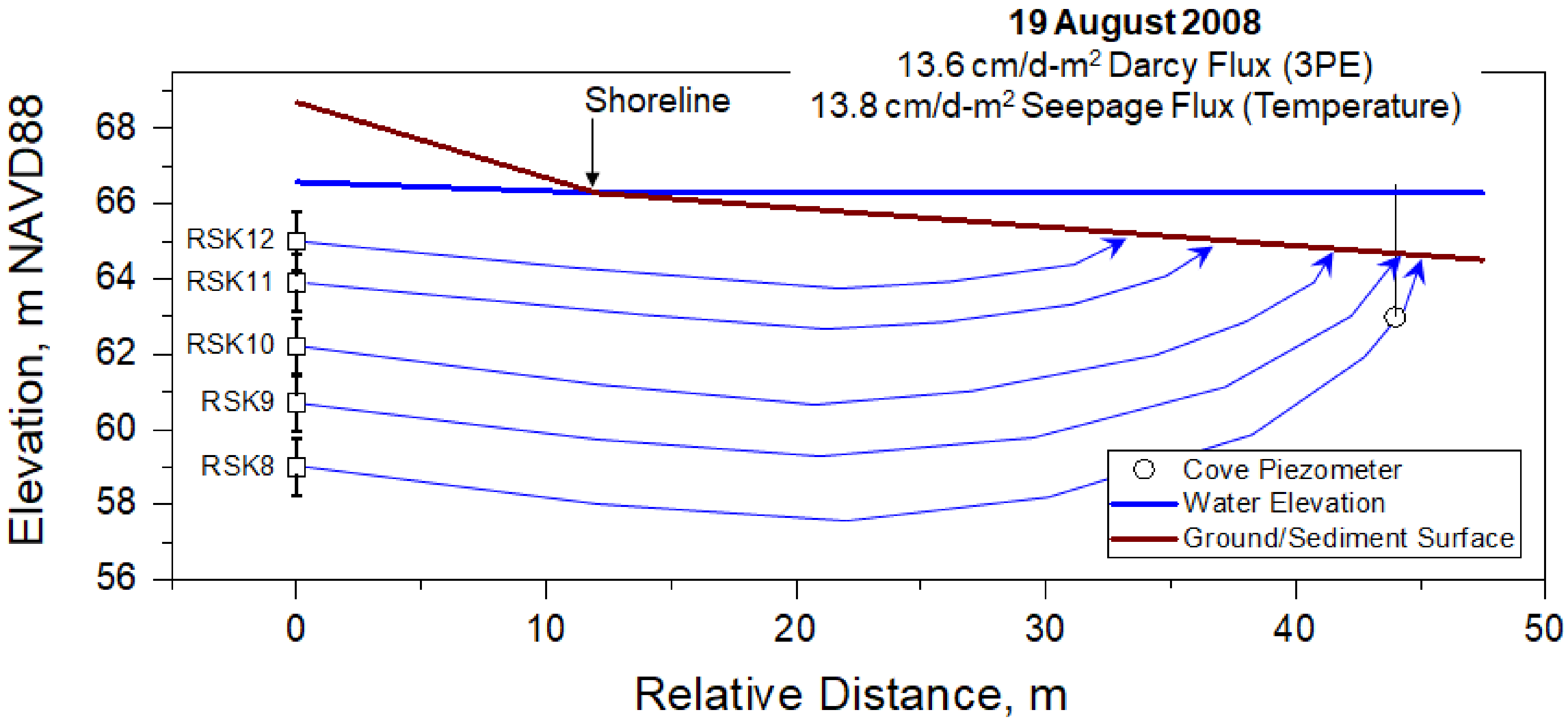
Median Flux Reduction Factors

Flow	2.9	Barium	7.6
Arsenic	4.3	Ammonium	12.8



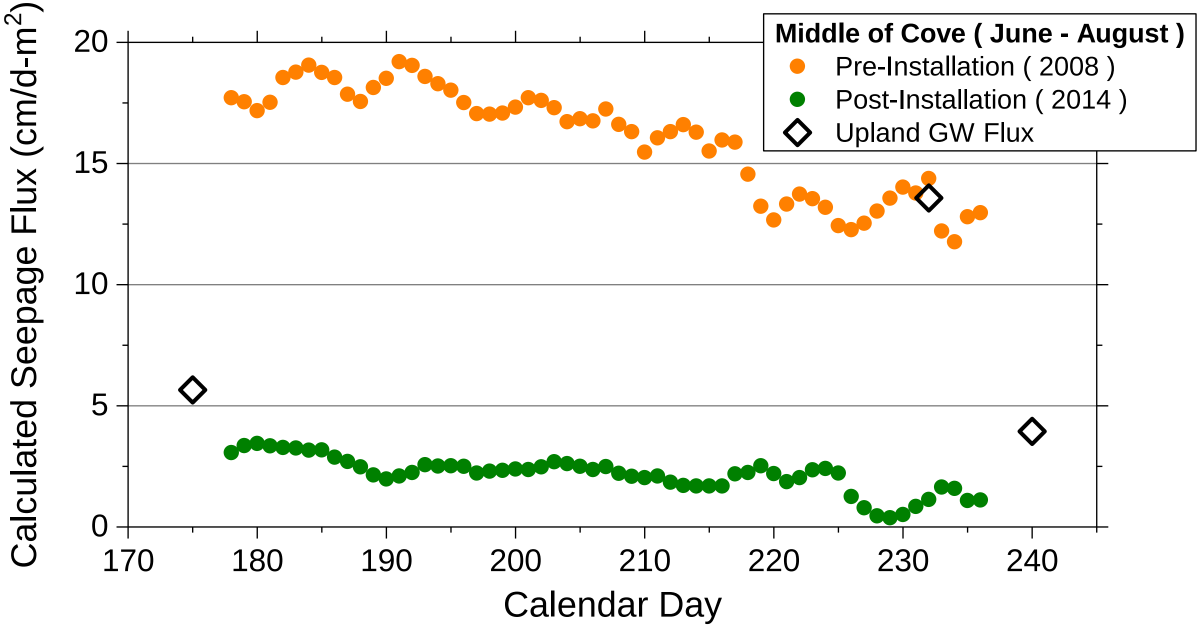
Application Illustration

- Compare upland GW flux to cove seepage flux
  – Darcy Flux (3PE) = "Effective Porosity" x "GW Velocity"
- Flow conservation indicates independent measures should be comparable

