Naval Facilities Engineering Systems Command

EXWC Engineering and Expeditionary Warfare Center

Groundwater-Surface Water Interactions (GSI)

Michael Mathioudakis, PE
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RITS 2026

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Information in this presentation is current as of 10 April 2026.

EXWC: Engineering and Expeditionary Warfare Center
NAVFAC: Naval Facilities Engineering Systems Command

Speaker Introduction

Michael Mathioudakis, PE

Environmental Engineer
GSI Environmental Inc.

- **BS Environmental Engineering** (Hydrogeology focus)
- **MS Geology and Geophysics** (Coastal Hydrology focus)
- 10 years working on investigation, remediation, and site characterization for DoW and private clients
- **FAA-licensed drone pilot** (Part 107) for mapping groundwater discharges to surface water

BS: Bachelor of Science
DoW: United States Department of War
FAA: Federal Aviation Administration
MS: Master of Science
PE: Professional Engineer

Presentation Overview

- Introduction
- What are GSI?
- When are GSI Important?
- Common Components of GSI Investigations
- How to Plan for and Scope GSI Investigations
- Unique Challenges of GSI Investigations for PFAS
- Case Study #1: Joint Base Cape Cod
- Case Study #2: Naval Station Newport
- Summary and Closing

Objectives

- Learn when and why GSI investigations are important for site characterization and remediation
- Summarize methods that can be used for GSI investigations
  - Field observations and measurements
  - Remote sensing
  - Hydrological methods
  - Geochemical methods
  - Geophysical methods
  - Modeling methods
- Present case studies with real-world examples of GSI investigations at DoW sites

(Mathioudakis 2014)

Past Related RITS Talks

2021 Monitoring Tools for Assessing Natural Attenuation in the Groundwater/Surface Water Transition Zone

2017 Natural Attenuation Processes at the Groundwater/Surface Water Interface

2009 Evaluating the Groundwater/Surface Water Interface

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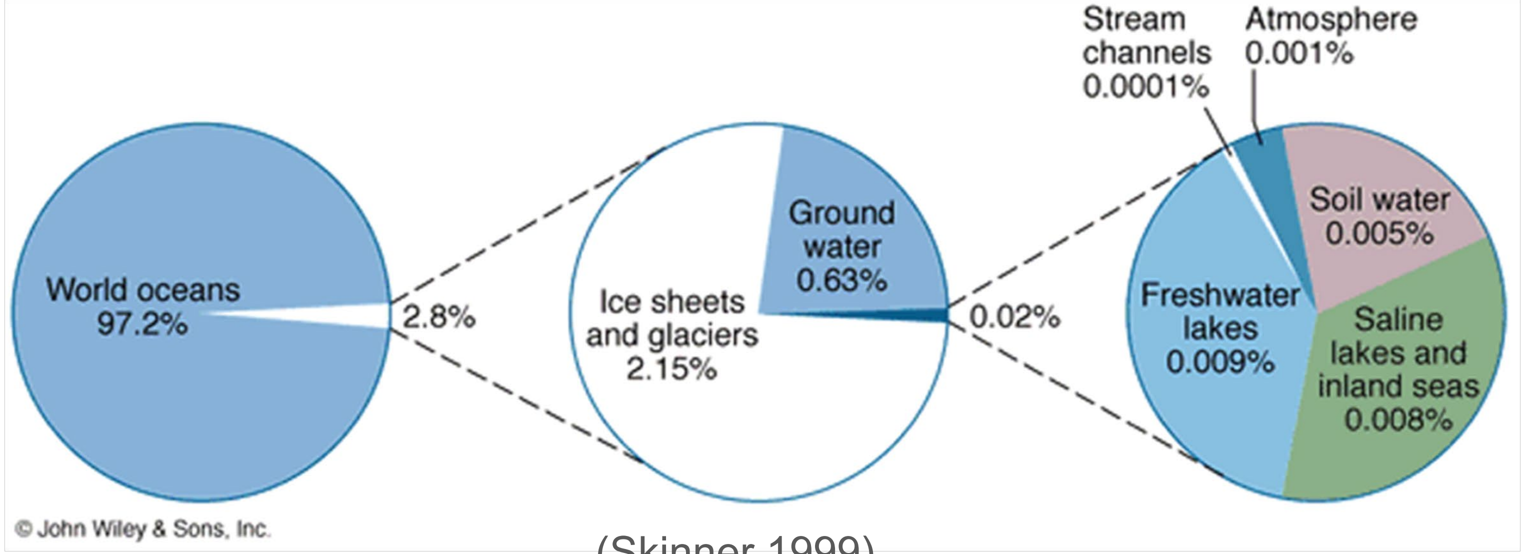
What are GSI?

- ~10,000x more water in groundwater than in rivers/streams (Gleick 1993)
- Significant flow component in rivers/streams is groundwater (**Baseflow**)
- Flow directly from aquifers to ocean: **SGD**
  - Total: ~3–4x river discharge to ocean
  - Fresh: ~1% of river discharge to ocean (Zhou et al. 2019) but plays a significant role in nutrient cycling, anthropogenic impacts, etc.



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(Skinner 1999)

SGD: submarine groundwater discharge

What are GSI?

- Hydrologic cycle driven by solar energy and gravity
- Transport time from source to sink depends on topography and geology
- Interfaces between groundwater and streams/rivers (*hyporheic zone*) and coastal waters (*subterranean estuary*) make up the GW-SW interface

(Skinner 1999)

GW: groundwater
SW: surface water

What are GSI?

Hyporheic zone

- Saturated portions of streambeds, banks, and floodplain containing water that originates from stream and returns to channel (Woessner 2017)
- Vital mixing zone for GW/SW, allowing for exchange of water, oxygen, and nutrients; **natural attenuation of contaminants via dilution and degradation**
- Bacteria and small invertebrates reside in hyporheic zone

(CCEHGI 2021)

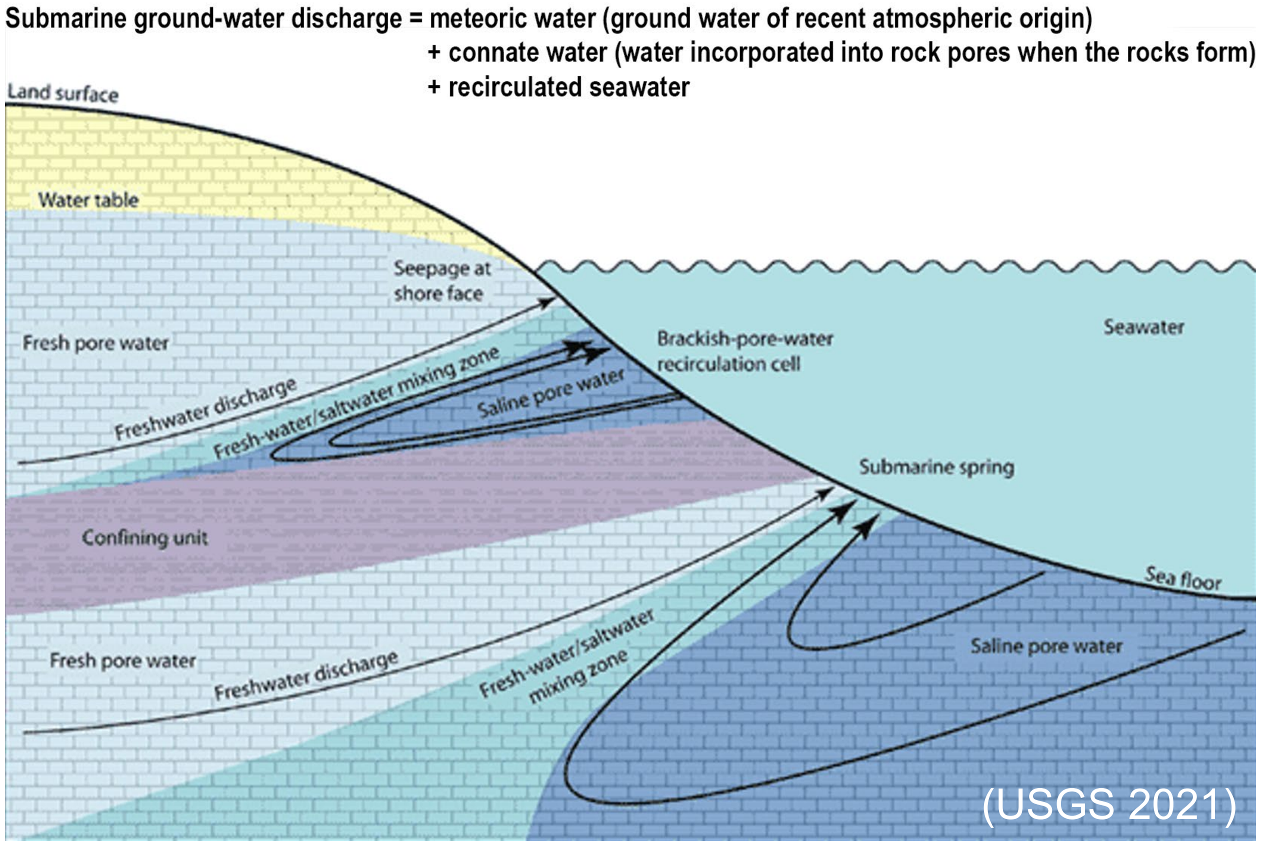
KEY POINT **GW mixes with SW in the hyporheic zone adjacent to streams/rivers.**

What are GSI?

Subterranean estuary

- Subsurface zone in which meteoric water mixes with seawater in coastal aquifers
    - Tidal and seasonal variations
    - Natural attenuation of contaminants via dilution and degradation
- Implications of GW flux (SGD)
    - Maintains nutrient, temperature, and pH balance in coastal waters

      excess nutrients → eutrophication
    - Anthropogenic impacts to coastal waters if GW impacted by contaminants
    - Chemical reactions between mixed waters and aquifer solids modify fluid composition



Submarine ground-water discharge = meteoric water (ground water of recent atmospheric origin)
+ connate water (water incorporated into rock pores when the rocks form)
+ recirculated seawater

