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## *Starting Soon*: Use and Measurement of Mass Flux and Mass Discharge

- Use and Measurement of Mass Flux and Mass Discharge (MASSFLUX-1, 2010) at http://www.itrcweb.org/GuidanceDocuments/MASSFLUX1.pdf
- Download PowerPoint file
  - Clu-in training page at https://clu-in.org/conf/itrc/ummfmd/
  - Under “Download Training Materials”
- Using Adobe Connect
  - Related Links (on right)
    - Select name of link
    - Click “Browse To”
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- Follow ITRC

No associated notes.

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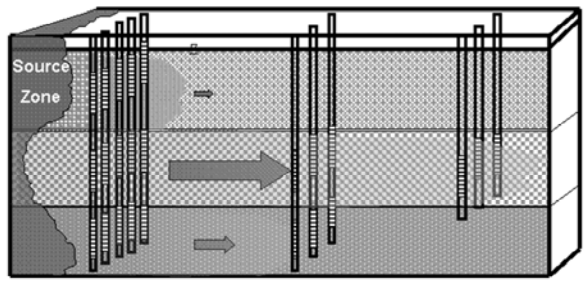
# Welcome – Thanks for joining this ITRC Training Class

## Use and Measurement of Mass Flux and Mass Discharge




An ITRC Technology Overview Document

Sponsored by: Interstate Technology and Regulatory Council (www.itrcweb.org)
Hosted by: US EPA Clean Up Information Network (www.cluin.org)

Most decisions at groundwater contamination sites are driven by measurements of contaminant concentration – snapshots of contaminant concentrations that may appear to be relatively stable or show notable changes over time. Decisions can be improved by considering mass flux and mass discharge. Mass flux and mass discharge quantify the source or plume strength at a given time and location resulting in better-informed management decisions regarding site prioritization or remedial design as well as lead to significant improvements in remediation efficiency and faster cleanup times. The use of mass flux and mass discharge is increasing and will accelerate as field methods improve and practitioners and regulators become familiar with its application, advantages, and limitations. The decision to collect and evaluate mass flux data is site-specific. It should consider the reliability of other available data, the uncertainty associated with mass flux measurements, the specific applications of the mass flux data, and the cost-benefit of collecting mass measurements.

The ITRC technology overview, Use and Measurement of Mass Flux and Mass Discharge (MASSFLUX-1, 2010), and associated Internet-based training provide a description of the underlying concepts, potential applications, description of methods for measuring and calculating, and case studies of the uses of mass flux and mass discharge. This Technology Overview, and associated Internet-based training are intended to foster the appropriate understanding and application of mass flux and mass discharge estimates, and provide examples of use and analysis. The document and training assumes the participant has a general understanding of hydrogeology, the movement of chemicals in porous media, remediation technologies, and the overall remedial process. Practitioners, regulators, and others working on groundwater sites should attend this training course to learn more about various methods and potential use of mass flux and mass discharge information.

ITRC (Interstate Technology and Regulatory Council) www.itrcweb.org

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  - **At Q&A breaks:** unmute your phone with #6 to ask out loud
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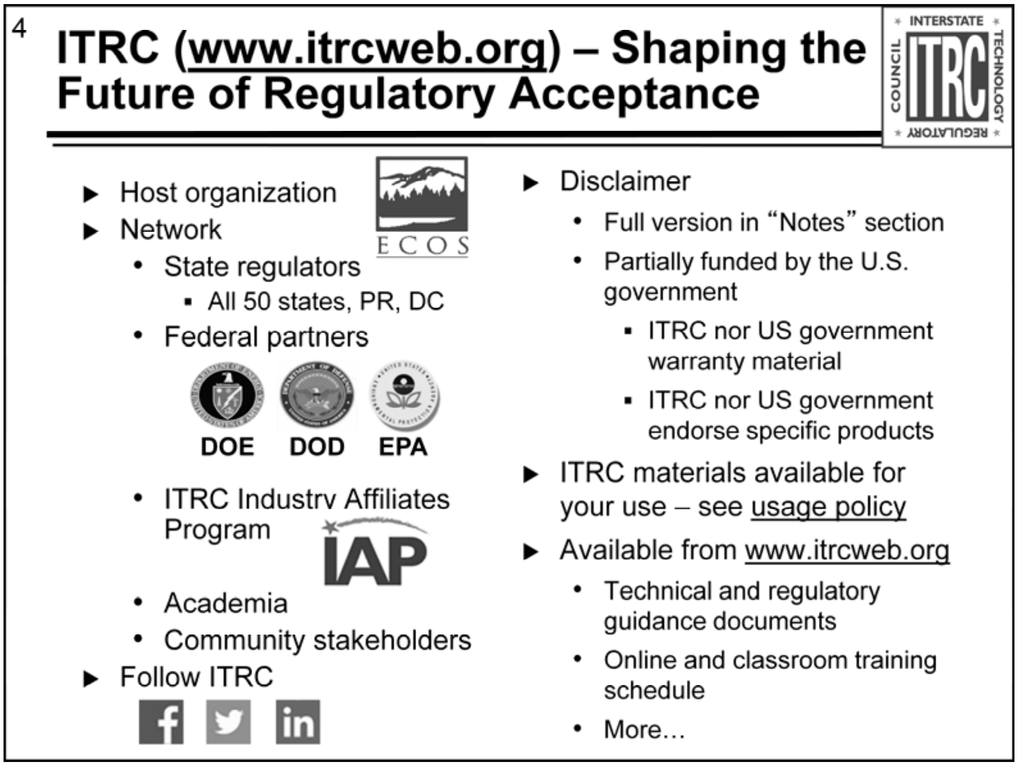


The Interstate Technology and Regulatory Council (ITRC) is a state-led coalition of regulators, industry experts, citizen stakeholders, academia and federal partners that work to achieve regulatory acceptance of environmental technologies and innovative approaches. ITRC consists of all 50 states (and Puerto Rico and the District of Columbia) that work to break down barriers and reduce compliance costs, making it easier to use new technologies and helping states maximize resources. ITRC brings together a diverse mix of environmental experts and stakeholders from both the public and private sectors to broaden and deepen technical knowledge and advance the regulatory acceptance of environmental technologies. Together, we're building the environmental community's ability to expedite quality decision making while protecting human health and the environment. With our network of organizations and individuals throughout the environmental community, ITRC is a unique catalyst for dialogue between regulators and the regulated community.

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# Meet the ITRC Trainers

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**Alex MacDonald** is a senior engineer in the technical support section of the Cleanup Unit at the Central Valley Regional Water Quality Control Board in Rancho Cordova, California. He has worked at the Water Quality Control Board since 1984. He primarily works on cleanup of the Aerojet site in Rancho Cordova, California and other nearby sites such as McClellan Air Force Base. Alex has also worked on cleanup at underground and above ground storage tanks sites; permitting and inspection of landfill and waste disposal to land sites; regulating application of biosolids sites; regulating NPDES sites that include wastewater treatment plants, power plants, industrial facilities, and groundwater treatment facilities; and permitting and inspecting dredging projects. Alex was a member of the ITRC Perchlorate team. Alex earned a bachelor's degree in Civil/Environmental Engineering from Stanford University in Palo Alto , California in 1977 and a master's degree in Civil/Environmental Engineering from Sacramento State University in Sacramento, California in 1987.

**Dr. Tamzen Macbeth** is a Vice President at CDM Smith out of Helena, Montana. She has worked for CDM since 2009. Previously, she worked for 7 years at North Wind Inc. Tamzen is an environmental engineer with an interdisciplinary academic and research background in microbiology and engineering. She specializes in the development, demonstration and application of innovative, cost-effective technologies for contaminated groundwater. Specifically, she is experienced in all aspects of remedies from characterization to remediation for DNAPLs, dissolved organic, inorganic, and radioactive contaminants under CERCLA and RCRA regulatory processes. She has expertise in a variety of chemical, biological, thermal, extraction and solidification/stabilization remediation techniques as well as natural attenuation. Her current work focuses developing combined technology approaches, and innovative characterization techniques such as mass flux and mass discharge metrics. Since 2004, Tamzen has contributed to the ITRC as a team member and instructor for the ITRC’s Bioremediation of DNAPLs, Integrated DNAPL Site Strategy, Molecular Diagnostics and DNAPL Characterization teams. Tamzen earned a bachelor's degree in Microbiology in 2000 and a master’s degree in Environmental Engineering in 2002 both from Idaho State University in Pocatello, Idaho, and a doctoral degree from in Civil and Environmental Engineering in 2008 from the University of Idaho in Moscow, Idaho.

**Dr. Charles (Chuck) J. Newell,** Ph.D., P.E. is a Vice President of GSI Environmental Inc in Houston, Texas and has worked for GSI since 1989. His professional expertise includes site characterization, groundwater modeling, non-aqueous phase liquids, risk assessment, natural attenuation, bioremediation, non-point source studies, software development, and long-term monitoring projects. He is a member of the American Academy of Environmental Engineers, a NGWA Certified Ground Water Professional, and an Adjunct Professor at Rice University. He has co-authored five U.S. EPA publications, eight environmental decision support software systems, numerous technical articles, and two books: Natural Attenuation of Fuels and Chlorinated Solvents and Ground Water Contamination: Transport and Remediation. He has taught graduate level groundwater courses at both the University of Houston and Rice University. He has been awarded the *Hanson Excellence of Presentation Award* by the American Association of Petroleum Geologists, the *Outstanding Presentation Award* by the American Institute of Chemical Engineers, and the *2001 Wesley W. Horner Award* by the American Society of Civil Engineers (for the paper, “Modeling Natural Attenuation of Fuels with BIOPLUME III”). He was recently cited as the *Outstanding Engineering Alumni* from Rice University in 2008. He earned a bachelor's degree in Chemical Engineering in 1978, a master’s degree in Environmental Engineering in 1981, and a Ph.D. in Environmental Engineering in 1989, all from Rice University in Houston Texas. Chuck is a professional engineer registered in Texas.

**Alec Naugle, P.G.** is a Senior Engineering Geologist in the Groundwater Protection Division at the California Regional Water Quality Control Board, San Francisco Bay Region where he has worked since 1999. Alec leads a unit that oversees solvent and petroleum hydrocarbon cleanups at Department of Energy laboratories and closed military bases, many of which are undergoing conversion for civilian use. He is also co-chair of the Region's technical groundwater committee, which supports the Board's planning activities related to groundwater quality and beneficial use. Prior to joining the Board, Alec worked as a consultant on various military and private sites in California and the Northeast and as a regulator in the UST program. Alec has been a member of ITRC since 2000 participating in the Permeable Reactive Barriers, Enhanced Attenuation: Chlorinated Organics, and Integrated DNAPL Site Strategy teams. Alec earned a bachelor’s degree in chemistry and geology from Marietta College in Marietta, Ohio in 1986 and a master’s degree in groundwater hydrology from the University of California at Davis in 2001. Alec is a Registered Professional Geologist in California.

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## What You Will Learn…

- What is mass flux and mass discharge
- Why these are useful metrics
- How mass flux and discharge can complement concentration-based measures
- What methods are available to measure mass flux and discharge
- How to calculate mass flux and discharge
- How existing site data may be used to estimate mass flux and discharge
- How to manage uncertainty
- Regulatory considerations with mass flux and discharge estimates

No associated notes.

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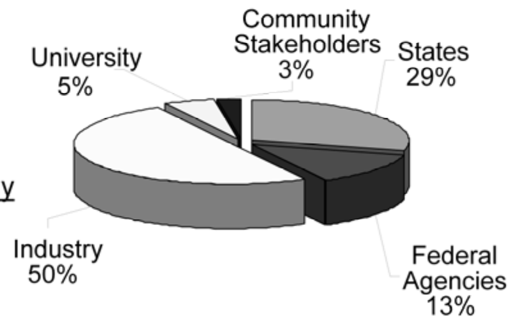
# ITRC Mass Flux Project

- **Use and Measurement of Mass Flux and Mass Discharge (MASSFLUX-1, 2010)**
- Other ITRC guidance
  - In Situ Bioremediation of Chlorinated Ethene: DNAPL Source Zones (BioDNAPL-3, 2008)
  - Integrated DNAPL Site Strategy (IDSS-1, 2011)
  - Integrated DNAPL Site Characterization and Tools Selection (ISC-1, 2015)
- Current team
  - Characterization and Remediation in Fractured Rock

**Integrated DNAPL Site Strategy Team**




ITRC's documents on DNAPLs are available from http://www.itrcweb.org/Guidance

# ITRC Technology Overview

- Use and Measurement of Mass Flux and Mass Discharge (ITRC MASSFLUX-1, 2010)
  - Concepts, measurement / estimation methods, and uses
  - Regulatory considerations
  - Case study review

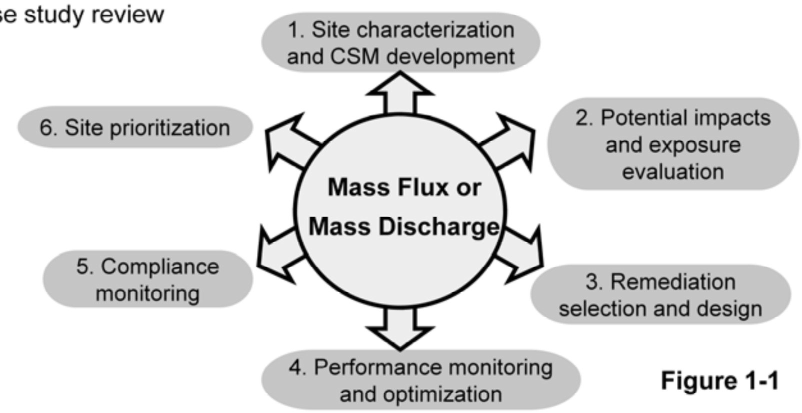



Figure 1-1

No associated notes.

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## Regulatory Considerations Associated with Mass Flux and Mass Discharge

- Precedent for use in a regulatory context
  - Federal Superfund
    - Signed Record of Decision (ROD) identifying a mass discharge interim goal was accepted in October 2009
  - Surface water regulations
    - Total Maximum Daily Loads (TMDL)
    - National Pollutant Discharge Elimination System (NPDES)
- Issues with regulatory acceptance
  - Complexity and uncertainty of mass flux measurements
  - How to relate mass flux to risk and exposure
  - Unclear how mass flux relates to standard regulatory metrics
    - e.g., Maximum Contaminant Levels (MCLs)

I NPDES permits you are required to report concentration and mass measurements

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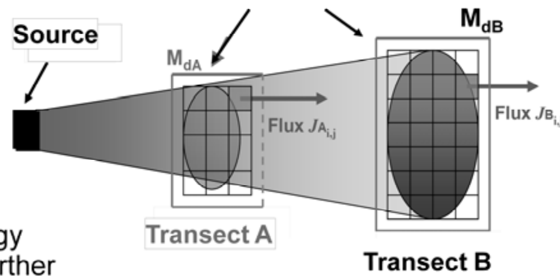
# Questions to Consider

- Why should I estimate mass flux/discharge at my site?
- How do I calculate mass flux/discharge?
- What are the cost/benefits of using mass flux/discharge?
- Can mass flux help measure compliance?
- Integrated DNAPL Site Strategy Tech-Reg Guidance (2011) further describes uses of mass flux/discharge estimates

**Mass Discharge ($M_d$) = Sum of all Measures of Mass Flux x Area**




**$J_{Aij}$= Individual mass flux measurement at Transect A**

**$M_{dA}$= Mass discharge at transect A (sum of all of the mass discharge estimates for each specific area [$J_{aij}$ x A])**

No associated notes.