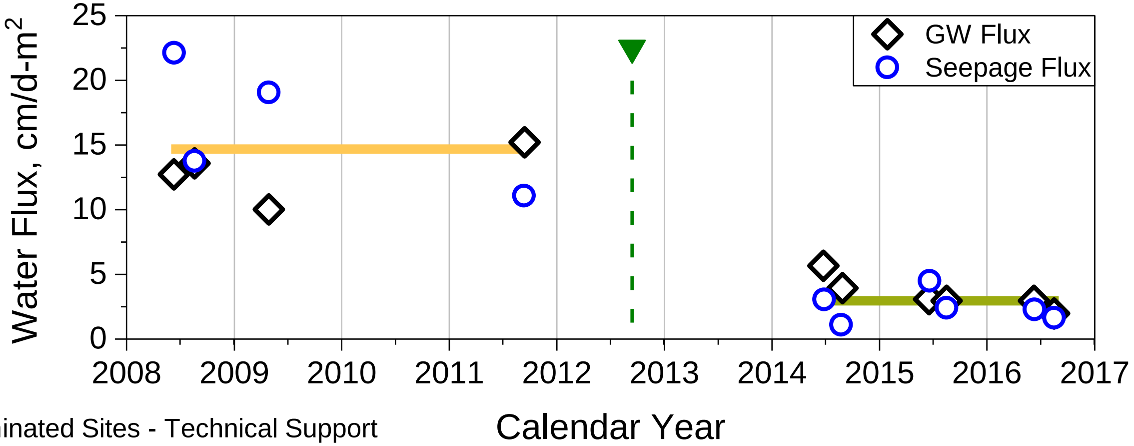


Application Illustration

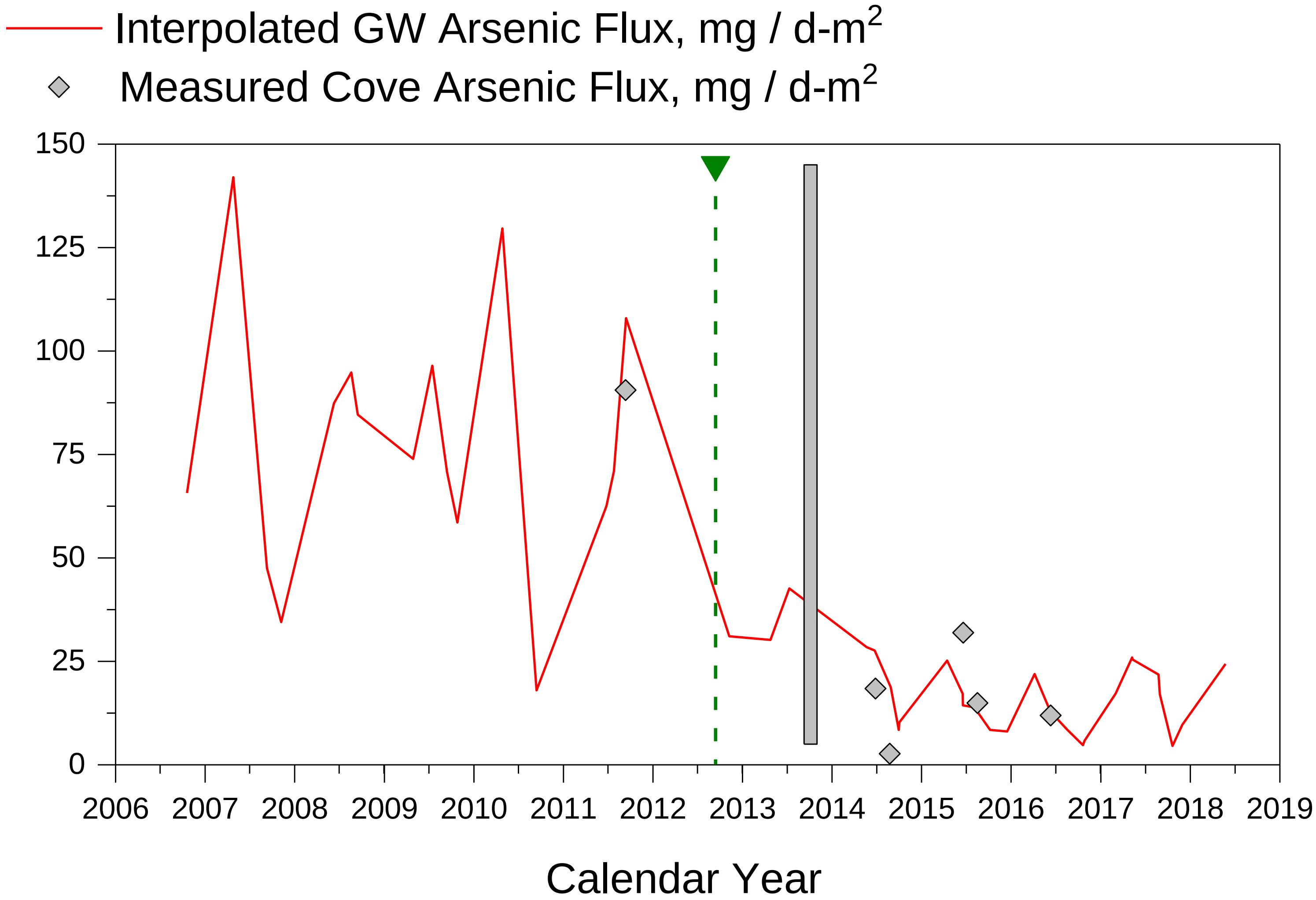
Sediment Temperature Profile Method



Comparison over entire monitoring period…

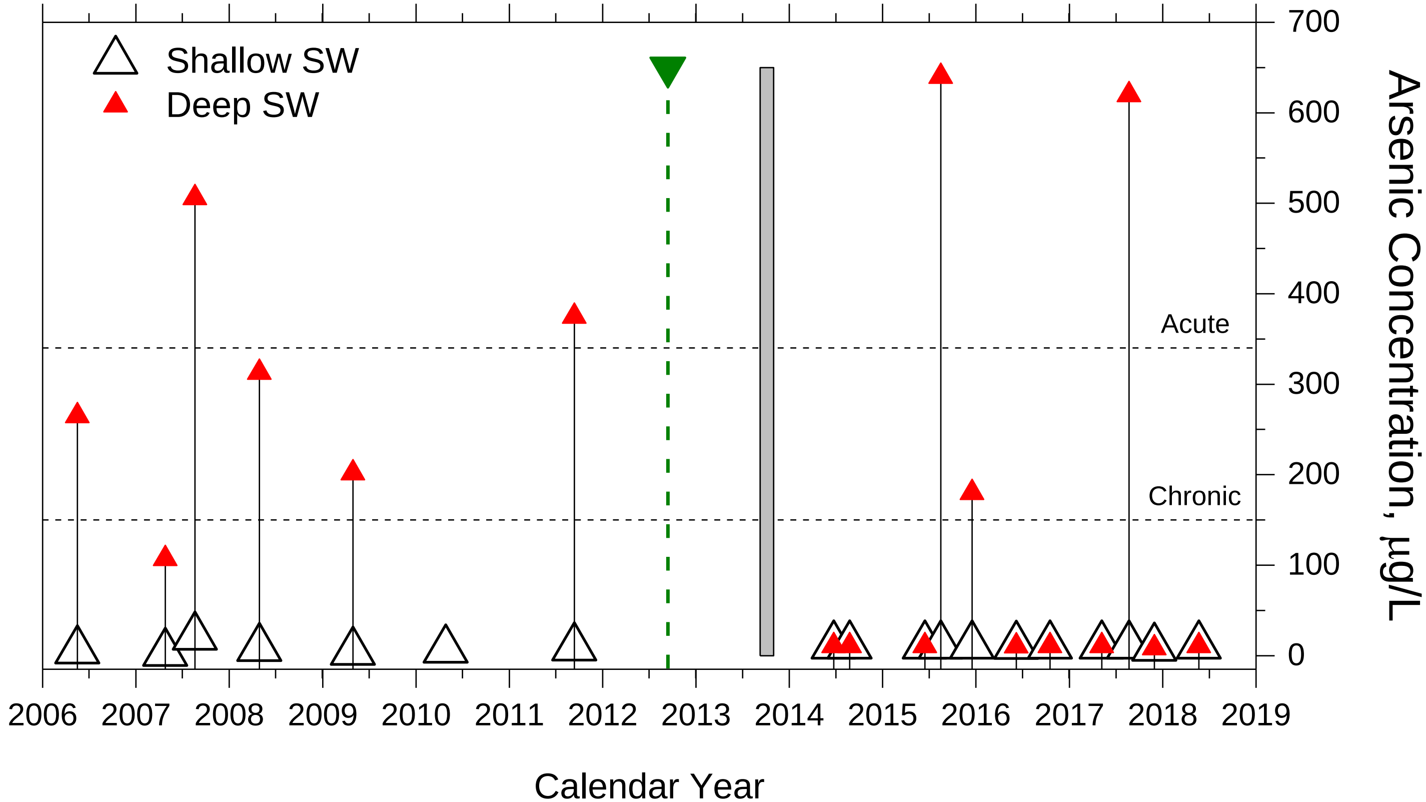


Application Illustration



Application Illustration

- Exceedances of Ambient WQ Criteria decreased in surface water
- Short-lived spikes due to sediment dissolution concurrent with NOM degradation



Application Illustration

Non-Time Critical Removal Action

BEFORE

AFTER

Application Illustration

- Evaluation of local groundwater flow conditions in upland GW and surface water body useful to interpret contaminant transport behavior
- This information can help guide design of the site characterization effort (e.g., sample locations) and remedy design
- *Seepage flux information needs to be tied to other lines of evidence or data types to understand contaminant behavior and facilitate site management decisions*

Application Illustration

- Methods to assess groundwater flow and seepage flux are relatively easy to implement and provide for great flexibility in site monitoring
- There is a range of equipment choices and mathematical tools that can be matched up with available resources
- Knowledge gained from determination of water flux benefits assessments of degradation, design of reclamation efforts, and monitoring of restoration success.

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