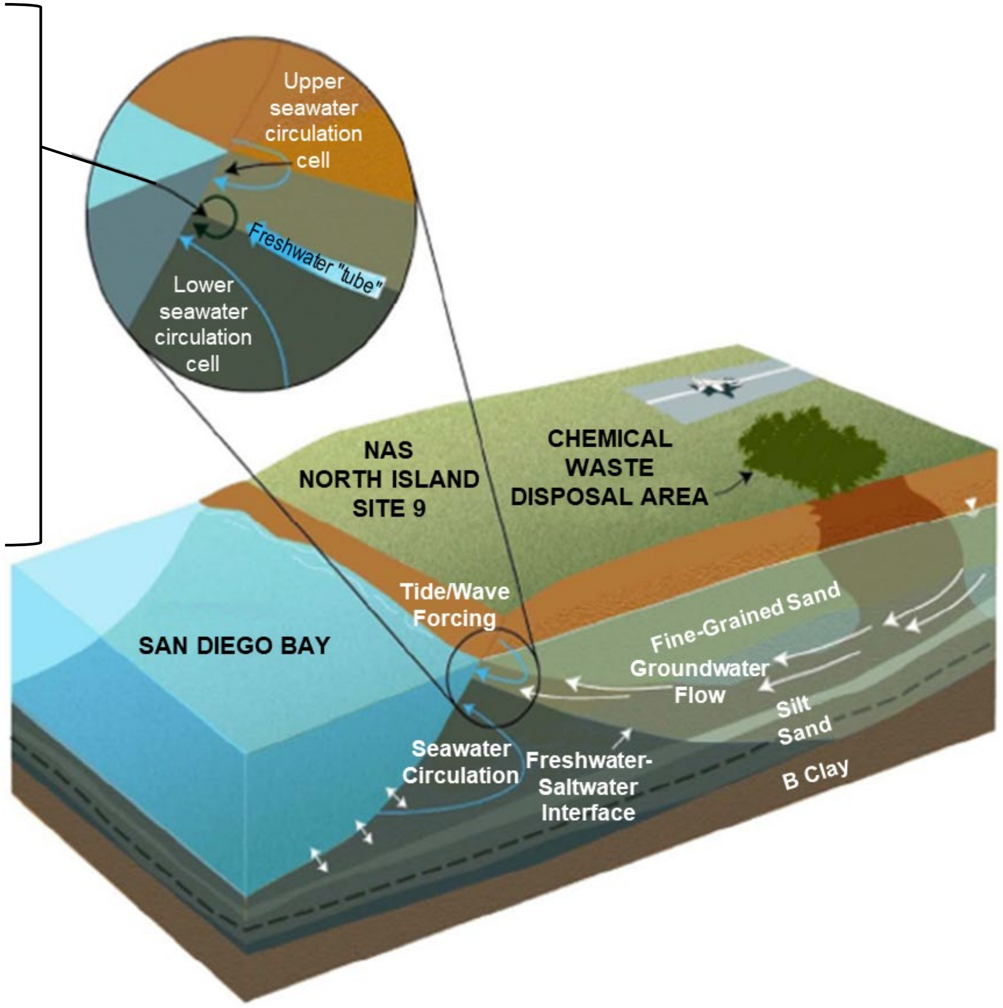
(USGS 2021)

KEY POINT

GW mixes with ocean water in subterranean estuary.

What are GSI?

- Hydrodynamic mixing
- Redox reactions
- Biotransformation
- Adsorption and ion exchange
- Mineral precipitation/ dissolution
- Sorption



(NAVFAC 2011)

Attenuation processes at the GW-SW interface

- Mixing/dilution
- Redox reactions
- Biotransformation
- Sorption
- Mineral precipitation/dissolution
- Ion exchange

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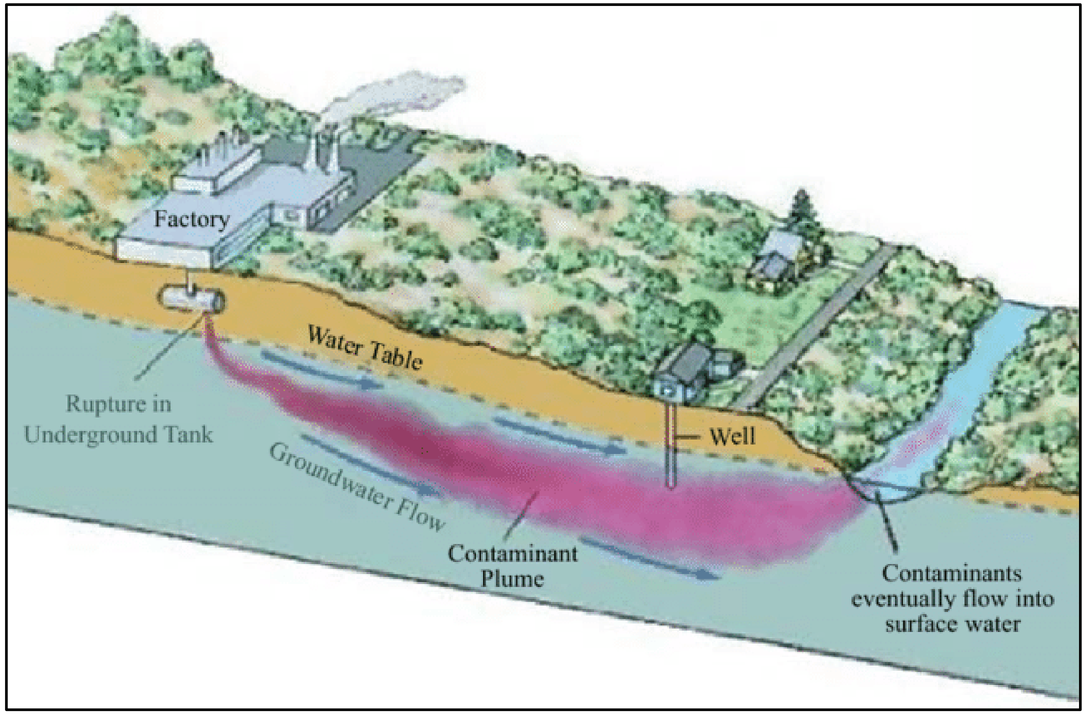
When are GSI Important?



(Earth Science Australia n.d.)

Cleanup sites (general)

- 75% of RCRA and CERCLA sites are located within 0.5 miles of SW body (EPA 2000)
- 47% of all CERCLA sites have impacted surface water (EPA 2000)

Cleanup sites (DoW)

- 43% of Navy installations on National Priorities List are in coastal areas (California, Florida, Virginia, Washington; Iery et al. 2022)
- Navy evaluated 32 sites in 2015 for optimization review; GW plumes at 25 of the 32 sites (78%) were discharging to SW and GW discharge zones (Iery et al. 2022)

CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act
EPA: United States Environmental Protection Agency

Navy: Department of the Navy
RCRA: Resource Conservation and Recovery Act

When are GSI Important?

Objectives of GSI investigation

CSM development/site characterization (sites near SW)

Defining extent of contaminant migration

- Are GW migration pathways complete?
  (i.e., Do plumes extend to SW?)

Informing risk assessment

- Should receptors in SWs be considered?

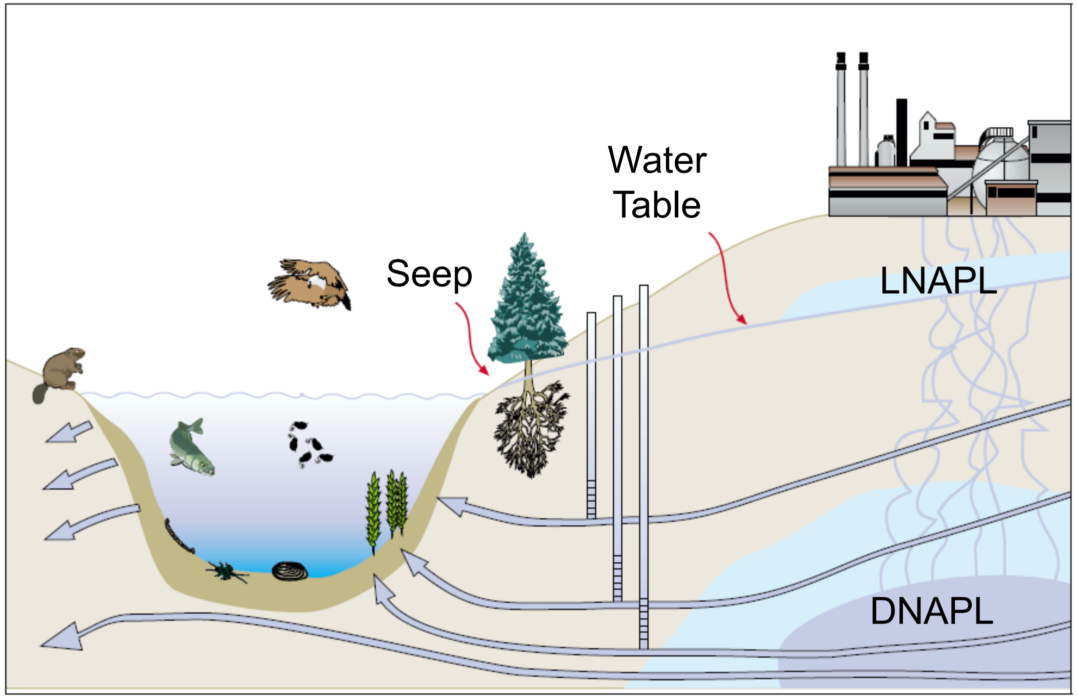
Quantifying GW discharge and contaminant flux

- How much contaminant mass is reaching SW?

Informing remediation strategies

- Will remediation impact natural flow regimes? (e.g., pumping wells causing saltwater intrusion)
- If plume is reaching SW, engineering controls might be needed

Monitoring remedy effectiveness



(EPA 2000)

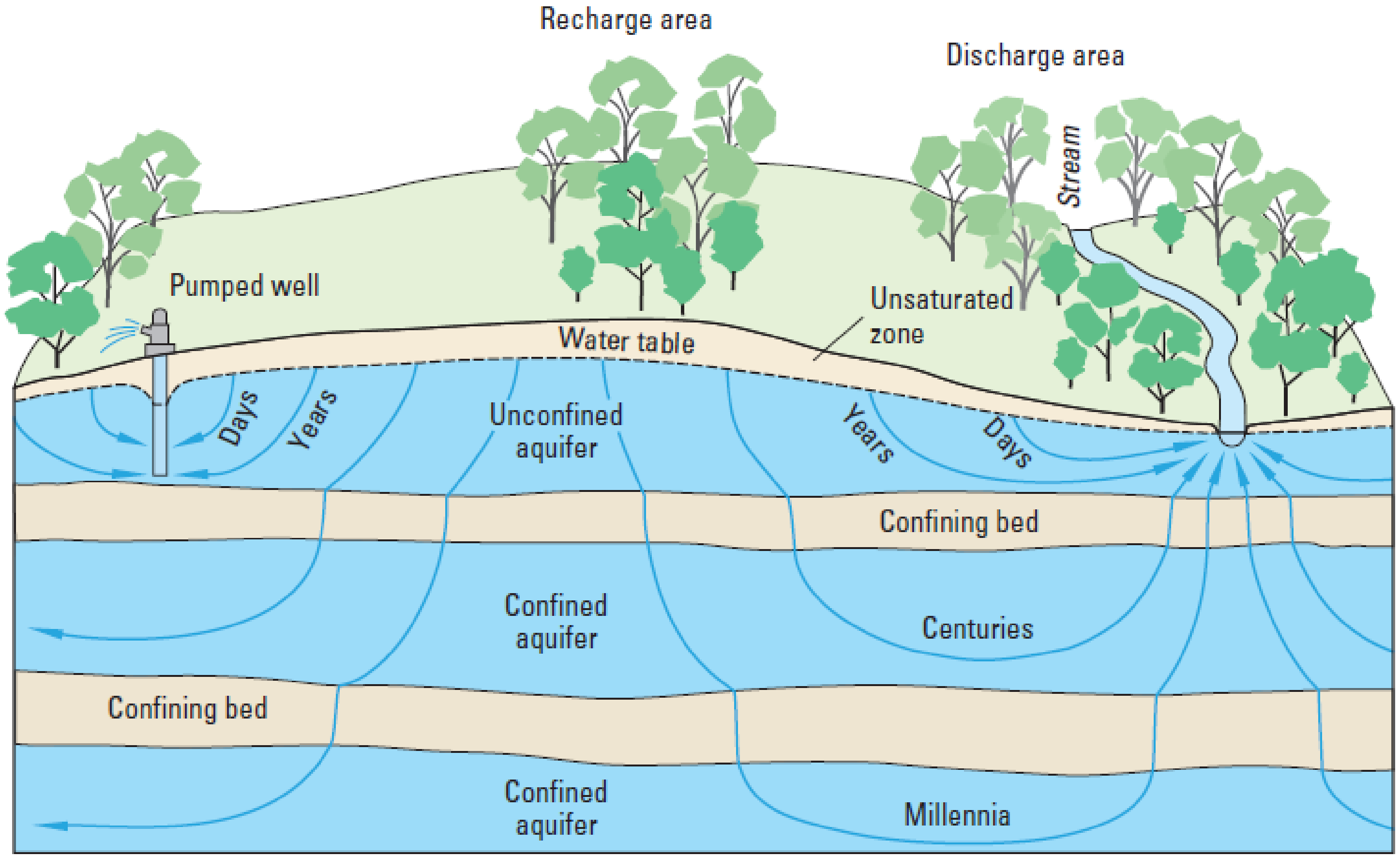
CSM: conceptual site model

L/DNAPL: light/dense nonaqueous phase liquid

When are GSI Important?