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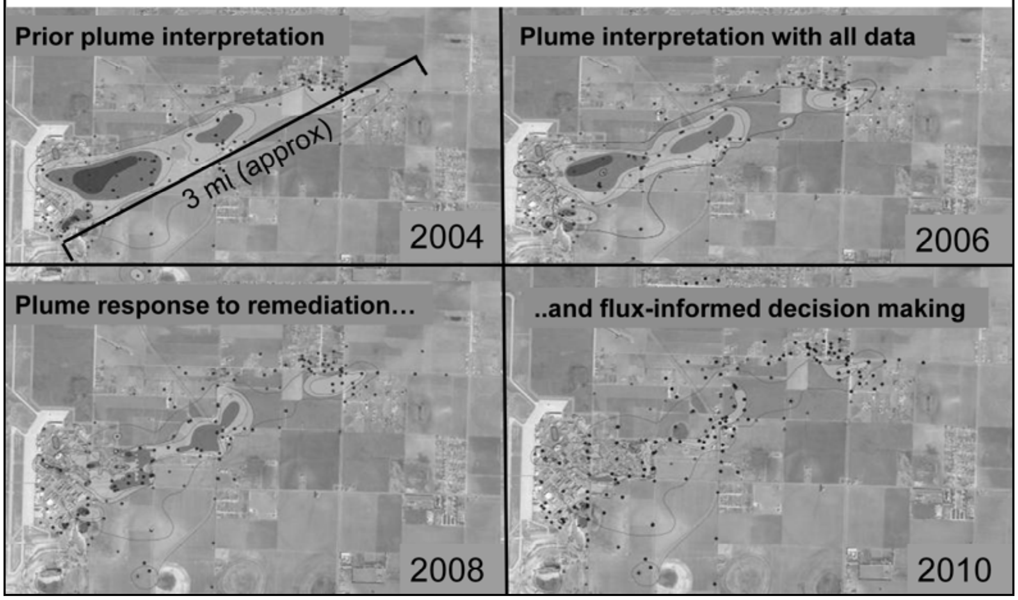
# Case Studies: Real Life Application of Mass Flux

Case study from F. Payne, ARCADIS




Near the end of today's presentation we have several case studies that show how mass flux has been applied at several sites across the country to help remediate sites more efficiently. Pay attention to the presentation between now and then so you can see how to apply mass flux concepts that helped this site at Reese Air Force Base significantly address its groundwater contamination as shown by the shrinking plumes depicted here.

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# Course Roadmap

- Mass concepts
- Measurement methods
- Application
- Case studies
- Summary

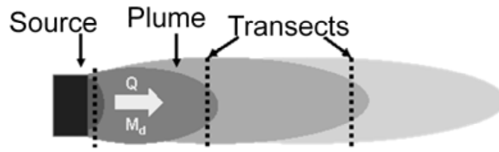


Figure 2-1

This section discusses the fundamental concepts of mass flux and discharge: the definitions, how these metrics compare to concentration data, how flux and discharge can be estimated, how flux and discharge change over time as sources and plumes evolve, and how flux and discharge can be valuable for site management.

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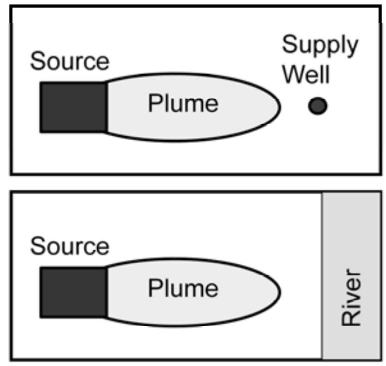
# Mass Flux and Mass Discharge: Why Care?

***Better Understanding Yields Smarter Solutions!***

- To augment concentrations, not replace them
- Allows targeted remediation strategies
  - Most flux is in a small fraction of the volume
- Provides meaningful performance metrics
  - Links partial treatment to risk reduction
- Basis for existing groundwater models
  - Already used but often ignored
- Recent advances in techniques




***Downgradient Risk Due to Mass Discharge NOT Concentration***

No associated notes.

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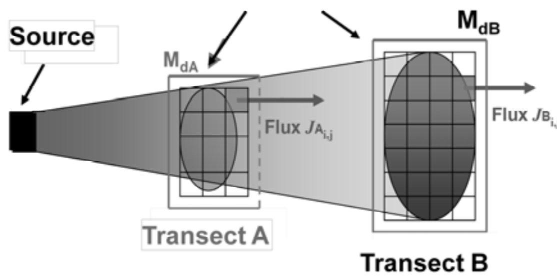
# Definitions

- Mass discharge
  - The total mass of any solute conveyed by a plume at a given location
  - $M_d$ is a scalar quantity, expressed as mass/time
- Mass flux
  - The rate of solute mass moving across a specific defined area, usually a portion of the plume cross-section
  - Mass flux is a vector quantity, expressed as mass/time/area

**Mass Discharge ($M_d$) = Sum of all Measures of Mass Flux x Area**




**$J_{Aij}$= Individual mass flux measurement at Transect A**

**$M_{dA}$= Mass discharge at transect A (sum of all of the mass discharge estimates for each specific area [$J_{aij}$ x A])**

Fundamental principles of contaminant hydrogeology. Terms are often confused – in particular, “mass flux” is often used for both concepts. Measures the total mass of contaminant, or other solute, in motion. Measuring mass flux identifies the variations in the mass and flow velocity across a plume.

Excellent fundamental descriptions are given in:

R. B. Bird, W. E. Stewart, and E. N. Lightfoot. Transport Phenomena. Revised 2nd ed., 2007. John Wiley & Sons, Inc.

C.W. Fetter. Contaminant Hydrogeology. 2nd ed., 1999. Waveland Press, Inc.

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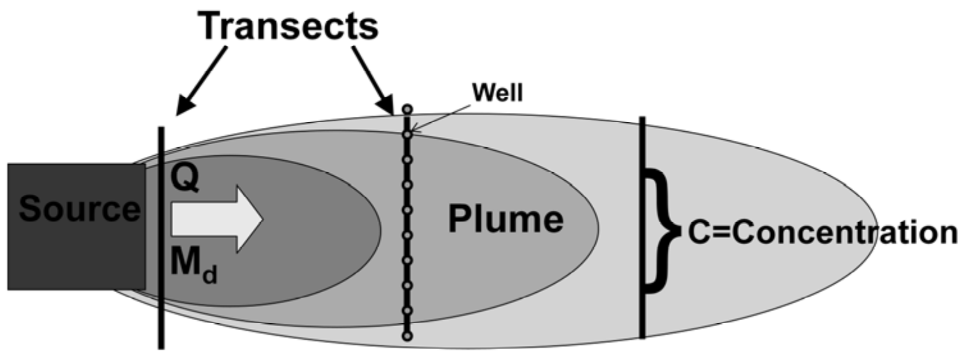
# Mass Discharge: Source or Plume Strength




**Across any Transect, a Contaminant Plume Conveys:**

Groundwater Discharge, **Q** (e.g., L/day)

Contaminant **Mass Discharge**, $\mathbf{M_d}$ (e.g., g/day or kg/year)

$$M_d = Q \times C \quad \text{(L/day x mg/L = mg/day)}$$

Figure 2-1

Transitioning into mass discharge—

Mass discharge is equivalent to source or plume strength. Looking down on a plume, a transect immediately down gradient of the source measures the mass loading to the plume, which changes with time, and transects further downgradient measure the mass in motion. The difference in mass discharge with distance is the natural attenuation rate, in a plume that is stable.

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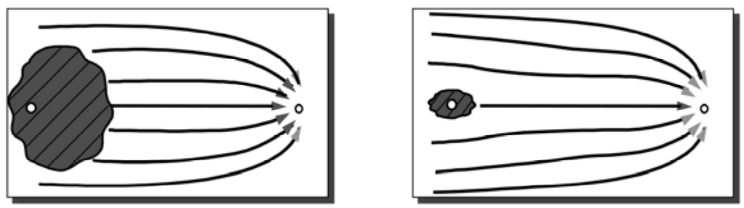
## Mass Discharge and Concentration

- Concentration-based approach may not account for important site characteristics
  - Large vs. small releases
  - Pumping rate at the receptor well

**Case A: Large Release**
**High Max. Conc. and High Md**

**Case B: Small Release**
**High Max. Conc. and Low Md**



***KEY POINT:*** **Evaluation of mass discharge ($M_d$) can increase understanding of site and be an important component of the site conceptual model**

No associated notes.

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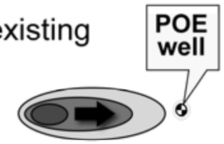
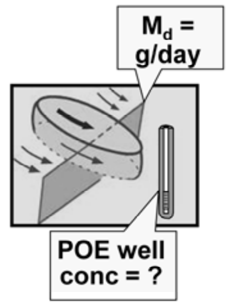
# Mass Discharge vs. Traditional Approach

- ***Traditional Approach:*** Measure existing plume **concentrations** to assess
  - Impact on receptor wells
  - Natural attenuation rates
  - Remedial options




- ***Mass Discharge Approach:*** Define rate of **mass discharge** across specified cross-sectional areas of plume to assess
  - Impact on receptor wells
  - Natural attenuation rates
  - Remedial options



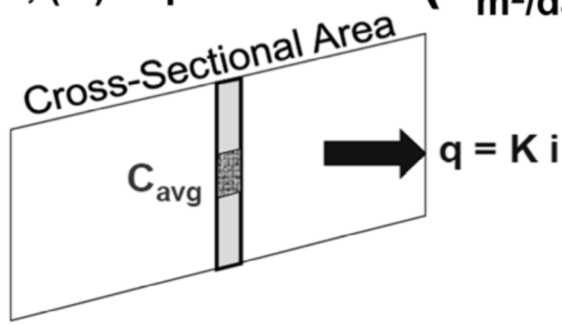

***KEY BENEFITS:*** **Mass discharge approach sometimes offers a better understanding of potential risks and attenuation rates, and can lead to sounder remediation strategies.**

Mass discharge approach based on Einarson and Mackay (2001) ES&T, 35(3): 67A-73A

No associated notes.

# What Is Mass Flux?

1. Specific Discharge, $q = K \times i$ $\left(\frac{L}{m^2/day}\right)$
2. Average concentration, $C_{avg}$ (g/L)
3. Mass Flux, $(J) = q \times C$ $\left(\frac{g}{m^2/day}\right)$

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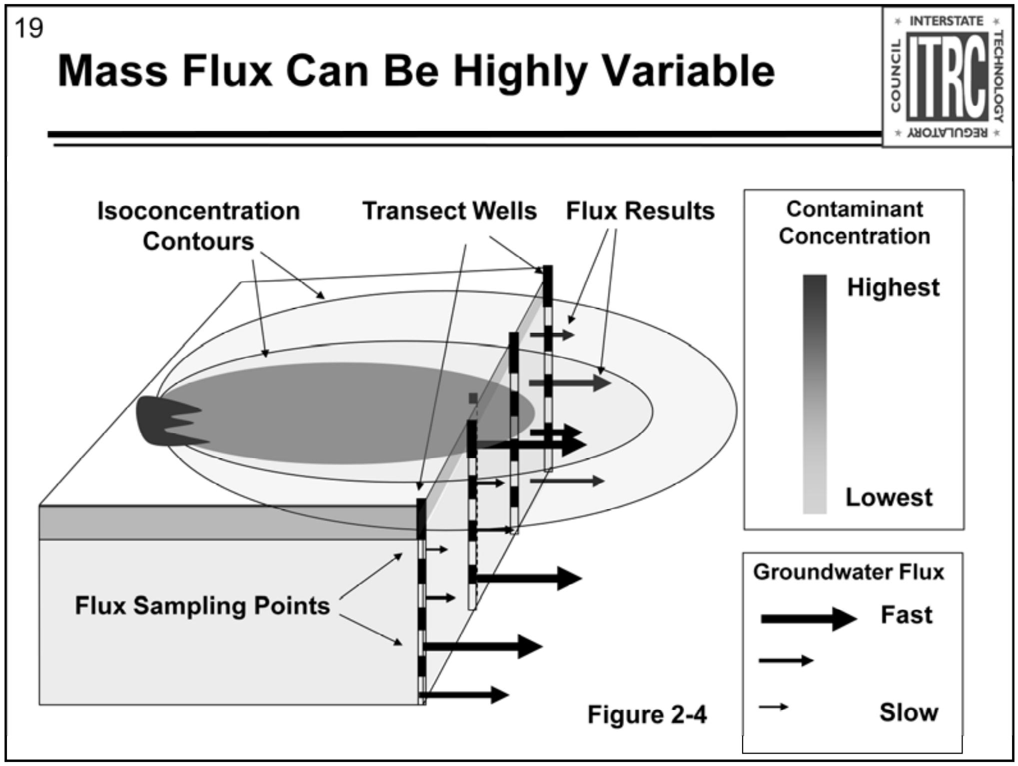
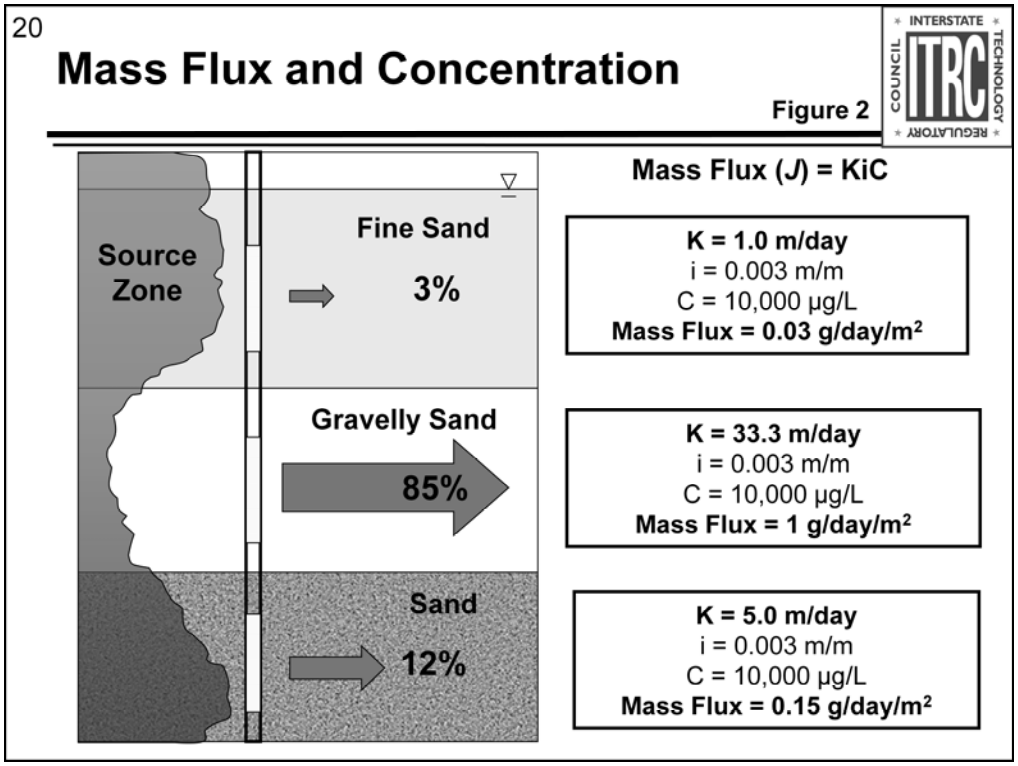