Unconfined conditions

Generally, GW reaches SW much faster (days/years) in unconfined aquifers than in confined aquifers (years/centuries/millennia)

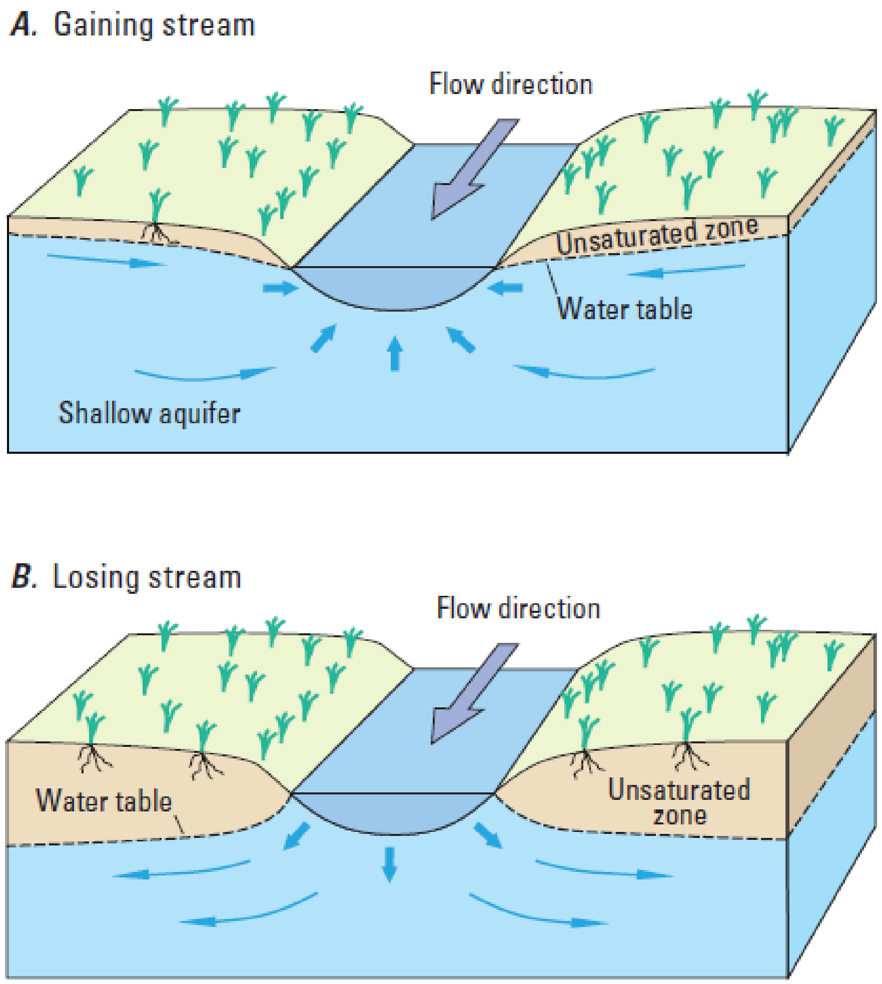


(USGS 2012)

When are GSI Important?

If SW is potential receptor

- Gaining/losing analysis is essential
  - Gaining: GW flowing into stream
  - Losing: SW flowing from stream into GW
    - Losing conditions are typically short-lived; most streams are "gaining" during baseflow conditions
    - If losing, GW Migration Pathway to SW is not complete, BUT…
    - GW head gradient moving away from stream can influence plume dynamics/contaminant transport



(USGS 2012)

Knowledge Check

In which scenarios should GSI be considered?

1. A small hydrocarbon release to shallow aerobic aquifer occurs approximately 2 miles from losing stream reach. Should GSI be considered?
2. Historical AFFF releases occurred from FTA approximately 1 mile from coastal estuary. Should GSI be considered?
3. DNAPL release occurs approximately 1 mile from gaining stream and penetrates confining layer in release vicinity due to hydraulic head of the DNAPL body. Should GSI be considered?

AFFF: Aqueous Film Forming Foam

FTA: fire training area

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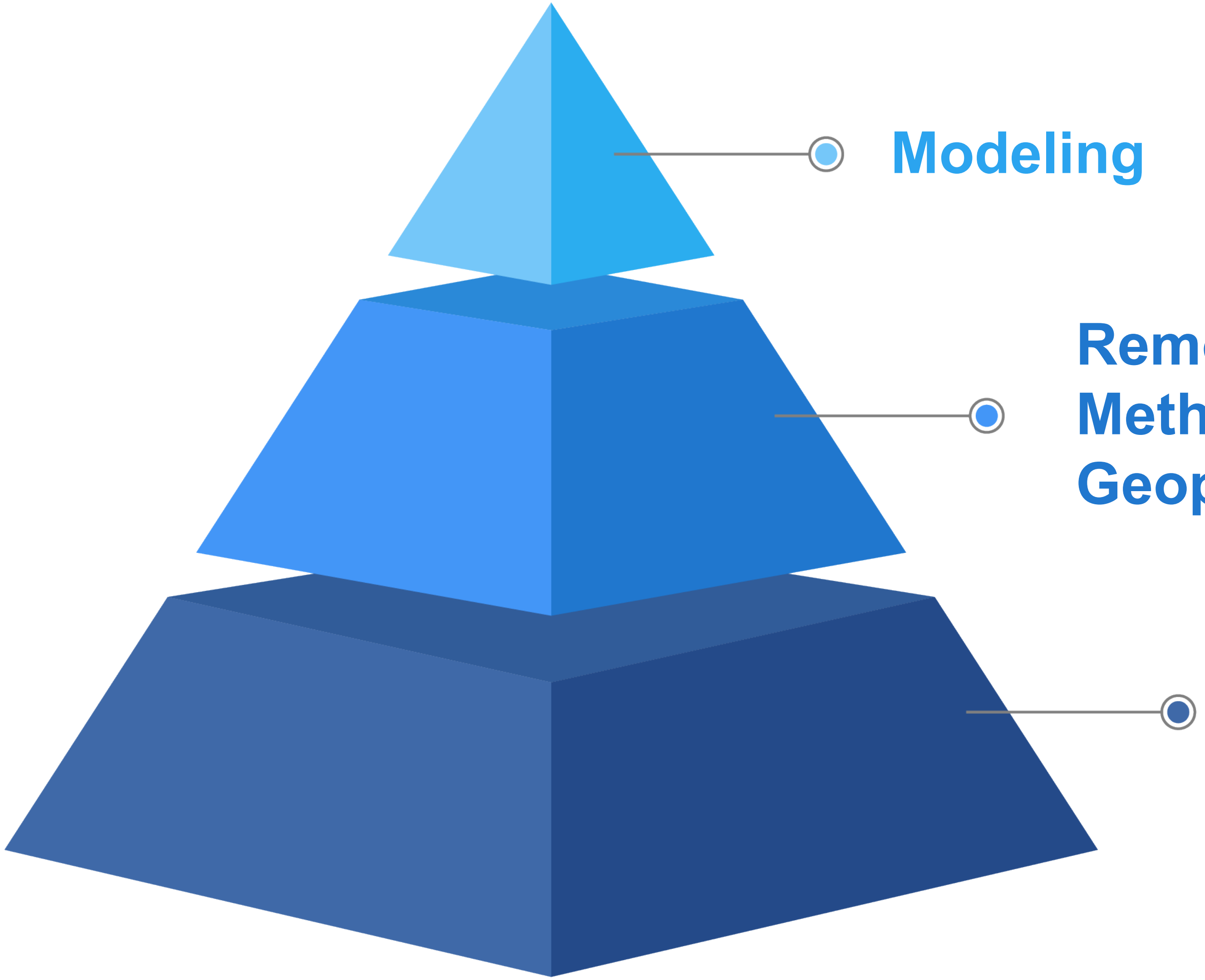
Common Components of GSI Investigations



Modeling

Remote Sensing, Hydrological Methods, Geochemical Methods, Geophysical Methods

Basic Field Observations and Measurements

GSI Methods: Field Observations and Measurements

1. **Look for visual evidence of GW seeps** (bubbling, iron oxide staining, etc.)
2. **Collect basic field measurements**, which requires understanding background values for GW/SW
   - **Temperature** (GW lower than SW in warm climate, higher in cold climate)
   - **DO** (GW typically lower than SW)
   - **Conductivity** (GW lower than coastal SW)
   - **Silica** and **radon** (GW higher than SW)
     - For porewater/shallow GW measurements, use push piezometers or trident probes
     - Basic mixing calculations (any parameter) give % GW in SW
3. **Consider advanced techniques** (next slides)