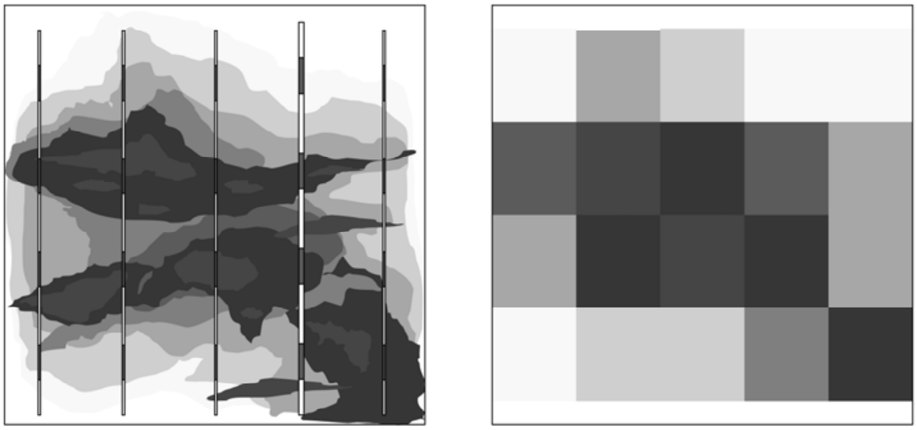

Both concentrations and groundwater velocity can vary dramatically over short distances. Both can also vary over time, seasonally and over longer time frames. The spatial variation in 3 dimensions is generally far more complex than typical representations of contaminant plumes suggest, and it can be important to understand these variations.




Illustrative example of an aquifer with identical concentrations and gradients in three sandy layers. But mass flux varies about 30-fold between layers, because the hydraulic conductivity varies, so that 85% of the flux is through only one layer. Even in unconsolidated aquifers, 80-90% of the mass flux may be through only 10-20% of the total plume volume.

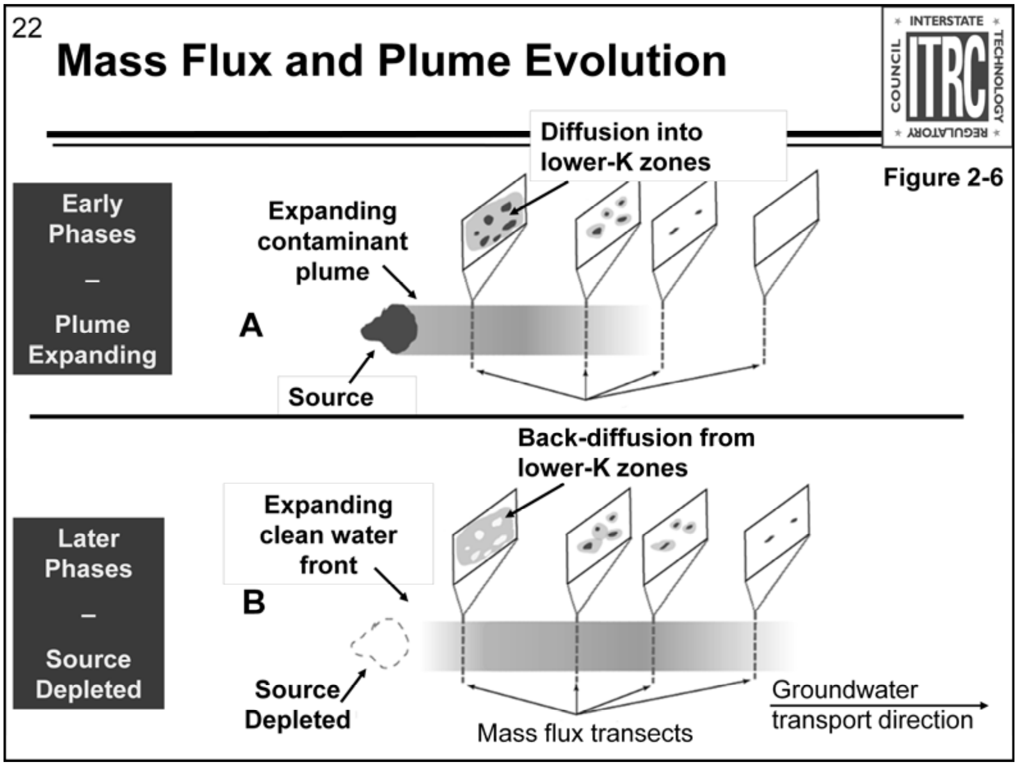
Note that the groundwater and mass discharge are based on the Darcy velocity (Q=Ki) and not the seepage velocity (Vs=Ki/p), where p = porosity. The seepage velocity, which is the average fluid velocity within the pores, is faster than the Darcy velocity, which refers to the rate of movement of water through the entire area of a plane across the flow direction.

# Interpolation



- Scale matters – what needs to be measured
- How to interpolate between highly variable data
- Most transects sample < 1% of the groundwater

No associated notes.




In the early phases, most of the mass is in the transmissive zones.
Later, mass diffuses into the lower-permeability zones.
Finally, plumes are sustained by back-diffusion, with relatively little flux in higher-K zones.
Mass flux distribution indicates where to treat most mass and whether back-diffusion is a likely problem.

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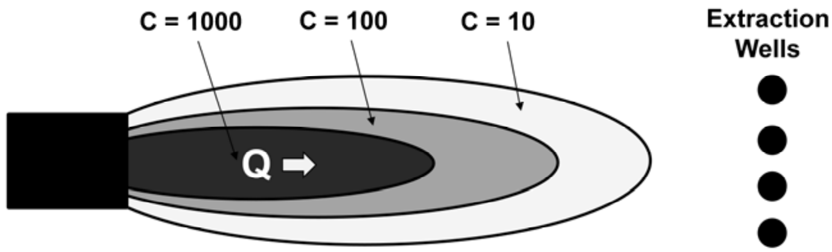
# Mass Flux and Mass Discharge Are Not New Concepts

- Basis for source depletion and natural attenuation models
- Ex situ treatments based on loading rates (e.g., Lb/hr)
- EPA, 2002: review of 20 pump and treat (P&T) sites
  - 35% of treatment systems to be replaced because mass loading estimates were inadequate




**Contaminant Loading = Q x C**

EPA, 2002 reference: EPA 542-R-02-008a-u, November 2002, Pilot Project to Optimize Superfund-financed Pump and Treat Systems: Summary Report and Lessons Learned. More information available at http://www.epa.gov/tio/download/remed/rse/phase_ii_report.pdf

## Uncertainty and its Management

- Uncertainty inevitable, but manageable
  - Similar uncertainty with concentration data
  - To successfully establish compliance goals consensus between stakeholders required
- Spatial heterogeneity and sample volumes
  - May need >> 1% (Li and Abriola, 2006)
- Source / Plume Boundary?
  - Hard to find and hard to define
- Solutions
  - Work Smart – Consider source architecture, plume evolution, hydrogeology, etc
  - Consider iterative investigation
  - Vertical variability is usually >> Lateral

No associated notes.

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## Advantages and Limitations

- Potential advantages
  - Improved conceptual site model (CSM)
  - More representative attenuation rates, exposure assessment
  - Improved remediation efficiency
  - Reduced remediation timeframe
- Limitations
  - Uncertainty
  - Cost

No associated notes.

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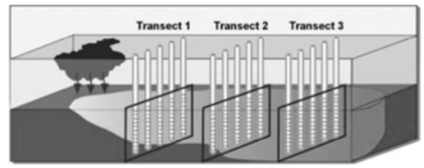
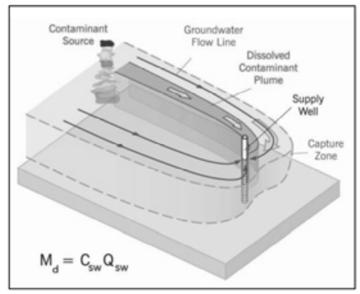
# Course Roadmap

- Mass concepts
- ➡ Measurement methods
- Application
- Case studies
- Summary



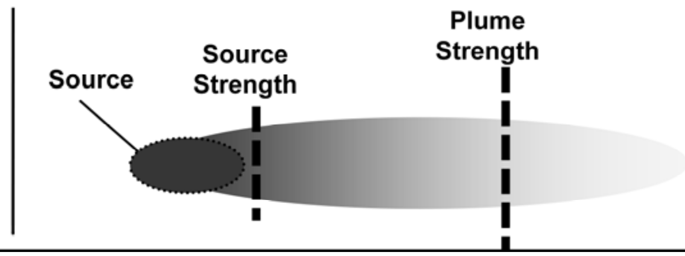




No associated notes.

# Five Methods for Mass Discharge

- *Method 1:* Transect Method (Sect. 4.1)
- *Method 2*: Well Capture/Pumping Methods (Sect. 4.2)
- *Method 3:* Passive Flux Meters (Sect. 4.3)
- *Method 4*: Using Existing Data (Isocontours) (Sect. 4.4)
- *Method 5*: Solute Transport Models (Sect. 4.5)

*All methods are "ready to go"*




No associated notes.

# Calculating Mass Discharge: Transect Method Simple Example

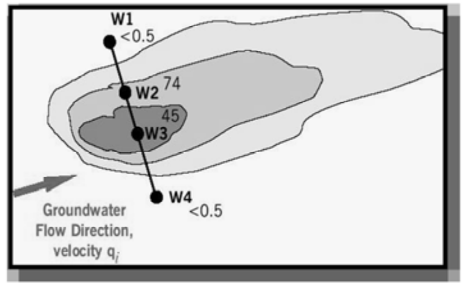
Nichols and Roth, 2004

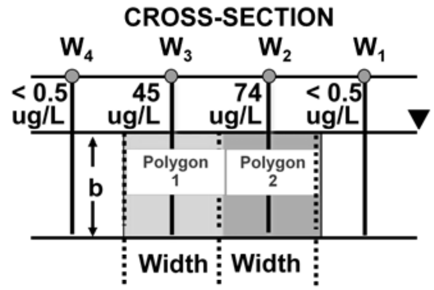
**Step-by-step approach assuming uniform groundwater velocity**

1. Characterize plume (C)
2. Characterize flow (q)
3. Draw transect: with simple approach, just build cross-sectional polygons ("window panes") for each well across flow
4. Determine area (W • b = A)
5. Multiply and sum together:

$$M_d = \Sigma (C_n \cdot A_n \cdot q)$$

**$M_d$ = Mass discharge**
**$C_n$ = concentration in polygon n**
**$A_n$ = Area of segment n**




No associated notes.

29

# Calculating Mass Discharge: Groundwater Darcy Velocity Term (q)

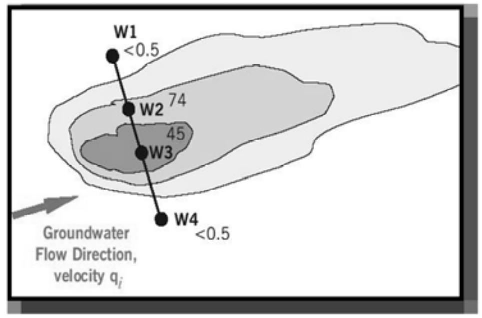
$M_d = \Sigma (C_n \bullet A_n \bullet q_n)$

Calculation of Darcy Velocity

$q = K \bullet i$

q = Groundwater Darcy velocity
i = Hydraulic gradient
K = Hydraulic conductivity*

- Hydraulic conductivity can be determined by pumping test, slug test, or estimated based on soil type
- Don't use porosity – hydraulic calculations for groundwater (such as Theis equation) don't rely on porosity



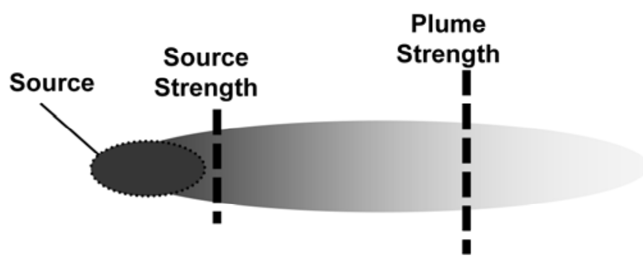

Variability in groundwater velocity - most applications of the transect method to date have assumed a uniform groundwater. Darcy velocity for the entire transect. However, different values for q may be used for different polygons if sufficient data are available.

No associated notes.

30

# Building Transects: General Rules

- Can be permanent or temporary installations
- No special well or sampling points needed
- Can be based on longer single screen wells or multilevel observations
- Transect must be perpendicular or close to perpendicular to groundwater flow




No associated notes.

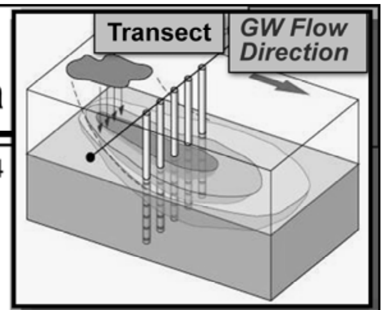
31

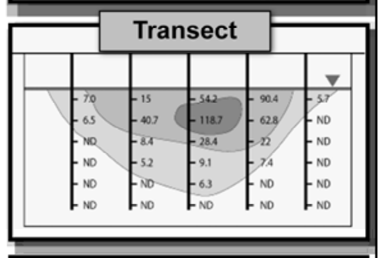
# Transect Method: Using High Resolution Data

Nichols and Roth, 2004

- Multi-level sampling means multiple level polygons
- Sum up all cells to get Mass Discharge ($M_d$) in units of
  - Grams per day (g/dy)
  - or
  - Kilograms per year (kg/yr)

**Figure 4-1**




In this case

**$M_d$ = 488 g/day (equal to 175 kg/year)**

**This is "Mag 7 Plume" (Newell et al., 2011)**

| | $W_1$ | $W_2$ | $W_3$ | $W_4$ | $W_5$ |
|---|---|---|---|---|---|
| $b_1$ | 7.0 | 15 | 54.2 | 90.4 | 5.7 |
| $b_2$ | 6.5 | 40.7 | 118.7 | 62.8 | 0 |
| $b_3$ | 0 | 8.4 | 28.4 | 22 | 0 |
| $b_4$ | 0 | 5.2 | 9.1 | 7.4 | 0 |
| $b_5$ | 0 | 0 | 6.3 | 0 | 0 |
| $b_6$ | 0 | 0 | 0 | 0 | 0 |

No associated notes.

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# How Many Points? Depends on Use

**Information from Table 1.1**

| **Remedial Applications** | **Mass Flux Data Use** | **Relative Data Density Needed** |
|---|---|---|
| Active remediation or MNA | Estimate source strength | Low |
| | Estimate plume stability | High* |
| | Estimate mass balance-natural attenuation capacity | Medium to High* |
| Evaluate risk to receptor(s) | Estimate risks and exposures at various points of potential exposure | Low to Medium |
| Select appropriate technology | Determine remedial action objectives | Low to High |
| | Determine appropriate remedial technology(ies) | |
| Develop/optimize remedial design | Evaluate heterogeneities in source architecture | High |
| | Estimate source strength reductions necessary to transition technology (e.g., in situ biorem. or MNA) | Low |
| | Estimate distribution of contaminants | High |
| Evaluate remedial performance | Compare actual mass removal to design. Compare electron acceptors to electron donors | Low to High** |
| Evaluate compliance / LTM | Determine mass discharge or flux limits to achieve remedial goals | Low to Medium |

*If using multiple plume transects **Depending on system design and treatment volume(s)

No associated notes.

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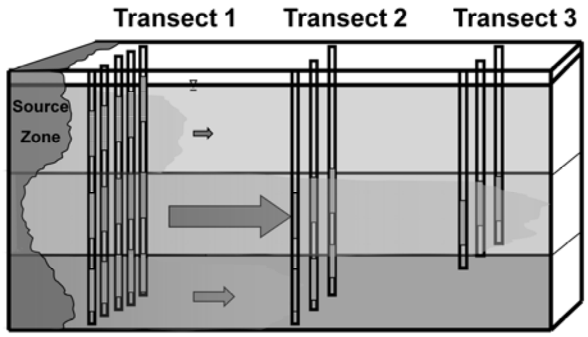
# Use of Multiple Mass Transects

Design Tailored to Site Conditions and Goals




Mass Discharge *vs. Distance*

Mass Discharge *vs. Time*

For more info see: "EPA's Calculation and Use of First-Order Rate Constants – MNA" EPA/540/S-02/500

No associated notes.

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## Two Related Concepts

- Pre-characterization
  - One option is to use Membrane Interface Probes (MIPs) or some other screening tools to determine where mass discharge is located
  - Then design a mass discharge monitoring system with more focused sampling on high mass flux areas
- *Site characterization* is different than *long-term monitoring*

No associated notes.

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## Tools for Transect Method: High-Resolution Piezocone

- High-resolution piezocone, MIP (Kram et al, 2008)
- Plus computational/visualization package (slices)
- Still experimental

Shows mass flux in 2 or 3 dimensions

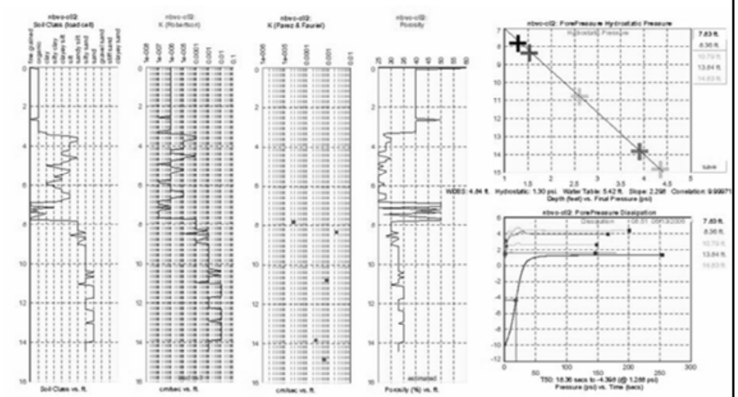


Figure 4-7

No associated notes.

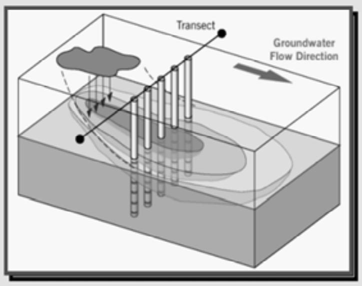
36

# Tools for Transect Method: Calculator

**Lead author: Shahla Farhat, Ph.D.**
**free at www.gsi-net.com**
**Microsoft Excel-based**

**Mass Flux Toolkit**

**To Evaluate Groundwater Impacts, Attenuation, and Remediation Alternatives**




Calculate Flux

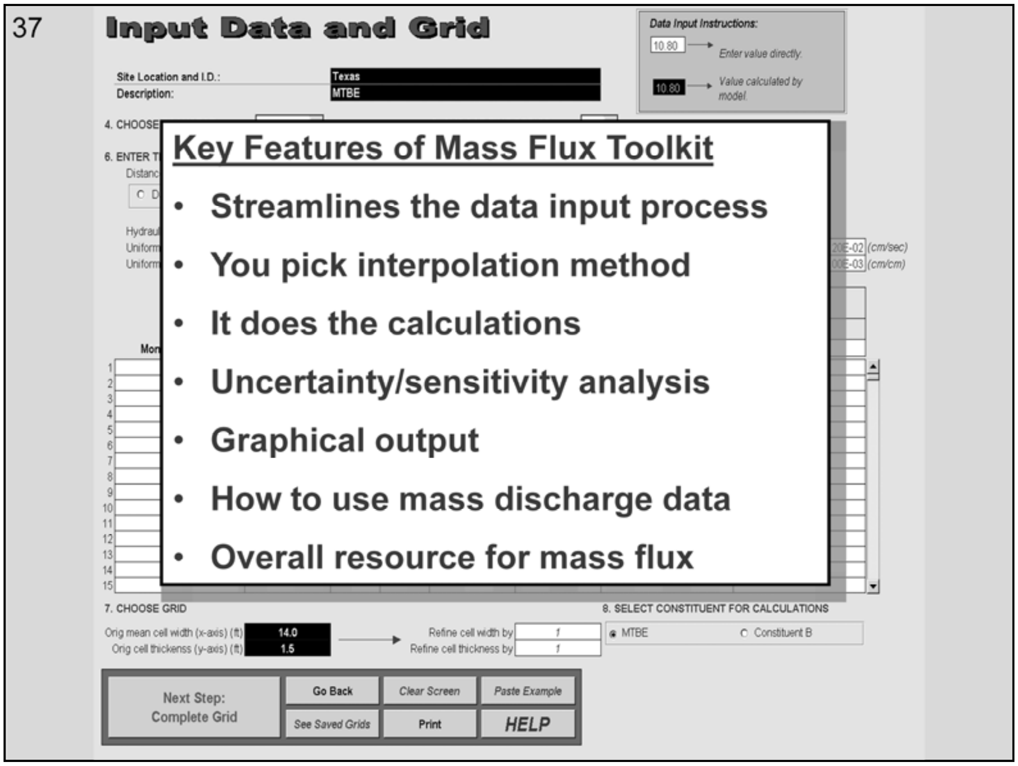
Impact of Flux

Learn About Flux

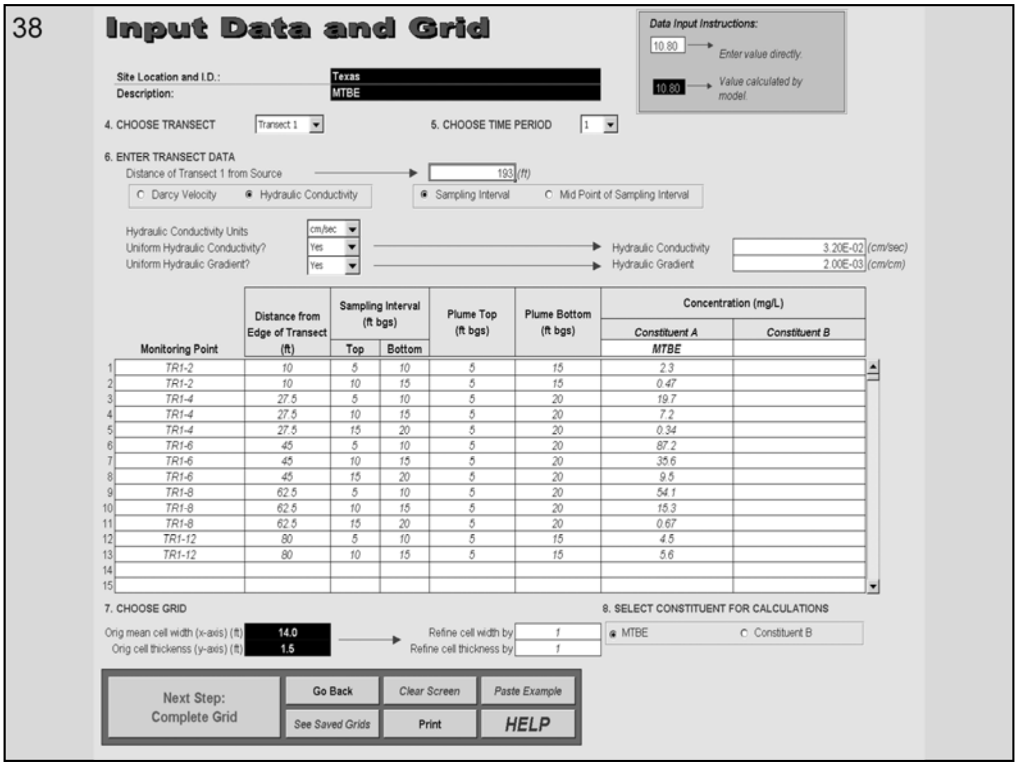
About Help

Version 1.0 Beta

No associated notes.




No associated notes.



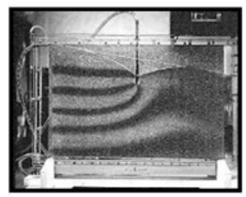

| | Monitoring Point | Distance from Edge of Transect (ft) | Sampling Interval (ft bgs) Top | Sampling Interval (ft bgs) Bottom | Plume Top (ft bgs) | Plume Bottom (ft bgs) | Concentration (mg/L) Constituent A MTBE | Concentration (mg/L) Constituent B |
|---|---|---|---|---|---|---|---|---|
| 1 | TR1-2 | 10 | 5 | 10 | 5 | 15 | 2.3 | |
| 2 | TR1-2 | 10 | 10 | 15 | 5 | 15 | 0.47 | |
| 3 | TR1-4 | 27.5 | 5 | 10 | 5 | 20 | 19.7 | |
| 4 | TR1-4 | 27.5 | 10 | 15 | 5 | 20 | 7.2 | |
| 5 | TR1-4 | 27.5 | 15 | 20 | 5 | 20 | 0.34 | |
| 6 | TR1-6 | 45 | 5 | 10 | 5 | 20 | 87.2 | |
| 7 | TR1-6 | 45 | 10 | 15 | 5 | 20 | 35.6 | |
| 8 | TR1-6 | 45 | 15 | 20 | 5 | 20 | 9.5 | |
| 9 | TR1-8 | 62.5 | 5 | 10 | 5 | 20 | 54.1 | |
| 10 | TR1-8 | 62.5 | 10 | 15 | 5 | 20 | 15.3 | |
| 11 | TR1-8 | 62.5 | 15 | 20 | 5 | 20 | 0.67 | |
| 12 | TR1-12 | 80 | 5 | 10 | 5 | 15 | 4.5 | |
| 13 | TR1-12 | 80 | 10 | 15 | 5 | 15 | 5.6 | |
| 14 | | | | | | | | |
| 15 | | | | | | | | |

No associated notes.

39

# Method 1 – Transects Advantages and Limitations

- Advantages
  - Commonly used – many applications
  - Direct measurement
  - Extension of accepted technology
- Limitations
  - High resolution data can be costly
  - Calculations can be time consuming



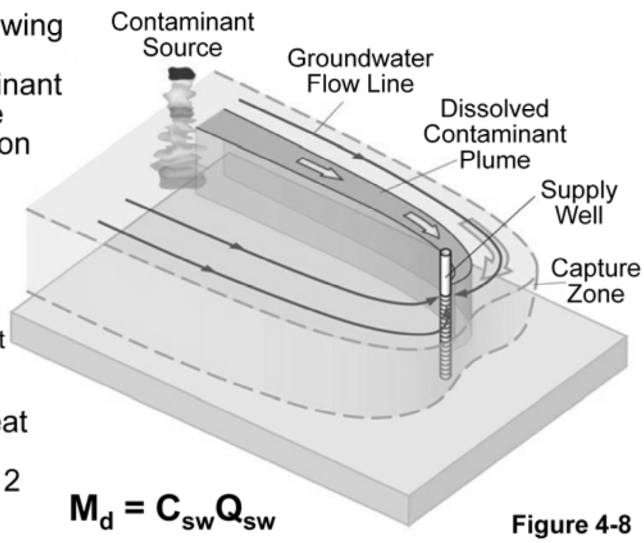
No associated notes.

40

# Method 2 – Well Capture/Pump Tests

Nichols and Roth, 2004

- Instead of plume flowing downgradient you capture the contaminant plume and measure flow, concentration on surface, but
  - Pumping should not induce dissolution at the source
  - Pumping needs to reach steady state
  - High confidence that plume has been captured
- Some pump and treat (P&T) systems can be ideal for Method 2




$M_d = C_{sw}Q_{sw}$

Figure 4-8

No associated notes.