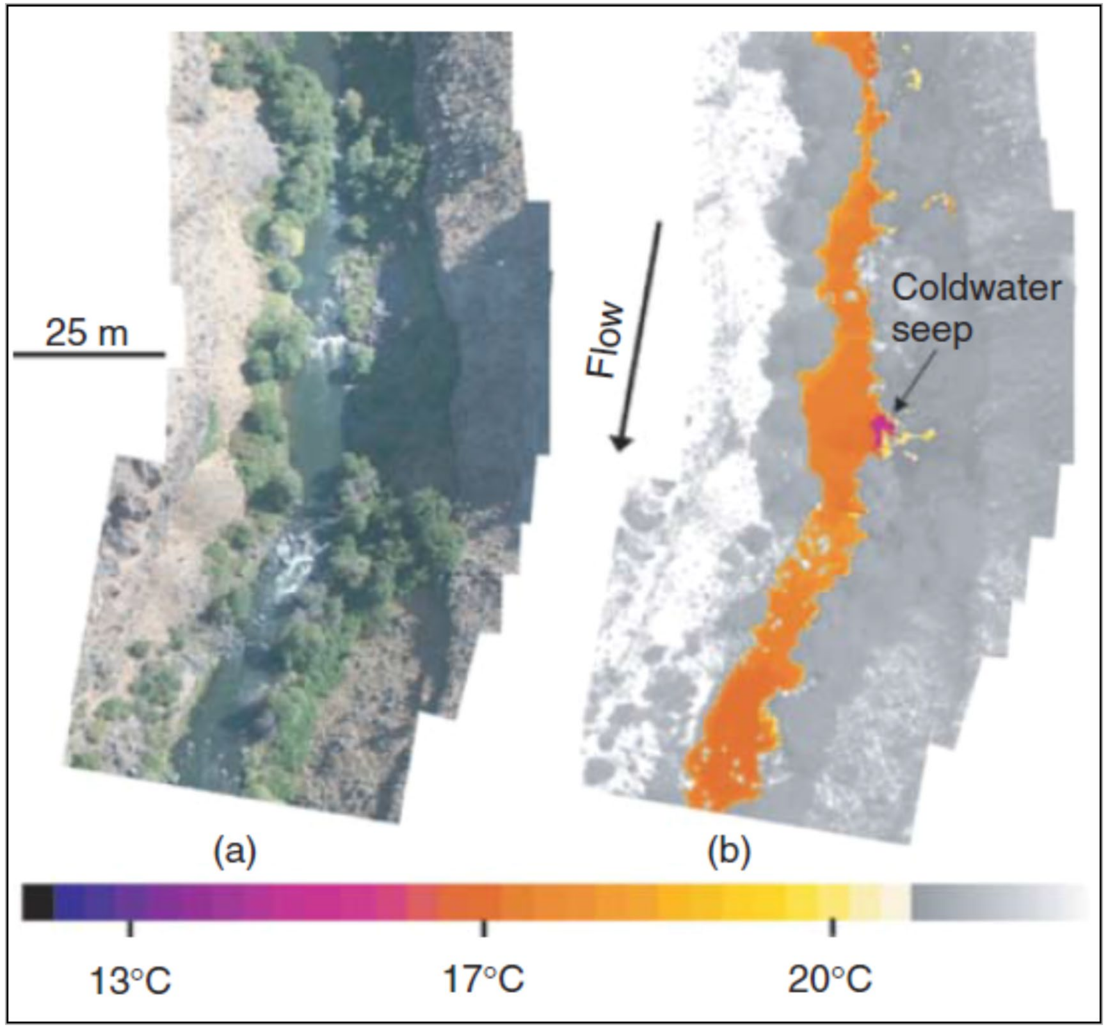
DO: dissolved oxygen

(Mathioudakis 2016)

(Phys.org 2020)

GSI Methods: Remote Sensing

- GW is insulated from sun; not subject to same temperature fluctuations as SW
- Thus, there is usually ΔT between GW and SW
- Magnitude of ΔT depends on locale, season, time of day, etc.
- Mapping temperature with TIR allows us to “see” groundwater discharges due to temperature contrast
- Requires understanding of background temperature of GW and SW



(Handcock et al. 2012)

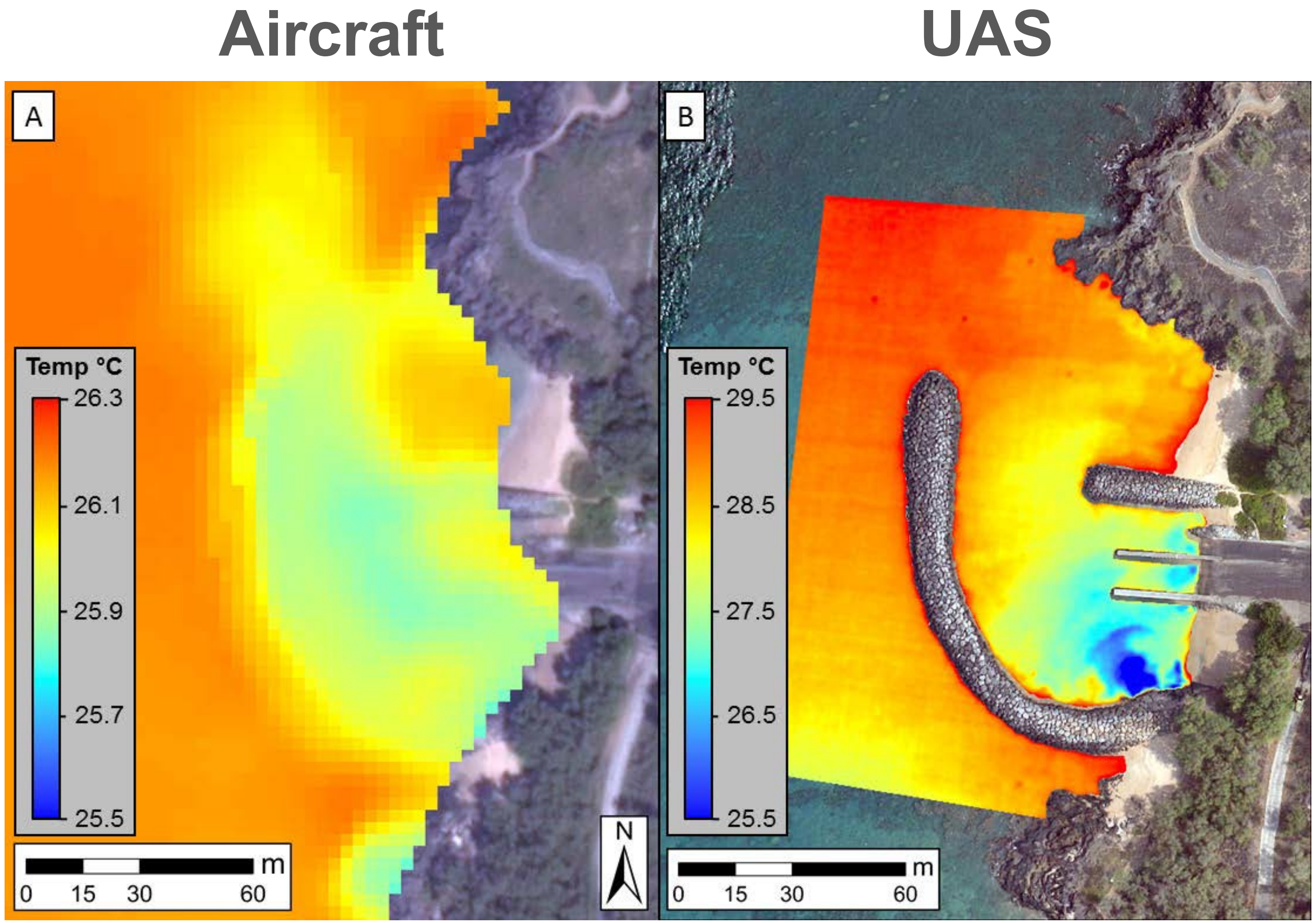
ΔT: temperature difference
TIR: thermal infrared imaging

GSI Methods: Remote Sensing

Platform choice should depend on scale of survey

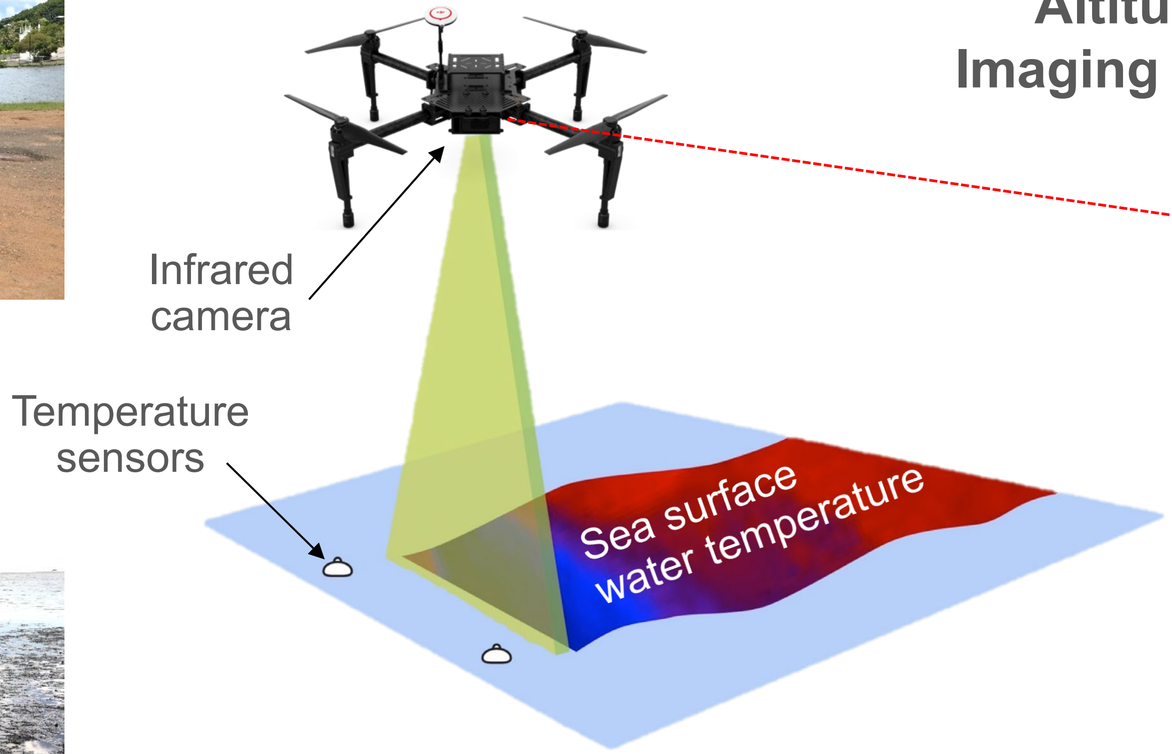
Satellite:	global/regional
Aircraft:	regional/local
UAS:	local/site

UAS: unmanned aircraft systems



(Kennedy 2016)