41

# Well Capture Mass Discharge Calculation

Nichols and Roth, 2004

**Measure Q, $C_{well}$ from well**

Calculate mass discharge based on total capture of plume by pumping system

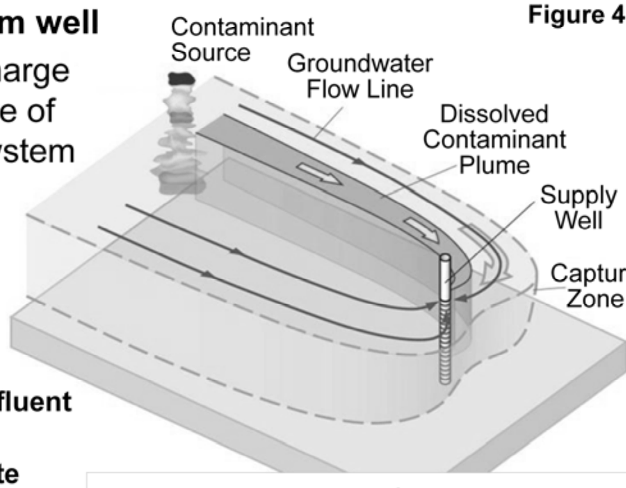
$$M_d = Q \times C_{well}$$

**$M_d$ = Mass discharge (grams per day)**

**$C_{well}$ = concentration in recovery well effluent (grams per liter)**

**Q = Well pumping rate (liters per day)**

**Figure 4-8**




$$\frac{gram}{\cancel{liter}} \times \frac{\cancel{liters}}{day} = \frac{grams}{day}$$

No associated notes.

42

# More Sophisticated Version Method 2

- Integral Pump Tests (IPT)
  - Steady state flow conditions, but handles changing heterogeneous concentrations in plume

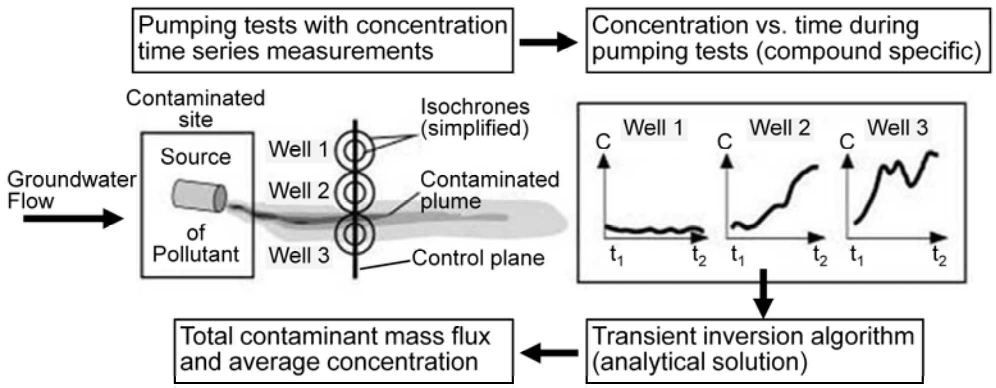


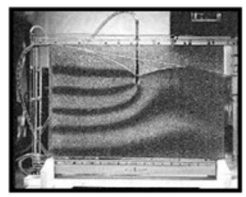

**Figure 4-9. Estimating Mass Flux Using Integral Pump Test Series Data**

No associated notes.

43

# Well Capture Methods Advantages and Limitations

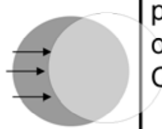
- Advantages
  - Fewer wells
  - Better integration of flow and concentration data
  - Can use existing pumping system
- Limitations
  - No mass flux data
  - Large volumes of water that need disposal/treatment
  - Possible to change plume characteristics
  - Difficult to assure full plume capture



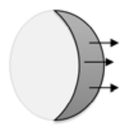
No associated notes.

# Method 3 – Passive Flux Meter

- Permeable sorbent
  - Accumulates contaminant based on flow and concentration



- Soluble tracers
  - Loses tracer based on groundwater velocity and flux convergence calculations



1. Contaminant adsorbed onto passive flux meter over time to get Concentration

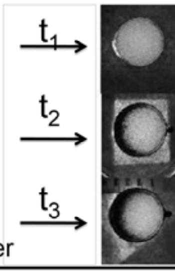
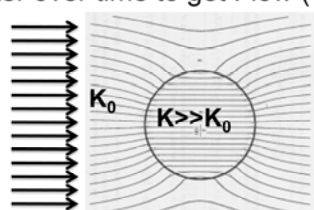



Photo: Dye intercepted in a meter

2. Tracer desorbs from passive flux meter over time to get Flow (Q)

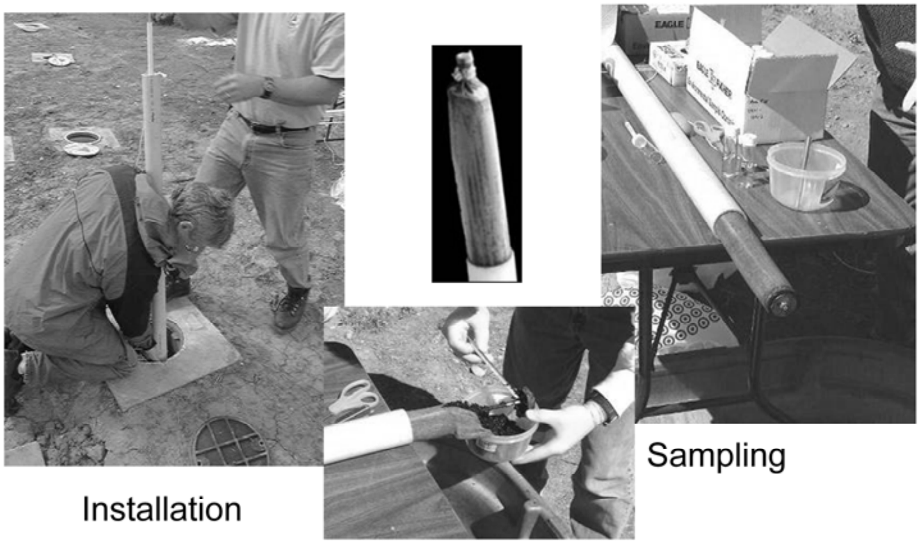



Groundwater Flowlines

Source: Hatfield and Annable

No associated notes.

# Passive Flux Meter




Installation

Sampling

Vendor: http://www.enviroflux.com/pfm.htm

No associated notes.

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# Passive Flux Meter
# Advantages and Limitations

- Advantages
  - “One stop shop” for both flow and concentration
  - Easy to install in the field
  - No waste generated
  - Vendor available to implement this method
- Limitations
  - Some method-specific issues (lower measurement in pushed wells, slight biodegradation of tracer at one site, competitive sorption under some conditions)
  - Relies on well convergence calculations

No associated notes.

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# Method 4 – Use Existing Data (Transect Based on Isocontours)

- Uses existing well network and plume map
- Combine with flow data

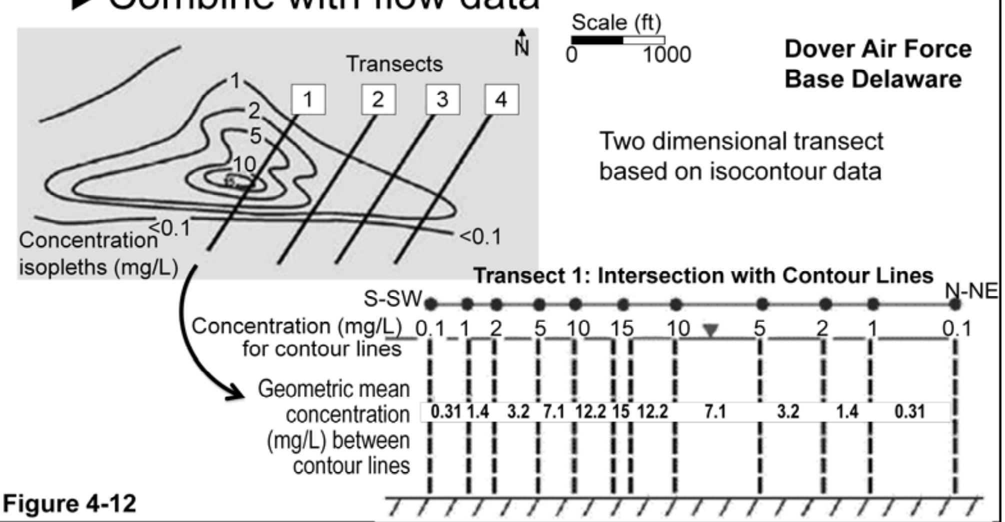



Figure 4-12

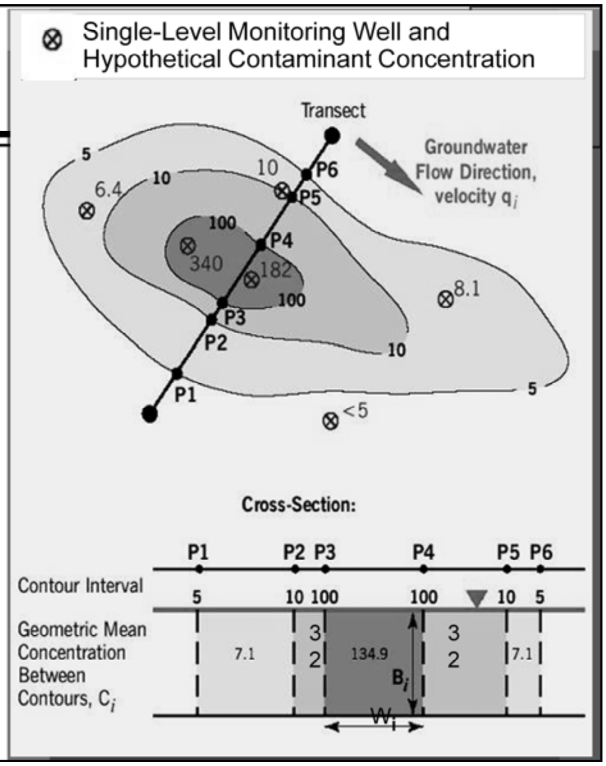
No associated notes.

48 **Calculating Mass Discharge from Isocontours**

### Plume Contour Data

1. Get isocontours from existing plume map
2. Build transect using points where isocontours intersect transect line (you can add actual wells if close to contour)
3. Apply Transect Method (Method 1) Calculations

Nichols and Roth, 2004




No associated notes.

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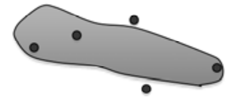
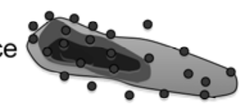
# Isocontour Method Advantages and Limitations

- Advantages
  - Does not need special field study. Can use existing, historical data from existing monitoring system
  - Limited additional expense
- Limitations
  - Wide range of opinion about usefulness of this method
  - Can be inaccurate if plume map is built with only a few wells. For example consider:
    - Gas station site with 5 wells throughout entire plume: **not likely** to provide high quality mass flux/mass discharge data



versus

    - Well characterized site with 40 wells in source zone: **likely** to provide higher quality data



No associated notes.

# Measurement Method 5 – Computer Models

- Using computer models


***Models Integrate Flow and Concentration***

1. Calibrate model
2. Get flow and concentration data across transect
3. Example Below from BIOSCREEN

DISSOLVED HYDROCARBON CONCENTRATIONS IN PLUME (mg/L at Z=0)

| Transverse Distance (ft) | Distance from Source (ft) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 32 | 64 | 96 | 128 | 160 | 192 | 224 | 256 | 288 | 320 |
| 100 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 50 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0 | 12.021 | 7.387 | 5.927 | 5.208 | 4.742 | 4.392 | 4.101 | 3.841 | 3.595 | 3.352 | 3.099 |
| -50 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 100 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| MASS FLUX (mg/day) | 9.1E+3 | 9.8E+3 | 7.8E+3 | 6.9E+3 | 6.3E+3 | 5.8E+3 | 5.4E+3 | 5.1E+3 | 4.8E+3 | 4.4E+3 | 4.1E+3 |

Time: 6 Years

Target Level: 0.005 mg/L

Displayed Model: Inst. Reaction

Model to D

No Deg

1st Orde

Instanta

Plume and Source Masses (Order-of-Magnitude Accuracy)

No associated notes.

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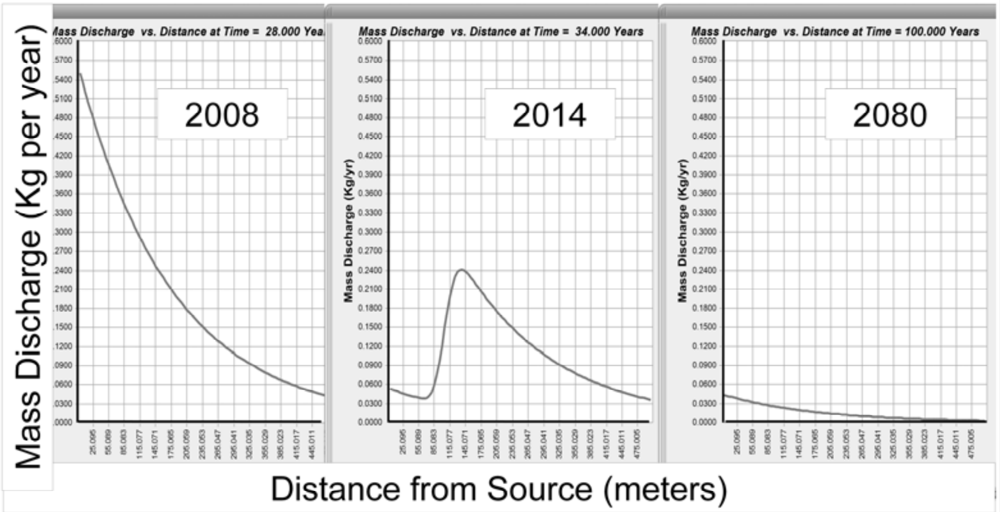
# REMChlor Model of Source Remediation

Source: Ron Falta, Clemson Univ.

Remove 90% of mass in 2010.
REMchlor shows mass discharge vs. distance in future years




No associated notes.

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# Measurement Method 5
# Models with Mass Discharge

| Model | Model application and type |
|---|---|
| **BIOSCREEN** | **Fuel Hydrocarbon MNA, Analytical** |
| **BIOCHLOR** | **Chlorinated Solvent MNA, Analytical** |
| **BIOBALANCE** | **Chlorinated Solvent MNA, Analytical** |
| **MODFLOW/MT3DMS** | **General. Numerical** |
| **MODFLOW/RT3DMS** | **General, Sequential Degradation, Numerical** |
| **MODFLOW/MT3D** | **General. Numerical** |
| **MODFLOW/RT3D - rtFlux** | **General. Numerical** |
| **REMChlor** ***New!*** | **Hydrocarbon, Chlorinated Solvent** |

**From Table 4-3**

No associated notes.

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## Computer Model Method Advantages and Limitations

- Advantages
  - Does not need special field study. Can use existing, historical data from existing monitoring system
  - Models are designed to combine flow, concentration data
- Limitations
  - Helpful to have experience/training in using models
  - Need good data – both flow and concentration data
  - Amount of data depends on what information is being used for
    - For example - need absolute or relative number?
    - Table 1.1 in Guide (shown under Transect Section) provides more detail

No associated notes.

## Five Methods for Mass Discharge

- *Method 1:* Transect Method (Sect. 4.1)
  - Commonly used. Based on familiar technology
- *Method 2:* Well Capture/Pumping Methods (Sect. 4.2)
  - Many pump and treat systems doing this now.
- *Method 3:* Passive Flux Meters (Sect. 4.3)
  - New technology, easy to install, one device for flow and concentration
- *Method 4:* Using Existing Data (Isocontours) (Sect. 4.4)
  - Uses existing data. Cost effective, but requires good monitoring network.
- *Method 5:* Solute Transport Models (Sect. 4.5)
  - Combines flow and concentration data. Helpful to have experience

No associated notes.

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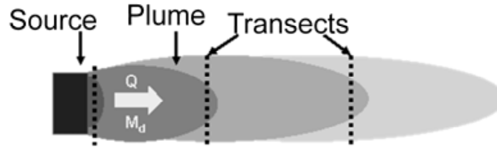
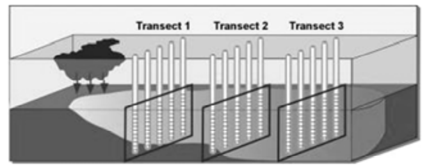
# Question and Answer

Follow ITRC

- Mass concepts

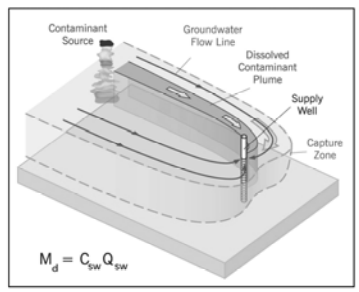



- Measurement methods




➡ Question and answer break

- Application
- Case studies
- Summary




No associated notes.

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# Course Roadmap

- Mass concepts
- Measurement methods
- Application
- Case studies
- Summary

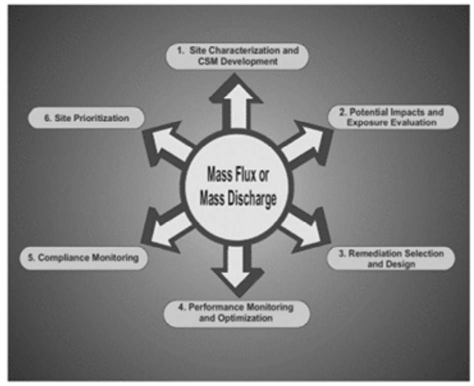
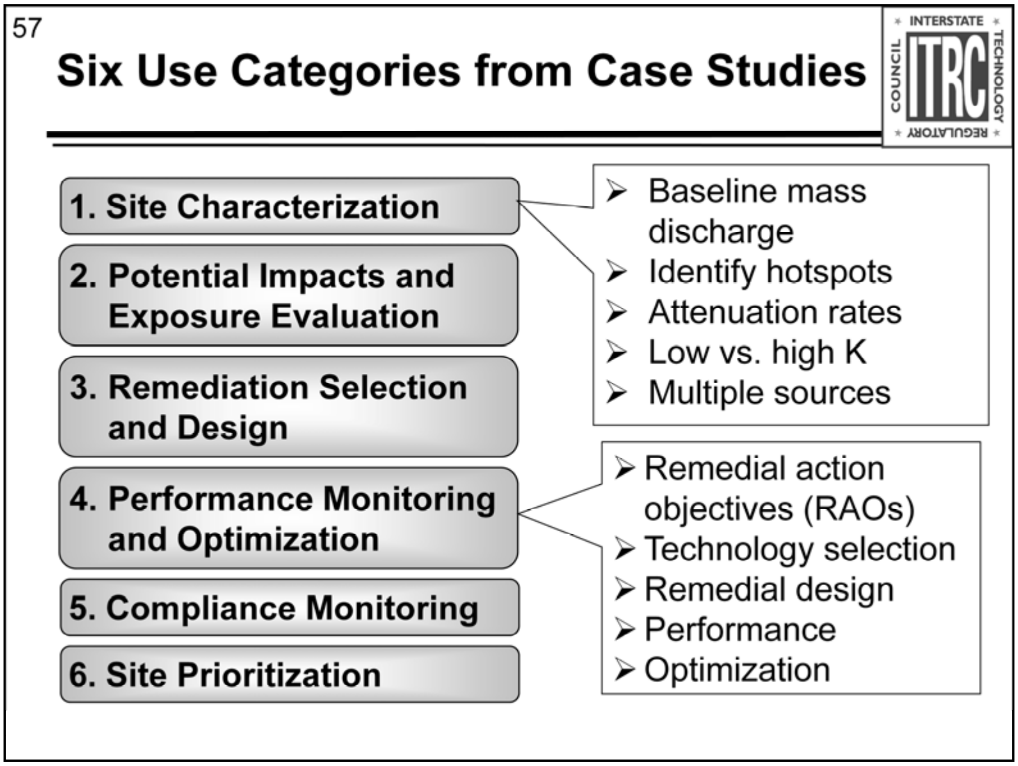



Figure 1-1

No associated notes.




•Based on review of case studies we identified five categories of mass flux and mass discharge “uses”:

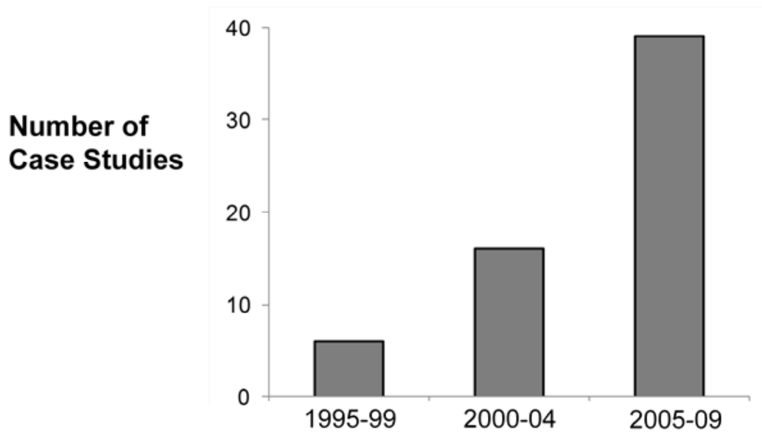
•Some categories, like “site characterization” and “remediation” are fairly broad and encompass several sub-categories

•And it should be noted that some sub-categories of “site characterization” may occur after a remedy has been selected, but there is reason to suspect things are working as planned due to incomplete site characterization, so the site characterization uses don’t necessarily happen in the beginning.

1. Site Characterization
2. Potential Impact Assessment
3. Remediation
4. Compliance Monitoring
5. Site Prioritization

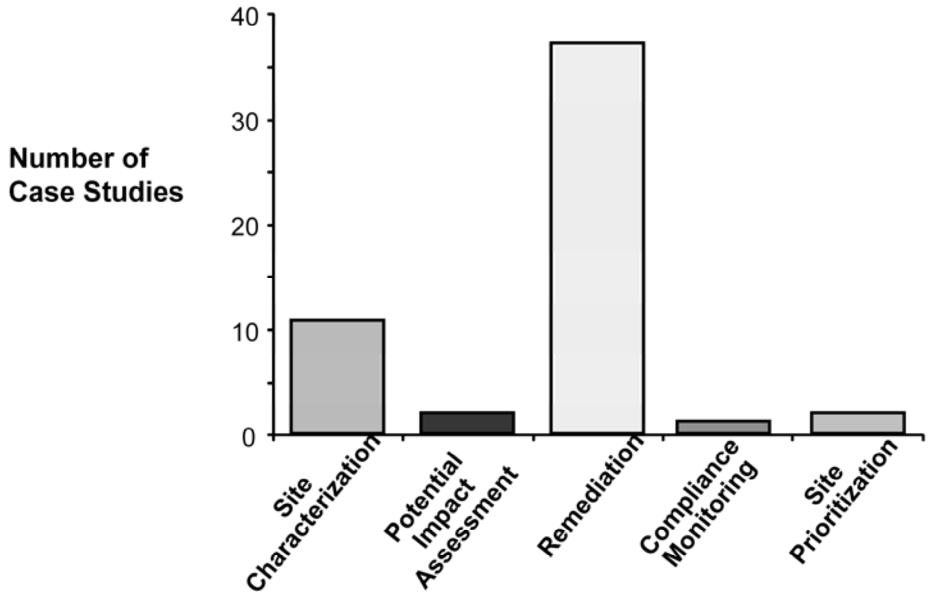
# Increasing Use of Mass Flux and Mass Discharge

Rapid increase in use since 1995




No associated notes.

# Over 61 Case Studies Documenting Mass Flux and Mass Discharge Use




The use of Mass Flux and Mass Discharge is increasing, as the chart shows

Includes all “use” categories:

1. Site Characterization
2. Potential Impact Assessment
3. Remediation
4. Compliance Monitoring
5. Site Prioritization

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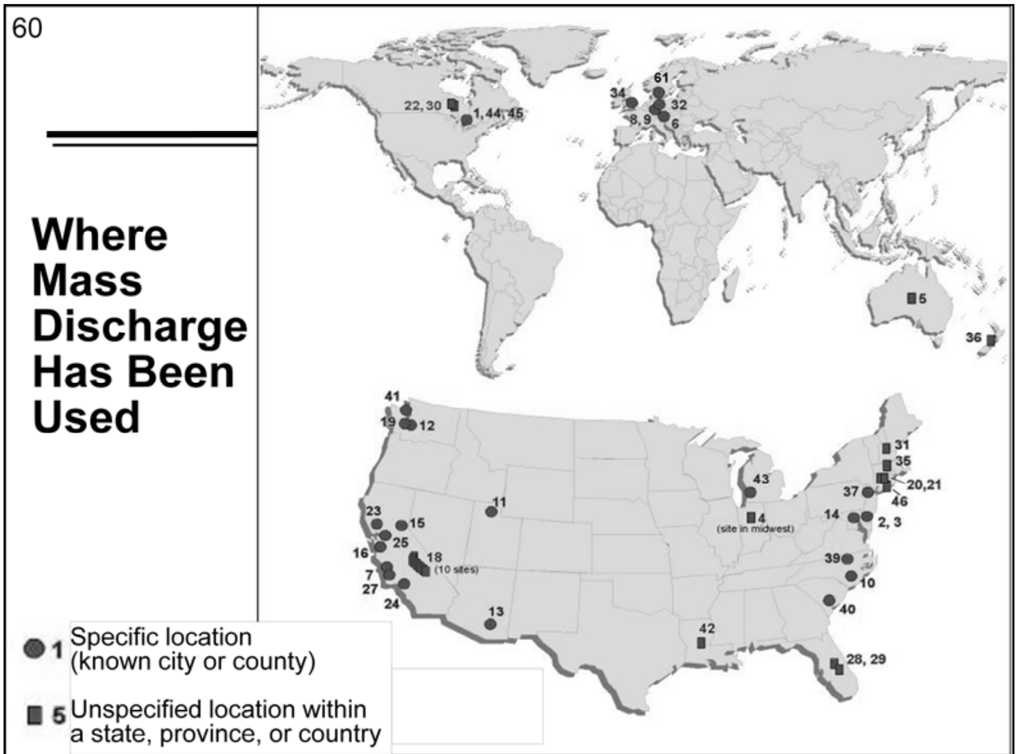
# Where Mass Discharge Has Been Used



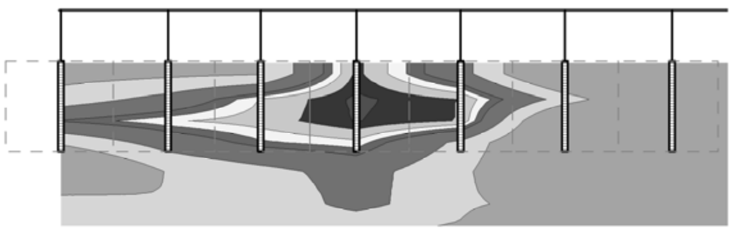

Specific location (known city or county)

Unspecified location within a state, province, or country

No associated notes.

# Reasons for Increased Use

- New studies → heterogeneous mass flux from source zones (e.g. Guilbeault et al., 2005)
- Improved monitoring techniques
- Recent focus on improving remediation efficiency
- New databases comparing technology performance based on source strength reduction



No associated notes.

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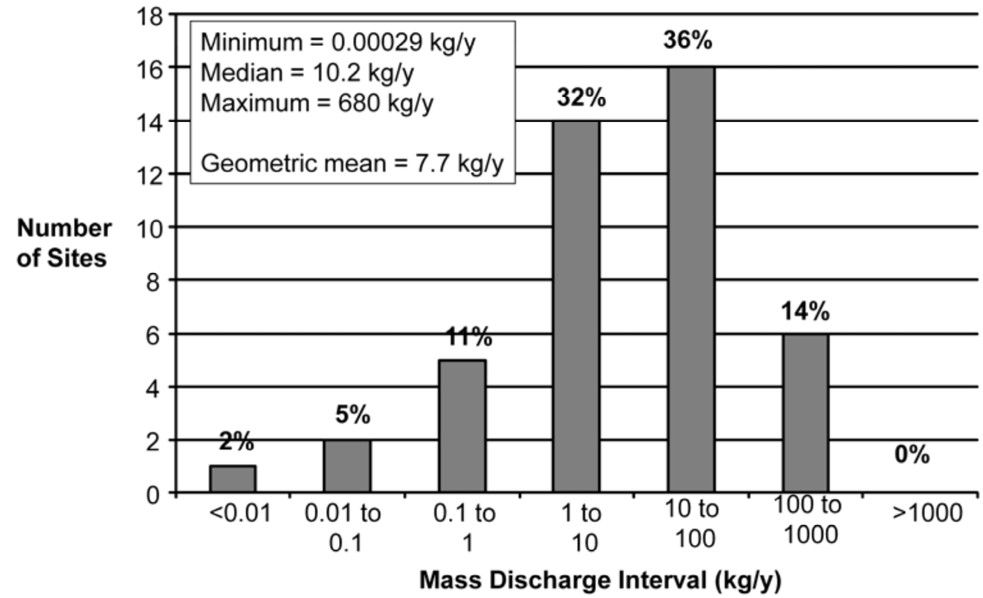
# Frequency of Sites with VOC/SVOC Mass Discharge Ranges




No associated notes.