GSI Methods: Remote Sensing—Coastal



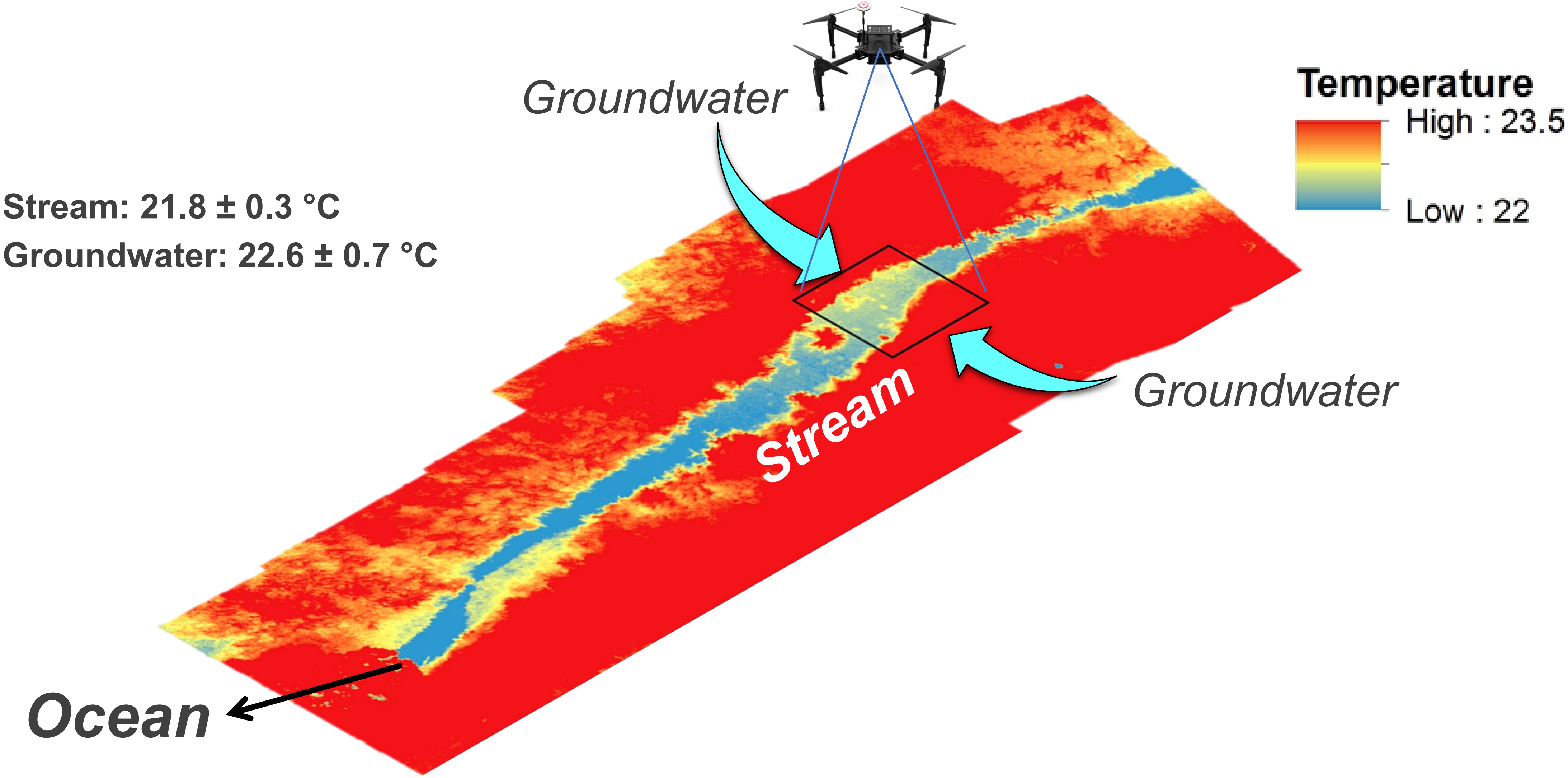
Altitude = 400 feet
Imaging width = 300 feet

(Mathioudakis 2016, 2017)

GSI Methods: Remote Sensing—Streams/Rivers

Stream: 21.8 ± 0.3 °C

Groundwater: 22.6 ± 0.7 °C



°C: degrees Celsius

(Mathioudakis 2017)

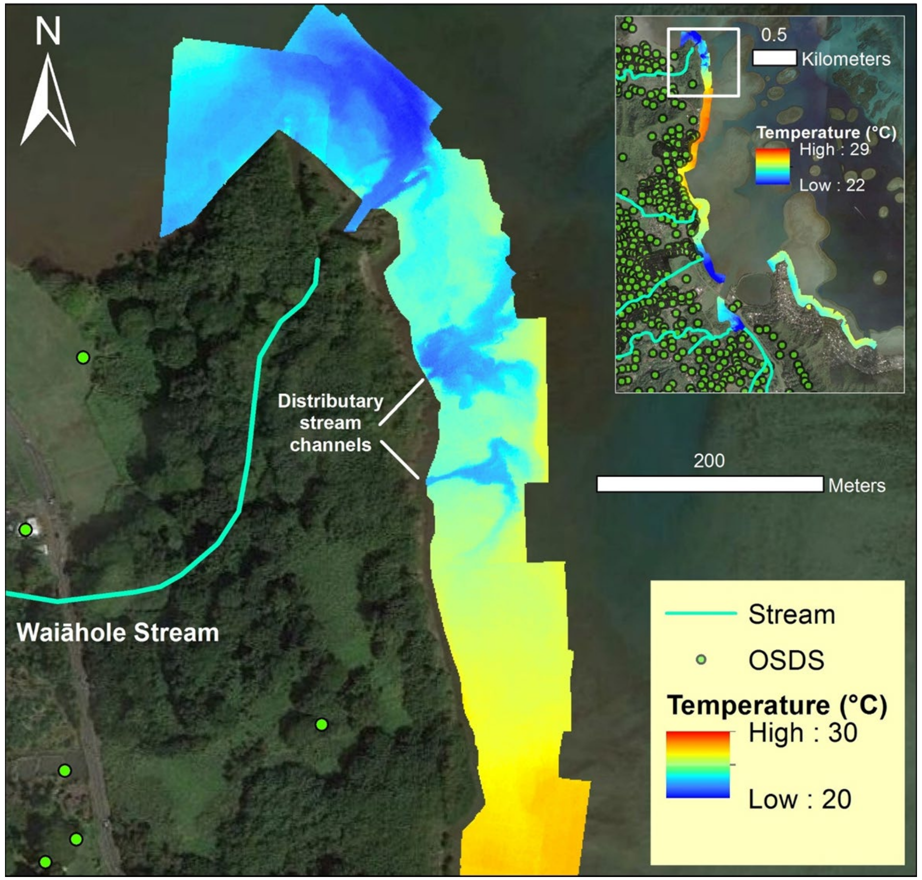
GSI Methods: Remote Sensing

TIR best practices

- Time surveys with low tide, ambient temperature, etc., for optimum contrast
- Deploy in situ temperature sensors (ground-truthing) and ground control points (georeferencing)
- Abide by FAA regulations: pilot licensing, aircraft registration, etc.
- Note relevant restrictions (e.g., no use of DJI drones by federal agencies or contractors)

KEY POINT

Temperature differences between GW and SW allow us to "see" GSI with TIR.



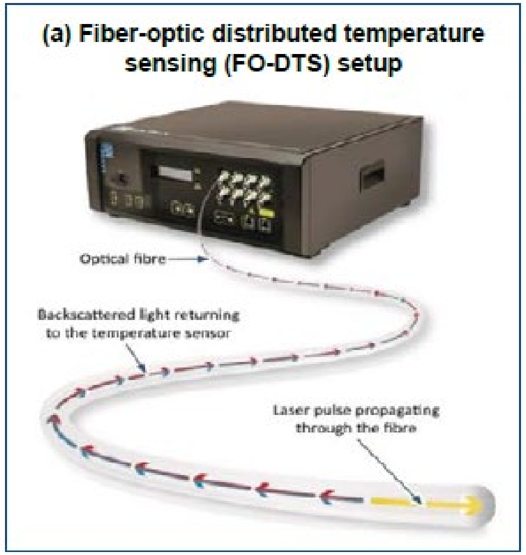
(Mathioudakis et al. 2025)

DJI: Da Jiang Innovations

GSI Methods: Fiberoptic Distributed Temperature Sensing

- Fiberoptic cable placed along GW-SW interface
- **Time-series measurements of temperature** along length of cable for detecting GW seeps
- While UAS-TIR is ideal for “snapshot” surveys, FO-DTS allows for evaluation of GW discharge over time where fluctuations are expected due to tides, rainfall, and other external factors

More on this later…



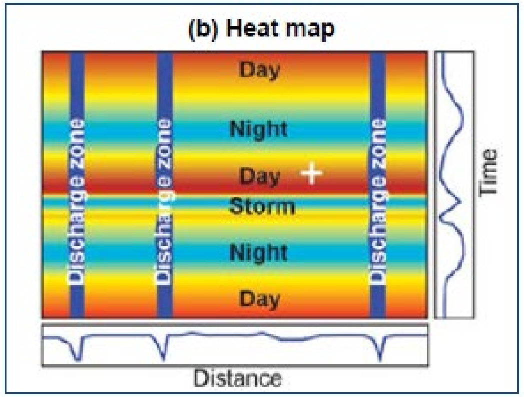
(a) Fiber-optic distributed temperature sensing (FO-DTS) setup

(a) FO-DTS control unit with fiber-optic cable

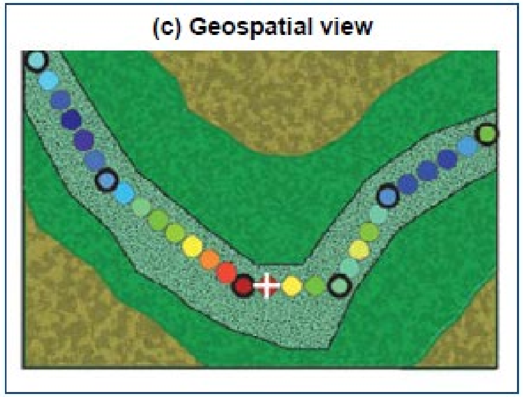
(b) FO-DTS data displayed in a heat map as temperature versus distance and time

(c) Temperature along the cable, with locations interpolated linearly between points

NOTE: FO-DTS photo courtesy of Silixa LLC. Images adapted from Domanski et al. (2020)



(b) Heat map



(c) Geospatial view

(NAVFAC 2025)

FO-DTS: Fiberoptic Distributed Temperature Sensing

GSI Methods: Hydrological

Physical measurements/analyses

- Seepage runs (gaining/losing analysis)
- Seepage meters
- UltraSeep
- Stream gauge/piezometer pairs

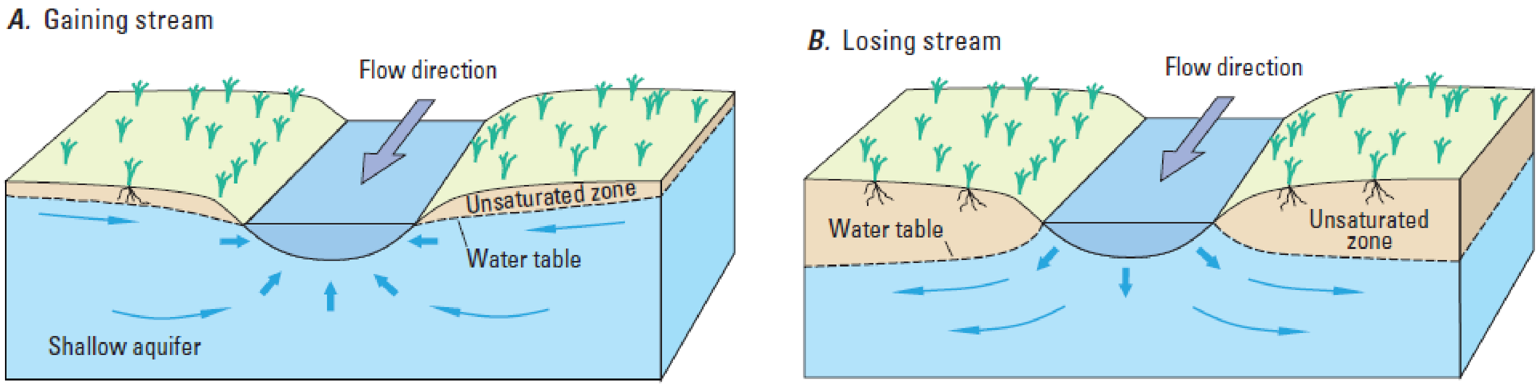
(Mathioudakis 2017)

(Mathioudakis 2017)

GSI Methods: Hydrological

Seepage runs (gaining/losing analysis)

1. Divide stream/river into reaches
2. Measure flow at upstream and downstream boundary of each reach and all tributaries/diversions
3. Use measurements in mass balance equation



(USGS 2012)