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# Mass Discharge Calculations for Various Sites

| Site | Contaminant | Mass Discharge (g/d) | Reference |
|---|---|---|---|
| Sampson County, NC | MTBE | 0.6 - 2 | (Borden et al, 1997) |
| Vandenberg AFB, CA | MTBE | 4 - 7 | Unpublished |
| Unnamed Site | MTBE | 4 | Unpublished |
| Elizabeth City, NC | MTBE | 7.6 | Wilson, 2000 |
| St. Joseph, MI | TCE | 167 | (Semprini et al, 1995) |
| Dover AFB, DE | CVOCs | 630 | (RTDF 1998) |

**Table adapted from Einarson and Mackay (2001) ES&T, 35(3): 67A-73A**

No associated notes.

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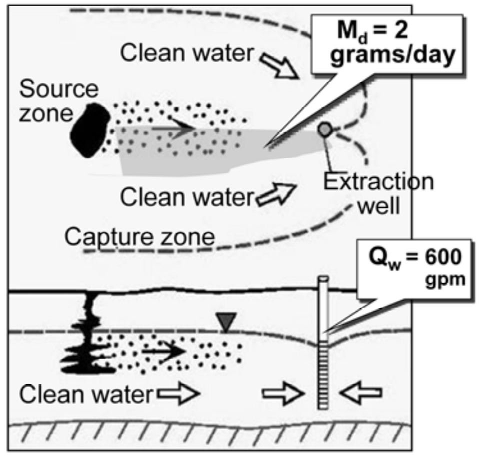
# Using Mass Discharge: Estimating Well Impacts

Einarson and Mackay, 2001

Use mass discharge of plume to predict constituent of concern concentration in downgradient water supply well

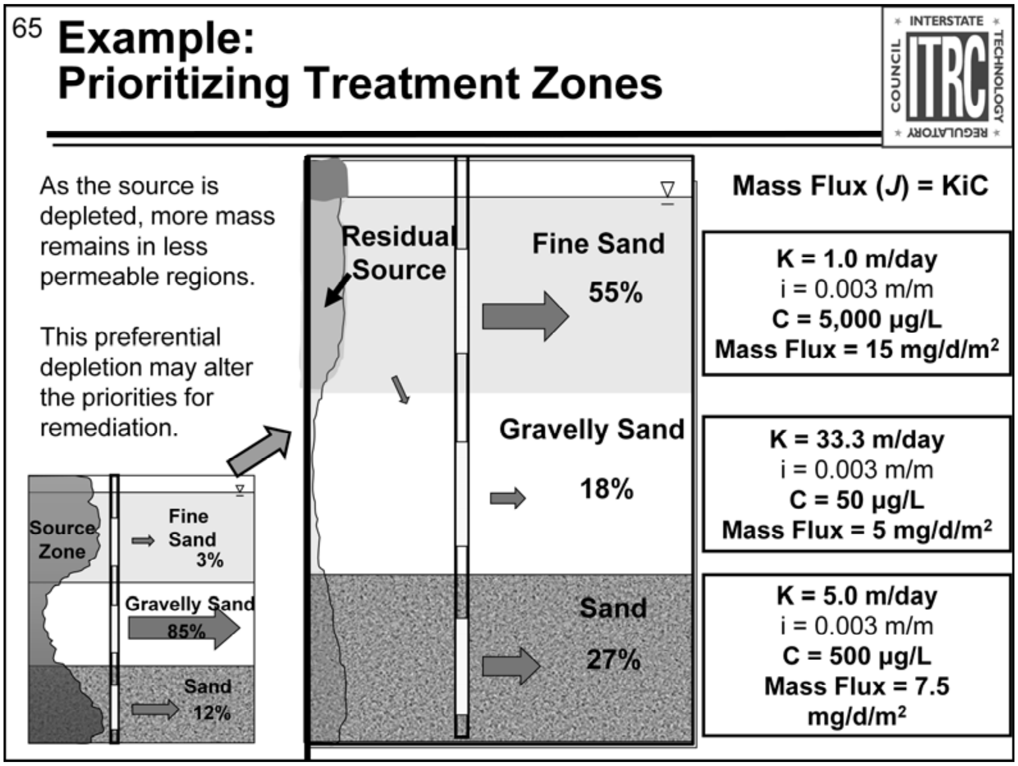
$$C_{well} = M_d \div Q_{Well}$$

$C_{well}$ = Concentration in extraction well
$Q_{well}$ = Pumping rate for extraction well




$$2\ \text{g/day} \times \frac{1}{600\ \text{gpm}} \div 1440\ \text{min} \times \frac{1\ \text{gal}}{3.79\ \text{L}} \times \frac{10^6\text{ug}}{\text{g}} = < 1\ \text{ug/L}$$

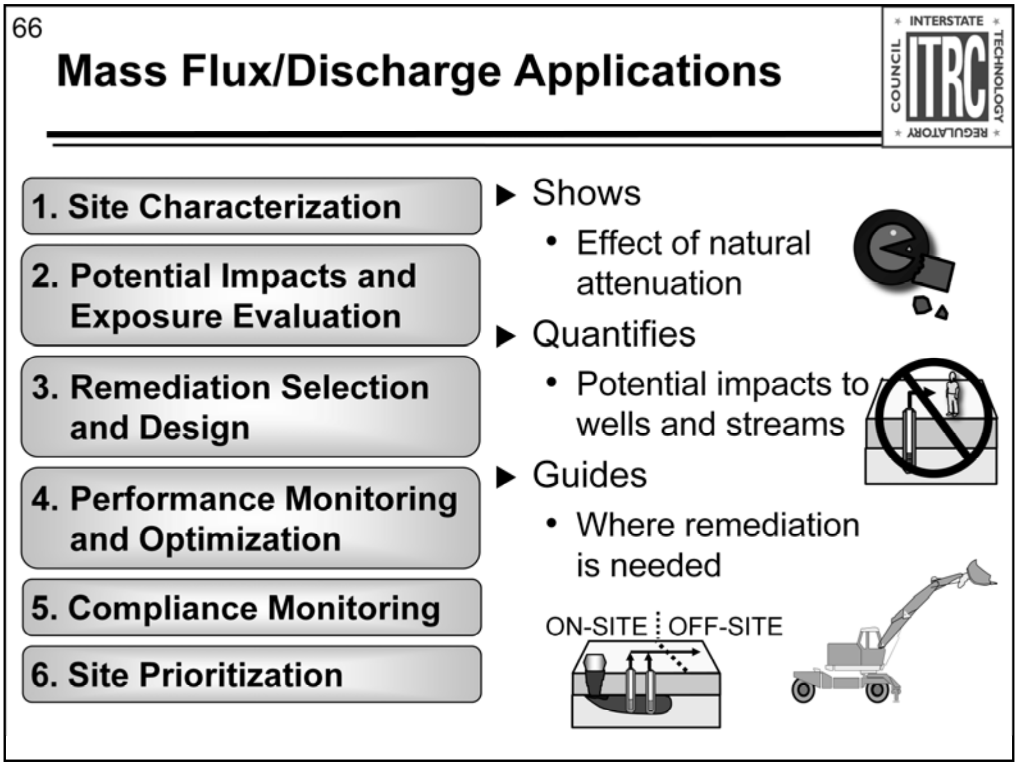
No associated notes.




This figure illustrates why using mass flux and mass discharge can improve remedy selection, design, and performance monitoring.

In this case, there are 3 sandy layers each with identical gradients (.003). But conductivity varies among them 33-fold, from 1 m/day in the fine sand layer at the top to 33 m/day in the gravelly sand, and the concentrations vary by two orders of magnitude from 50 ug/L in the gravelly sand to 5,000 ug/L in the fine sand top layer. In this figure, the highest concentration is in the least permeable layer.

As a result, the mass flux is highest in the fine sand at 15 mg/day/m2 and lowest in the gravelly sand at 5 mg/day/m2.




No associated notes.

## Regulatory Precedence

- Federal Superfund…signed Record of Decision (ROD) identifying a mass discharge interim goal [Well 12A site, WA, Oct 2009]
- Surface water regulation (e.g., Total Maximum Daily Loads (TMDL), National Pollutant Discharge Elimination System (NPDES)) is based on mass discharge
- Groundwater extraction gives estimate of mass discharge over capture zone
- Natural attenuation relies on mass discharge reduction

I NPDES permits you are required to report concentration and mass measurements

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# Regulatory Acceptance – Needs

1. Develop comfort level with mass flux and mass discharge (Mf & Md) concepts, estimation methods, and uncertainties
2. Understand how mass discharge relates to risk-based concentration standards
3. Envision a future compliance role for Mf & Md:
   - To assess threat potential to receptors
   - To assess remedy performance
   - As a trigger for switching to MNA (or another remedy)

No associated notes.

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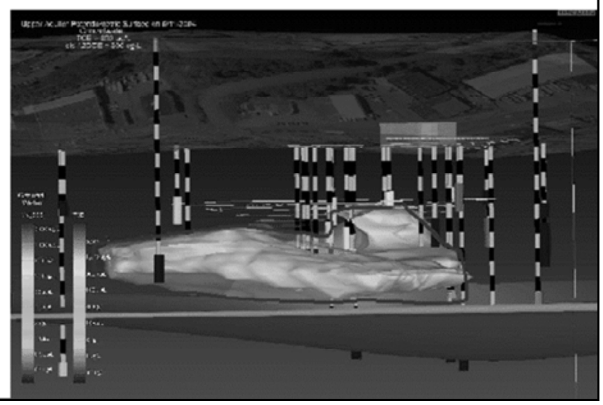
## Course Roadmap

- Mass concepts
- Measurement methods
- Application
- Case studies
- Summary



So far we've heard very useful information about how mass flux and mass discharge can be used to support site characterization and remediation, and amount some of the interesting methods for estimating mass flux and mass discharge.

Even though the use of these mass data isn't new, the frequency of use of mass data has grown rapidly in the past few years. To gain some insights on how these data are being used across the industry, we conducted a detailed review of about 65 case studies where mass flux or discharge were estimated.

The results of this detailed review are included in tables in an appendix at the back of the Overview document, including a summary of site-specific mass discharge estimates with different methods, value added to the site through the use of mass, numbers and spaces between wells when used with the transect method, etc.

What we're going to do now is review several case studies that demonstrate how estimating mass flux and discharge can add value at some of your own sites.

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## Frequency of Method Applications

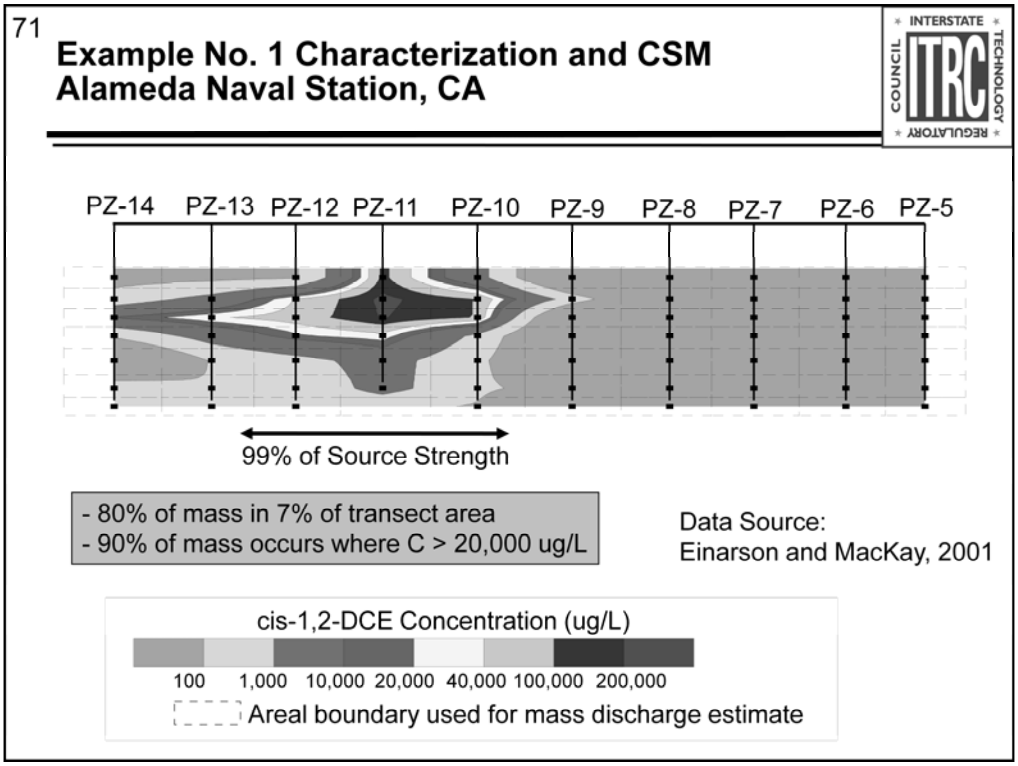
| Mass Flux and Mass Discharge Measurement/Estimation Method | No. Sites Where Applied |
| --- | --- |
| Transects with groundwater sample collection | 41 |
| Integral Pump Test(s) | 7 |
| Transects with passive flux meters | 5 |
| Isoconcentration contours | 2 |
| Mass Balance | 2 |
| Solute Transport Model | 1 |

This table lists the frequency that various methods were used to estimate mass flux and discharge in the published case studies.

We can see from this table that the most common method for estimating mass discharge is the use of transects with the collection of groundwater samples. This method is probably the most common because it's relatively simple to apply in the field.

From the published case studies, we have seen more recent use of integral pump tests to estimate mass discharge at transects, as well as passive flux meters.

Many of these reported case studies were specifically intended to compare methods for mass flux estimation or performance of an in-situ treatment technology.




The data for this site were published in a class mass flux paper written in 2001 by Einarson and MacKay and published in Environmental Science & Technology.

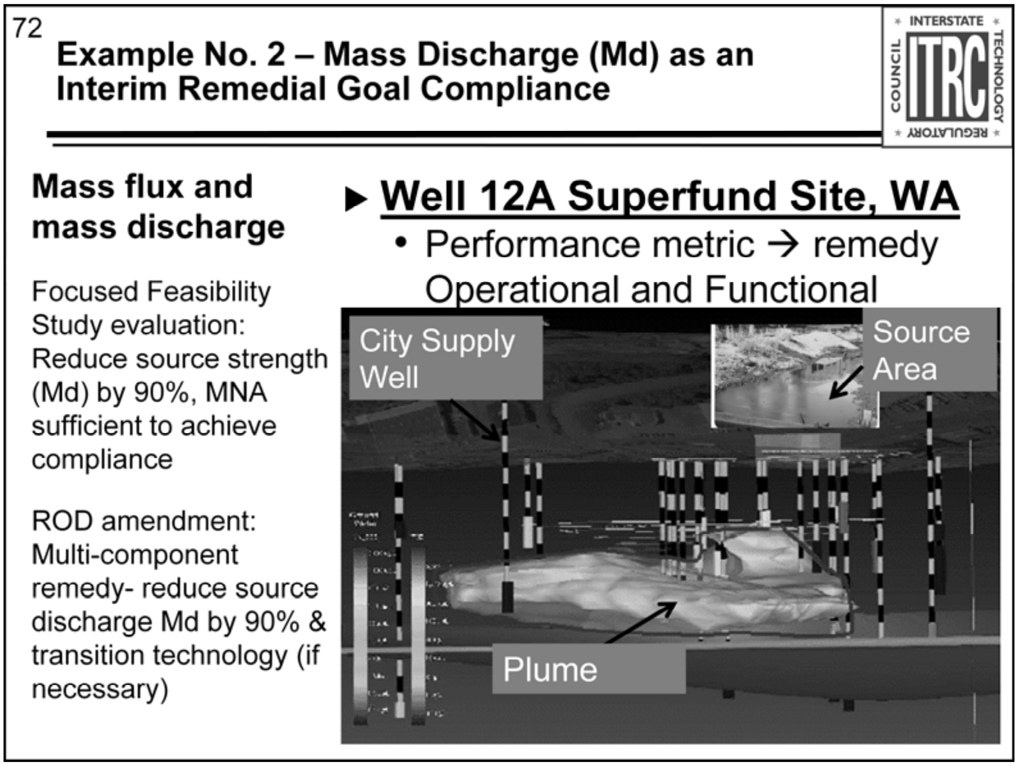
This contour map shows the distribution of concentrations of cis-1,2-DCE in a transect that is approximately 30 meters in length.

These data show the same trend that we have seen in other sites where high resolution monitoring has been conducted.

And more than 80% of the mass is situated in less than 7% of the transect.

Over 99% of the mass is situated in less than 30% of the transect cross-sectional area.

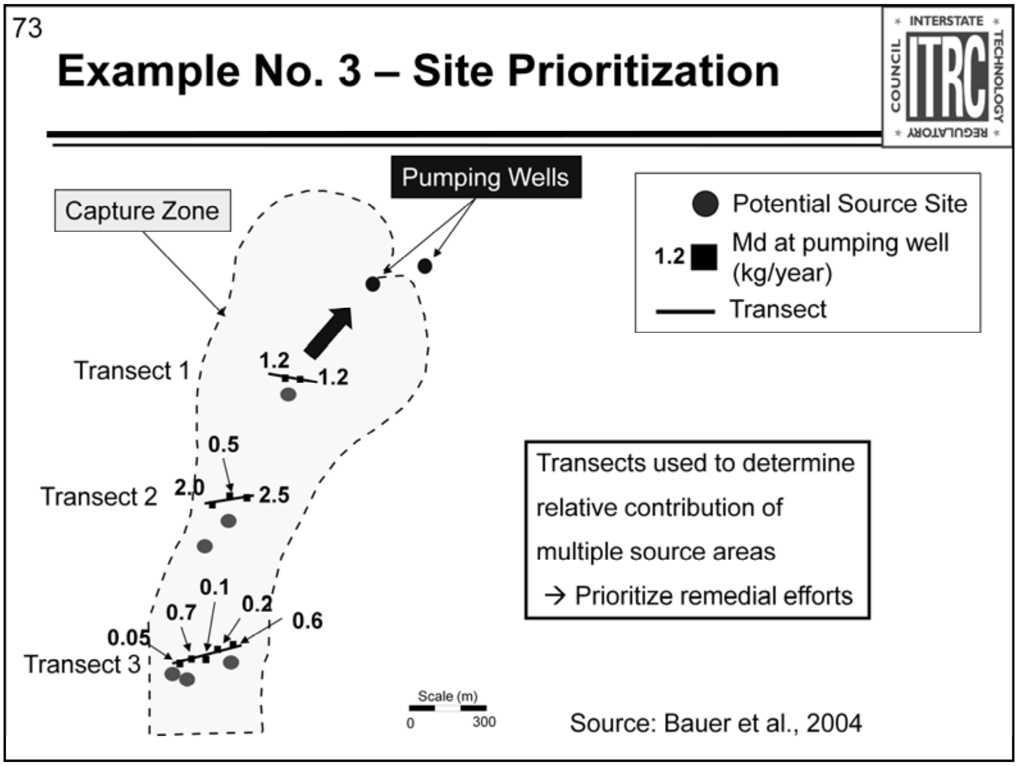
Identifying the core of the plume mass such as was done at this site can help to focus remediation and monitoring efforts which may result in substantial cost and time savings.




Next we'll talk about the Well 12A Superfund Site in Washington where mass discharge was negotiated as an interim remedial goal.

As part of the Focused Feasibility Study, groundwater modeling determined that a reduction in source strength of 90%, which represents an order of magnitude decrease, would be sufficient for compliance to be achieved through MNA.

So here's an example of a site where mass flux and mass discharge are being used not only as a performance metric to evaluate treatment efficiency, but also as a decision guide for when to transition from active treatment to MNA.




Our third example is a regional basin with a commingled PCE plume that was created as a result of multiple source sites throughout the basin.

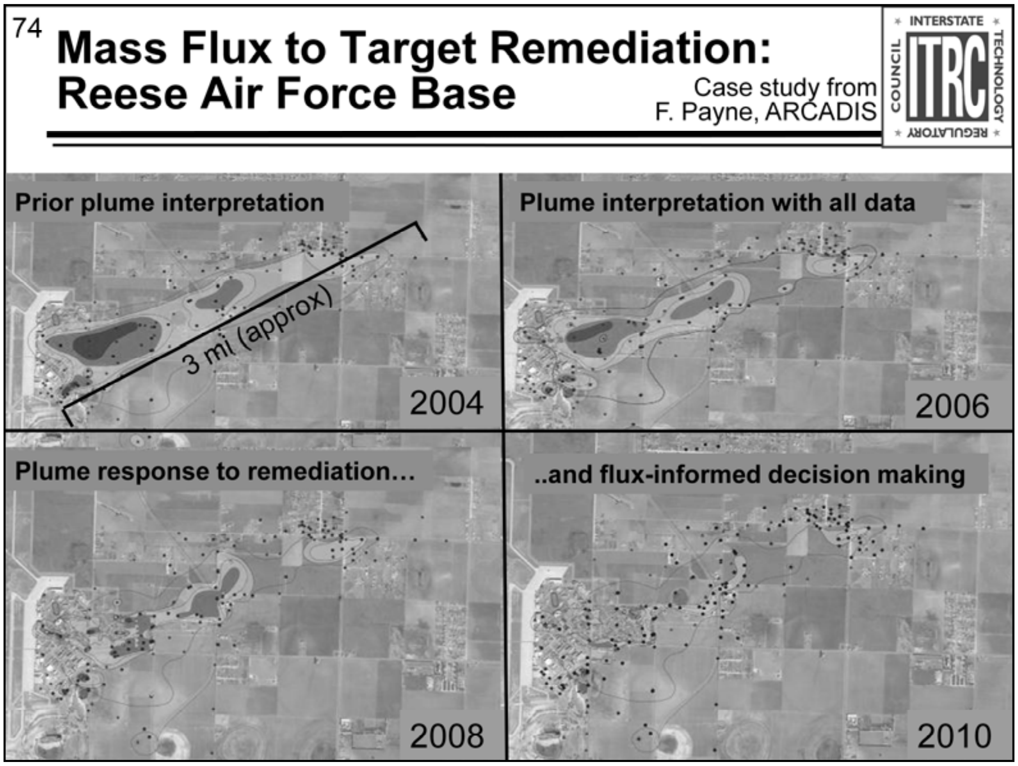
The red symbols indicate locations of potential sources contributing to the commingled PCE plume in the basin.

The yellow zone represents the capture zone for the regional supply wells shown here in blue.

The purpose of mass discharge monitoring was to evaluate which sites required further investigation and remediation, and which sites required no further action.

In the basin, multiple transects of pumping were installed downgradient of specific sites. The southern transect had a negligible mass discharge, so it was decided that these potential source sites in the south were not a priority for further investigation.

This example where sources at multiple sites are prioritized, is analogous to what we see at larger sites where multiple source zones exist. At these large sites, we can use a similar approach to prioritize which source zones need immediate treatment, and which can either be designated as a lower priority or requiring no further action.




The fourth example, Reese AFB, is really interesting. This example was provided by Fred Payne at Arcadis.

Here's a site that back in 2004 had a 3-mile long TCE plume. Response to remediation had stagnated.

When Arcadis became involved, they recognized that more characterization of the source zone was needed to define how the mass was distributed.

This enhanced characterization of mass flux in the source zone resulted in the decision to focus active bioremediation where mass was highest in the source zone.

The enhanced mass flux characterization was also used to optimize the use of groundwater extraction wells to accelerate mass removal from the source zone.

This is an example of what Fred appropriately calls "Flux-informed decision-making", where the mass flux distribution was used to improve the efficiency of the remediation effort.

Through this effort the mass in the plume has been reduced by a factor of ten and is still decreasing today.

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No associated notes.

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## Mass Flux and Mass Discharge Summary

- Estimating mass may
  - Improve conceptual site models
  - Enhance remedial efficiency
  - Refinement of exposure assessment
- More effective site management
- Can use historical data and existing monitoring networks in some cases
- Can enhance compliance measurements

No associated notes.

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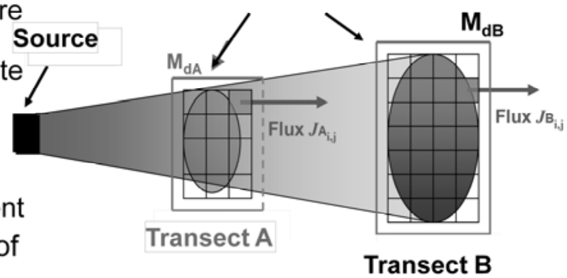
# Questions to Consider

- Why should I estimate mass flux/discharge at my site?
  - Characterization, exposure assessment, remedy selection, optimization, site prioritization, compliance
- How do I calculate mass flux/discharge?
  - Figure 2-2 of the document
- What are the cost/benefits of using mass flux/discharge?
  - Life cycle cost reduction, targeted remediation
- Can mass flux help measure compliance?
  - Mass reduction

**Mass Discharge ($M_d$) = Sum of all Measures of Mass Flux x Area**




**$J_{Aij}$= Individual mass flux measurement at Transect A**

**$M_{dA}$= Mass discharge at transect A (sum of all of the mass discharge estimates for each specific area [$J_{aij}$ x A])**

No associated notes.

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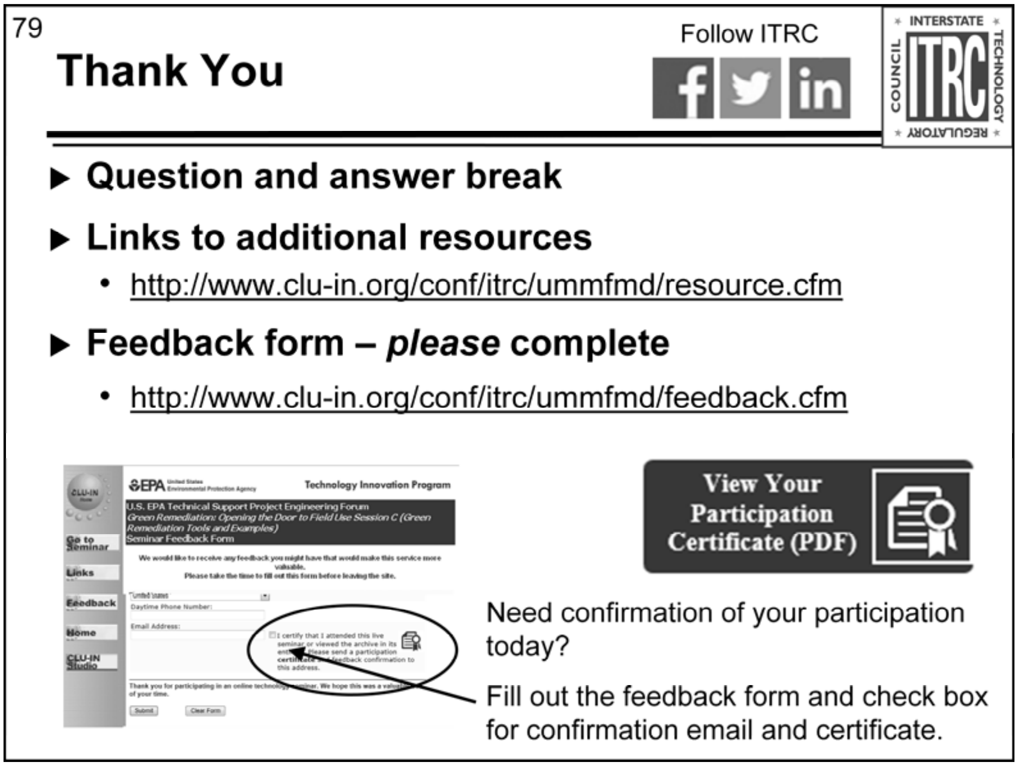
# Additional ITRC Technical and Regulatory Guidance

- Integrated DNAPL Site Strategy (IDSS-1, 2011)
  - Further describe uses of mass flux and mass discharge estimates
  - Cleanup strategy
  - Goals and objectives
  - Treatment trains
  - Monitoring
- Integrated DNAPL Site Characterization (ISC-1, 2015)
  - DNAPL characteristics
  - Life cycle of a DNAPL site
  - Integrated site characterization: plan, tools selection, implementation
- Characterization and Remediation in Fractured Rock – coming soon

No associated notes.




Links to additional resources:
http://www.clu-in.org/conf/itrc/ummfmd/resource.cfm

Your feedback is important – please fill out the form at:
http://www.clu-in.org/conf/itrc/ummfmd/feedback.cfm

**The benefits that ITRC offers to state regulators and technology developers, vendors, and consultants include:**

✓Helping regulators build their knowledge base and raise their confidence about new environmental technologies

✓Helping regulators save time and money when evaluating environmental technologies

✓Guiding technology developers in the collection of performance data to satisfy the requirements of multiple states

✓Helping technology vendors avoid the time and expense of conducting duplicative and costly demonstrations

✓Providing a reliable network among members of the environmental community to focus on innovative environmental technologies

**How you can get involved with ITRC:**

✓Join an ITRC Team – with just 10% of your time you can have a positive impact on the regulatory process and acceptance of innovative technologies and approaches

✓Sponsor ITRC's technical team and other activities

✓Use ITRC products and attend training courses

✓Submit proposals for new technical teams and projects