(Mathioudakis 2017)

$$\boxed{GW\ Input = Q_{GW} = Q_{downstream} - Q_{upstream} + \Sigma Q_{diversions} - \Sigma Q_{tributaries}}$$

(GW Input = downstream flow – upstream flow + diversion flow – tributary flow)

GSI Methods: Hydrological

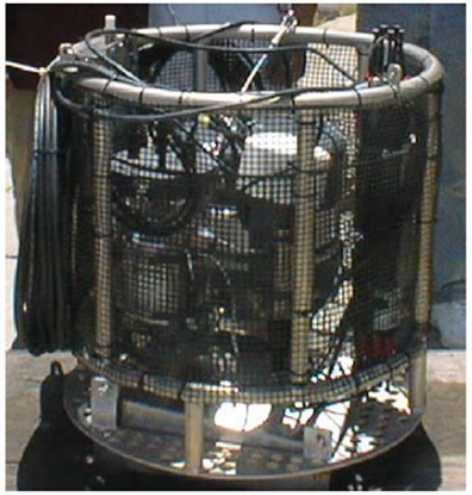
(USGS 2016)

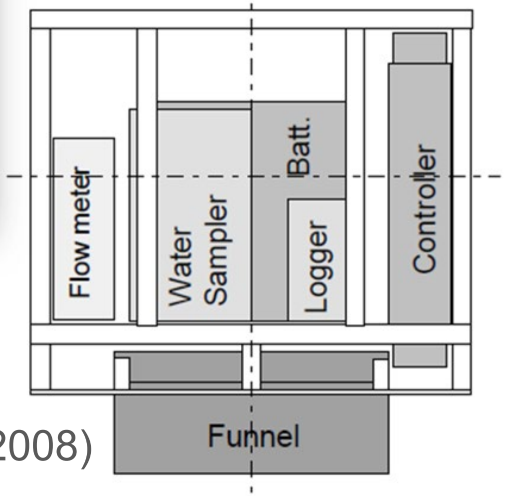
Seepage meters

Directly measure flux (volume/time) between GW and SW

- **Installation**: Bottomless cylinder (e.g., drum or pipe) is pushed into lake or stream bed, isolating portion of sediment
- **Connection**: Clear collection bag filled with known volume of water is attached to tube at top of cylinder
- **Measurement**: Change in water volume after set time indicates GW flux (or discharge) rate
- **Calculation**: Flux rate is determined by volume change, time, and area of cylinder

GSI Methods: Hydrological





(ESTCP 2008)

UltraSeep

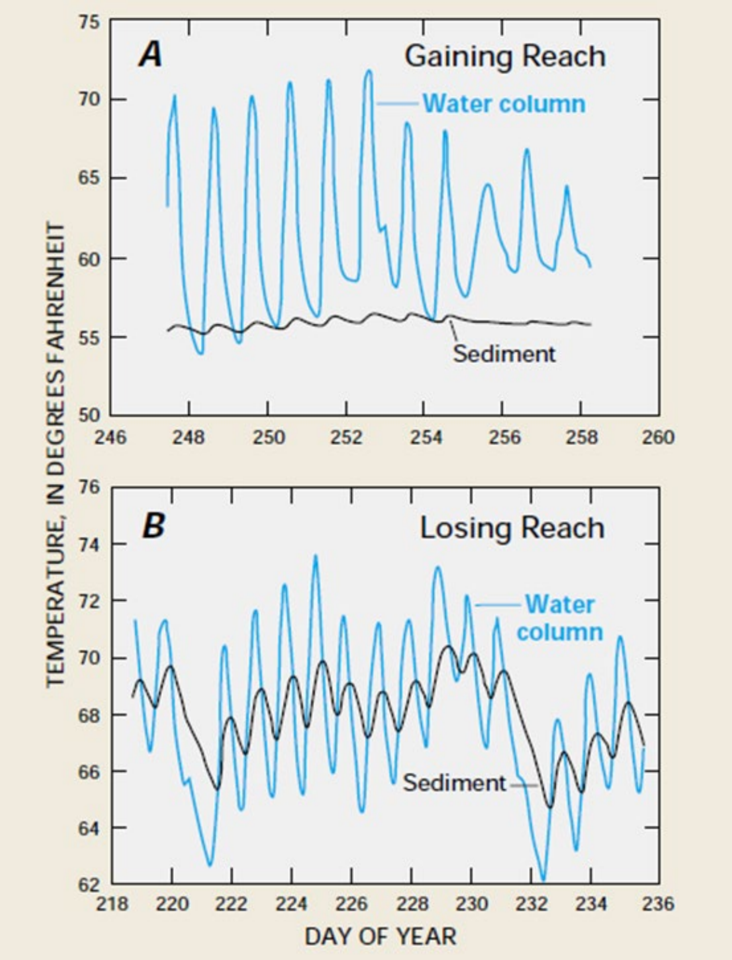
- Integrated seepage meter and water sampler for quantifying discharge rates and chemical loading from GW to SW
- Continuous flow detection and automated sample collection
- Time-series data can be collected to show GW discharge and concentrations over time

ESTCP: Environmental Security Technology Certification Program

GSI Methods: Hydrological

Stream gauge/ piezometer pairs

- Compare temperatures and/or elevations of stream and water table to determine when stream is gaining and losing at particular location
- Quantify gradient and hydraulic conductivity to allow for volumetric flux calculation
- Use BFI method



(Constantz 2008)

(Mathioudakis 2017)

BFI: Baseflow Index

GSI Methods: Geochemical

(Mathioudakis 2017)

Methods

Most geochemical methods rely on tracers (natural or artificial) and associated analytical model or calculations to quantify GSI via **mixing model approach**

- Natural tracers (radon, isotopes, ions)
- Artificial tracers (injected tracer dyes, bromide)
- SBPFM

SBPFM: sediment bed passive flux meter

GSI Methods: Geochemical

Natural tracers

- Radon, isotopes (water, nitrogen), ions (salinity)
- Analysis depends on concentration differences in GW and SW for chosen tracer (e.g., radon higher in GW than SW)
- Water sampling at surface discharge location and at “endmembers” (background/ baseline locations for GW and SW)

(Mathioudakis 2017)

GSI Methods: Geochemical

Artificial tracers

- Inject conservative (nonreactive) tracer in GW (fluorescein dye, rhodamine dye, bromide, etc.)
- Measure concentrations and time lag at discharge location
- Tracer acts as proxy to estimate mass discharge and flow time from source to receptor
- Accurate estimates of breakthrough time (days/weeks/years based on GW velocity) are critical to not miss the response
  - Start measuring response early!

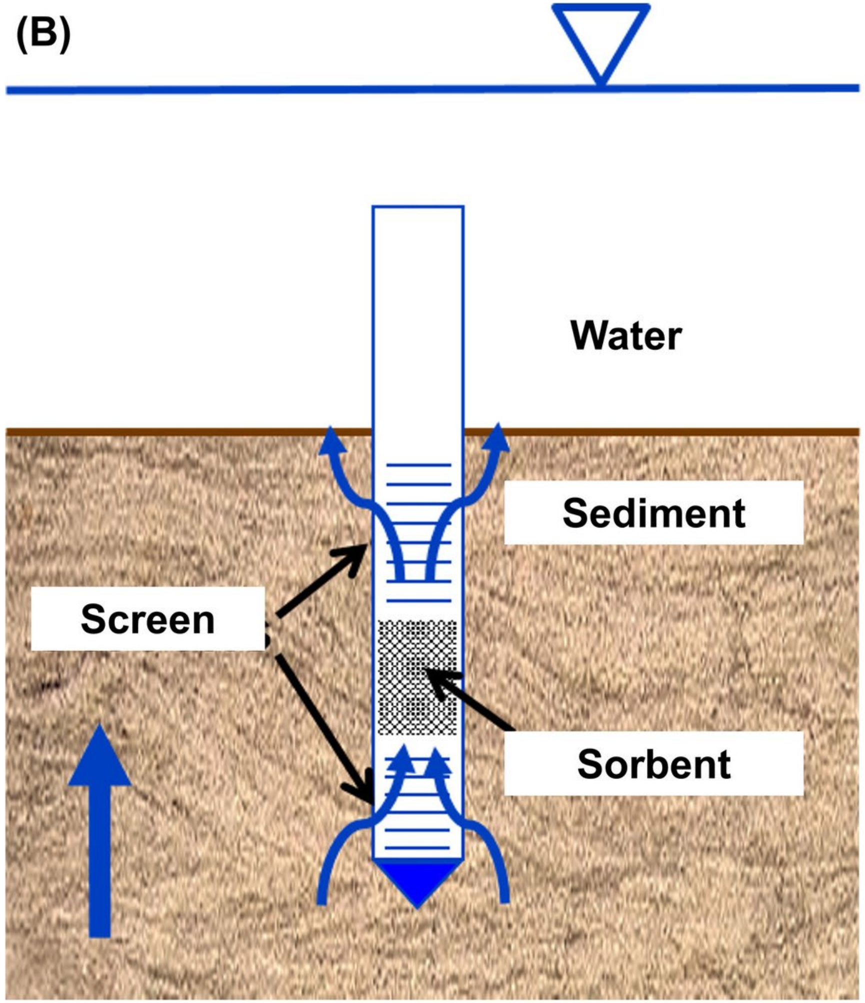
(Whittier et al. 2014)

GSI Methods: Geochemical

SBPFM

Direct-push probe used to measure GW and contaminant mass fluxes in lake or stream beds by passively intercepting ambient flow through a sorbent matrix

1) **Deployment**: SBPFM pushed into sediment
2) **Passive Interception**: Ambient vertical water flow (up or down) moves through screens and sorbent matrix
3) **Tracer Elution**: Water-soluble tracers (e.g., alcohols) within sorbent are displaced at rate proportional to water flux, measuring water flow
4) **Contaminant Capture**: Dissolved contaminants in sediment water are retained (sorbed) onto matrix, proportional to contaminant mass flux
5) **Retrieval and Analysis**: Lab analysis quantifies remaining tracers and captured contaminants to calculate fluxes

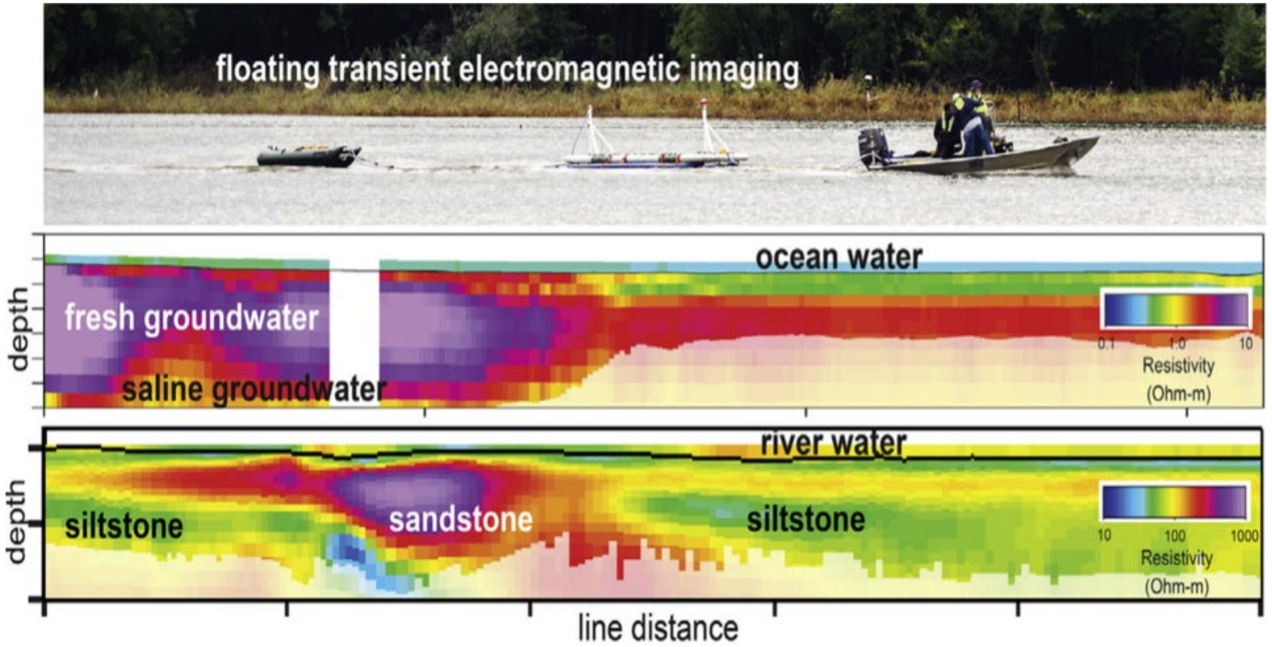


(Haluska et al. 2024)

GSI Methods: Geophysical

Waterborne frequency domain EM

- Ideal for coastal surveys of GSI
- Detects variations in subsurface electrical resistivity using EM induction
- Noninvasive; does not require direct electrical contact with water or earth
- Ideal for moving or continuous surveys and at sites with very resistive surface layers that hinder electrical contact



(EPA 2025)

EM: electromagnetic

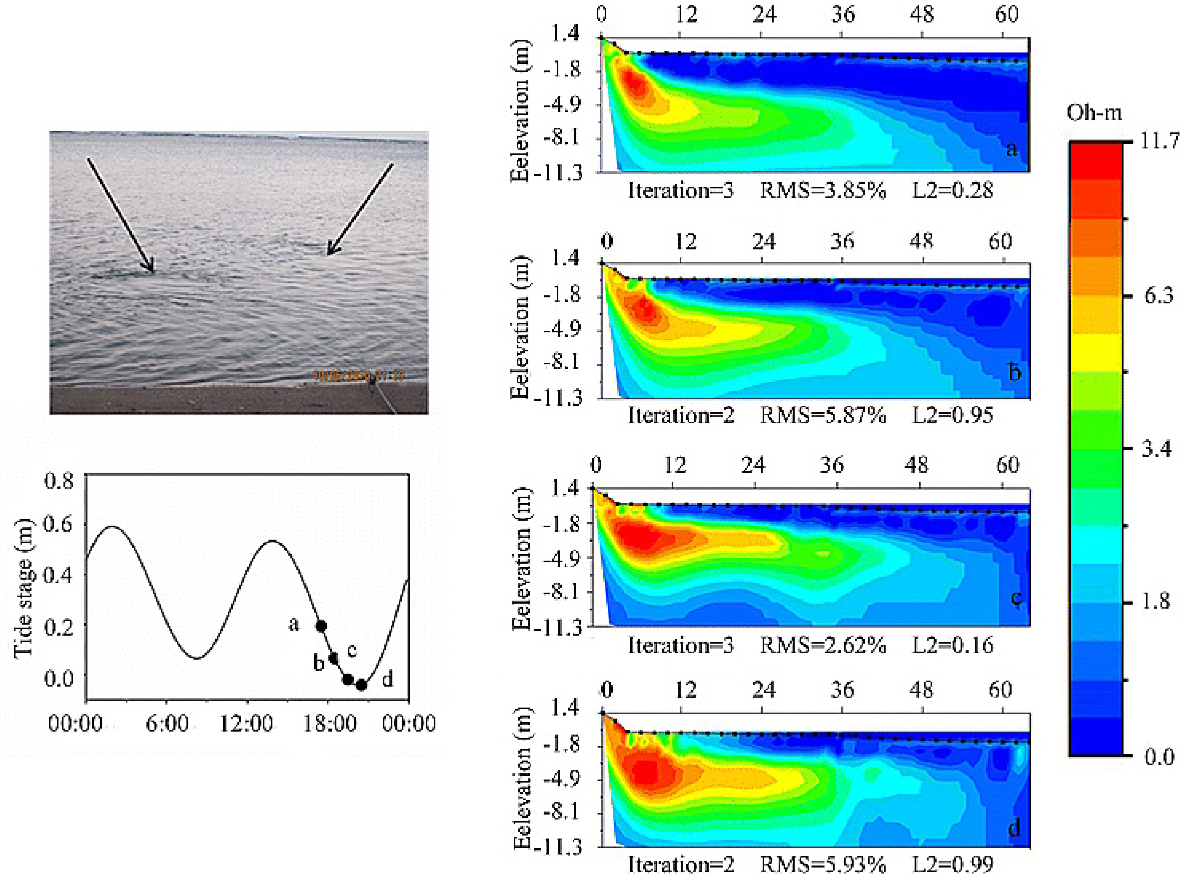
GSI Methods: Geophysical

ERT

- Ideal for tidal analysis of GSI at coastal sites
- Electrical resistivity is resistance to flow of electrons (current); inverse of electrical conductance

  Fresh water = more resistive

  Saltwater = less resistive
- Like temperature or salinity, resistivity can be used as tracer
- Fresh water discharges to saltwater are more resistive compared to seawater



(Dimova et al. 2012)

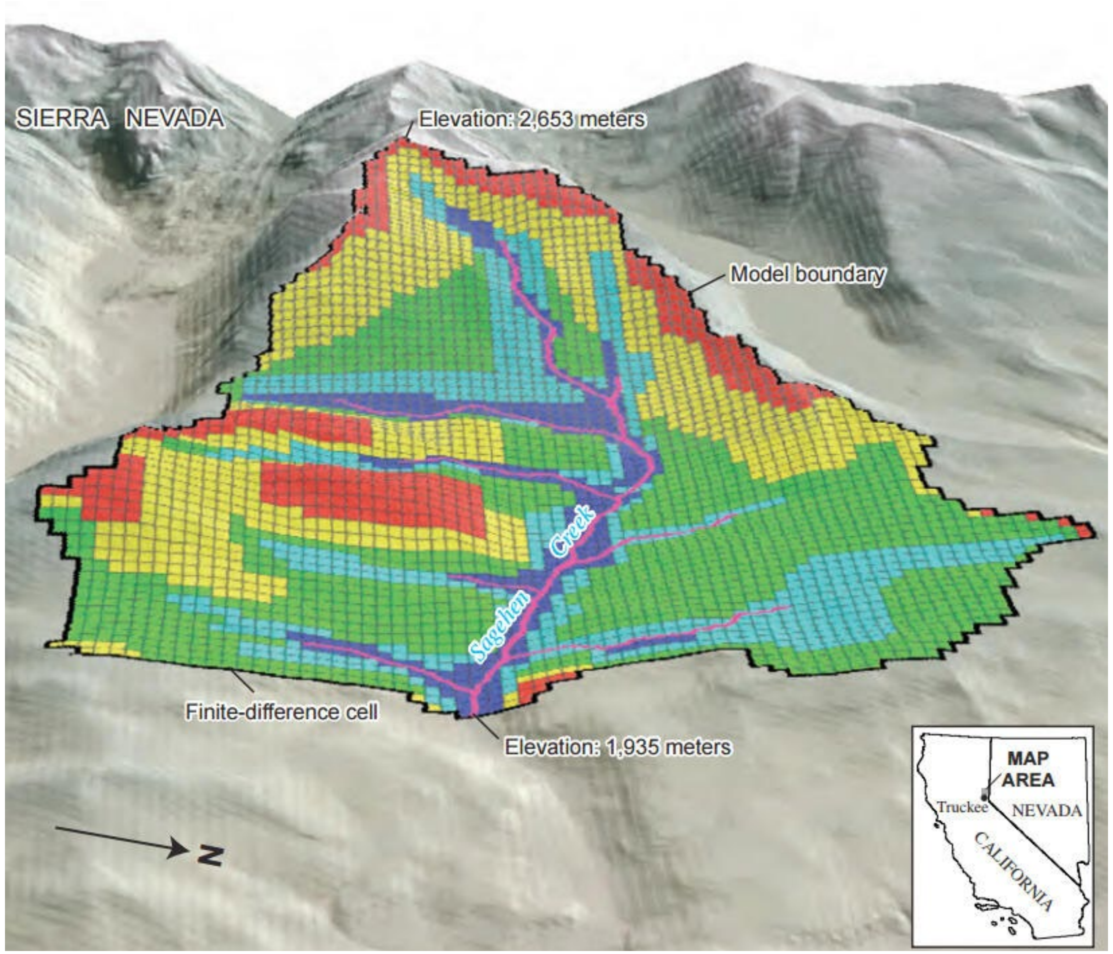
ERT: electrical resistivity tomography

Break

GSI Methods: Modeling

Modeling basics

- Computer code (algorithm) that solves groundwater flow equation
  - Diffusion equation for transient flow; Laplace equation for steady state flow
- Operates on conservation of mass principle
- Source code free and public domain; GUIs (GMS, GW Vistas) require licenses



(USGS 2023)

GMS: Groundwater Modeling System
GUI: graphical user interface

GSI Methods: Modeling

Basic flow model/code

MODFLOW: USGS's modular hydrologic model

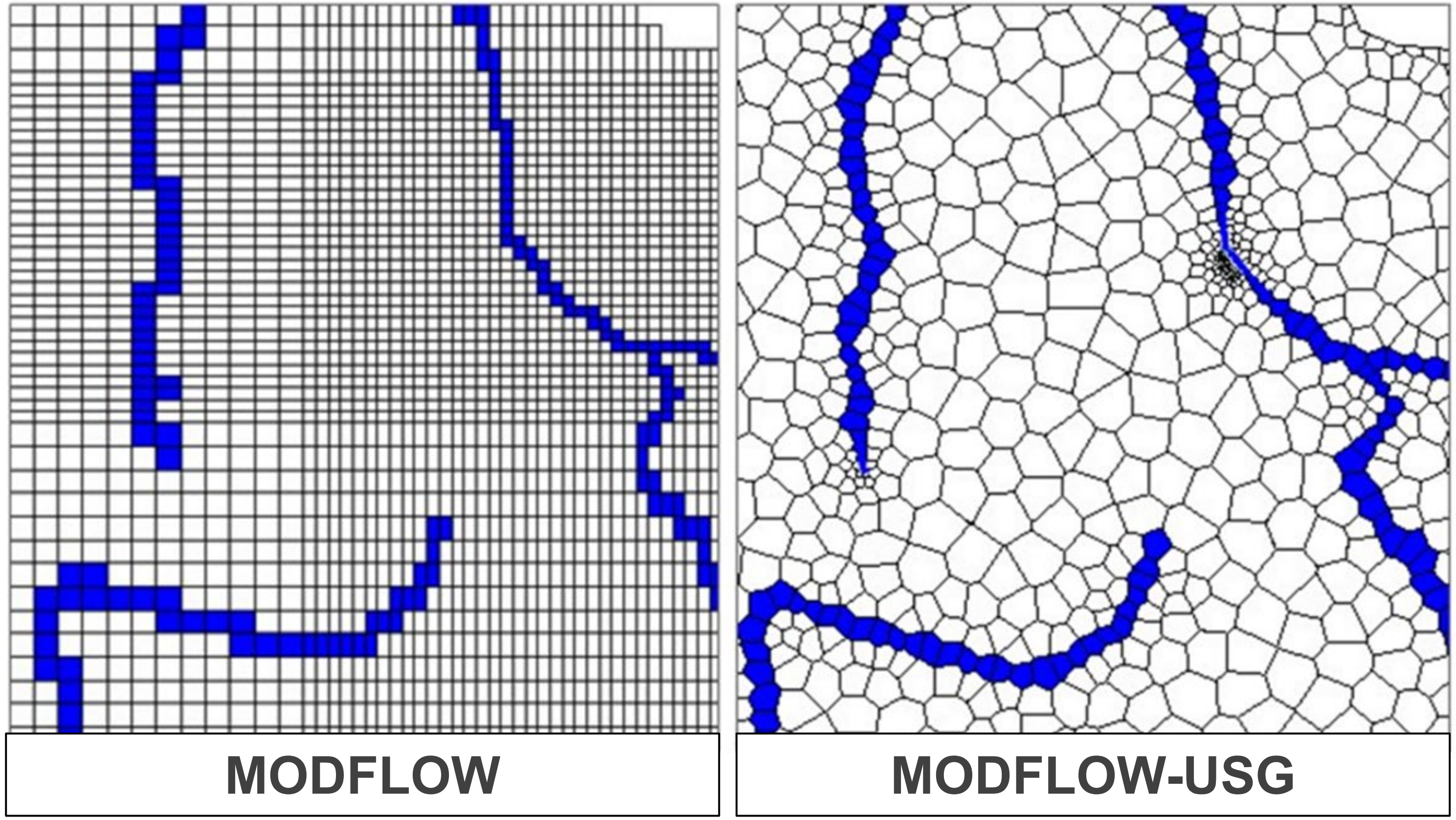
- *International standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions.* (USGS 2022)
- All models start in MODFLOW
- MODFLOW-USG (2013) added unstructured grid capabilities

Relevant add-on packages

- **MODPATH**: Computes flow paths from MODFLOW outputs
- **MT3DMS/MT3D-USGS**: Simulates groundwater solute transport
- **SEAWAT**: Simulates variable-density groundwater flow and transport
- **GSFLOW**: Simulates coupled GW/SW flow
- **SWI6**: Sharp-interface saltwater intrusion package

GSI Methods: Modeling

MODFLOW-USG (unstructured grids)

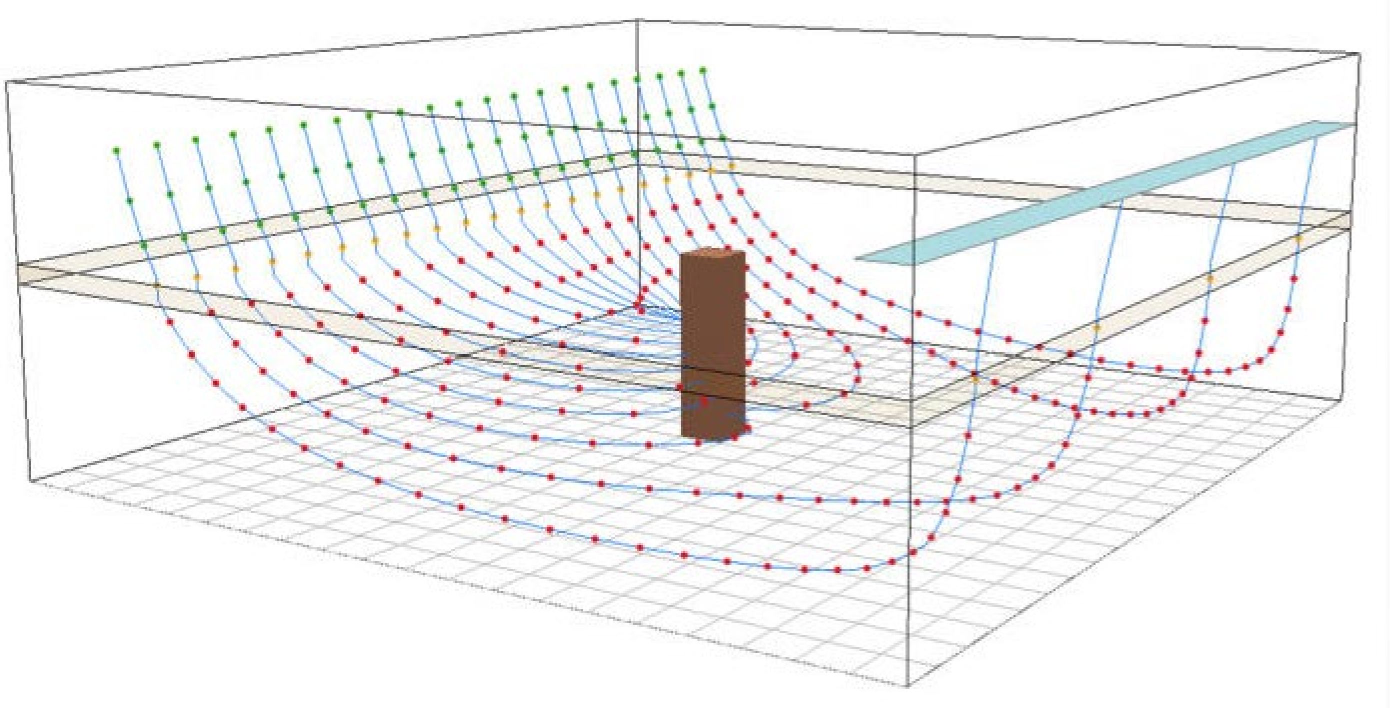


(Waterloo Hydrogeologic 2013)

GSI Methods: Modeling

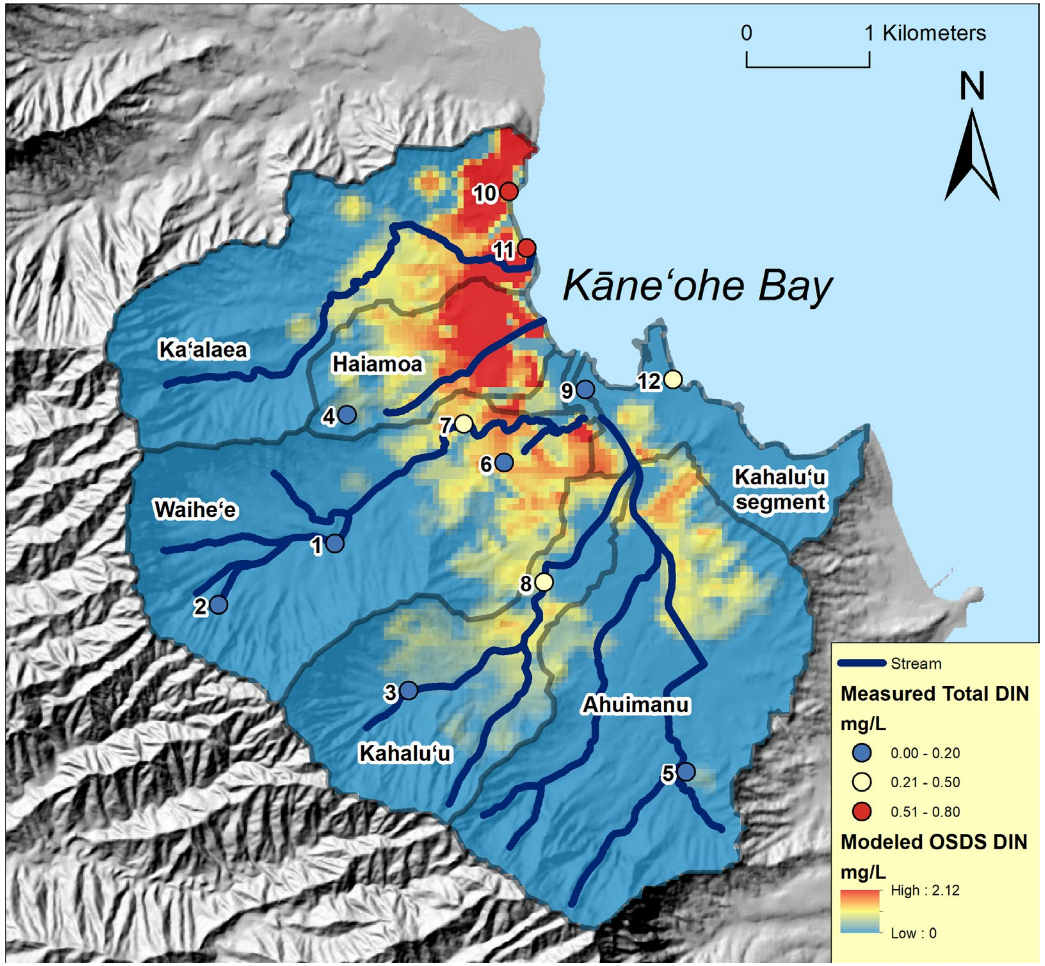
MODPATH

- Computes flow paths from MODFLOW outputs
- Relevant applications include determining/ delineating
  - GW travel times and flow paths
  - Capture zones
  - Radius of influence
  - Source of GW seeps



(USGS 2017)

GSI Methods: Modeling



(Mathioudakis et al. 2025)

MT3DMS

- Advection-dispersion solute transport
- Can simulate transport within streams and lakes, including solute exchange with connected groundwater
- Chemical reaction package includes ability to simulate interspecies reactions and parent-daughter chain reactions
- Relevant use cases include the following
  - Simulating contaminant transport based on known chemical properties
  - Simulating three-dimensional heat transport (heat is a GW tracer)

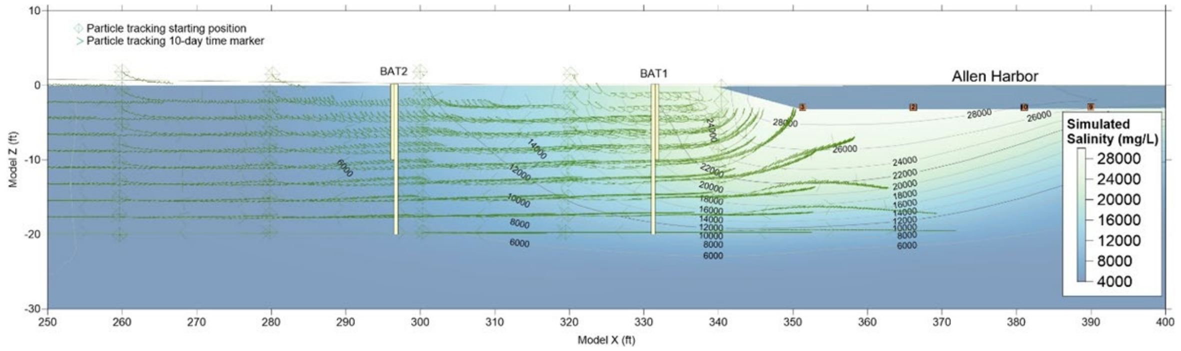
GSI Methods: Modeling

SEAWAT

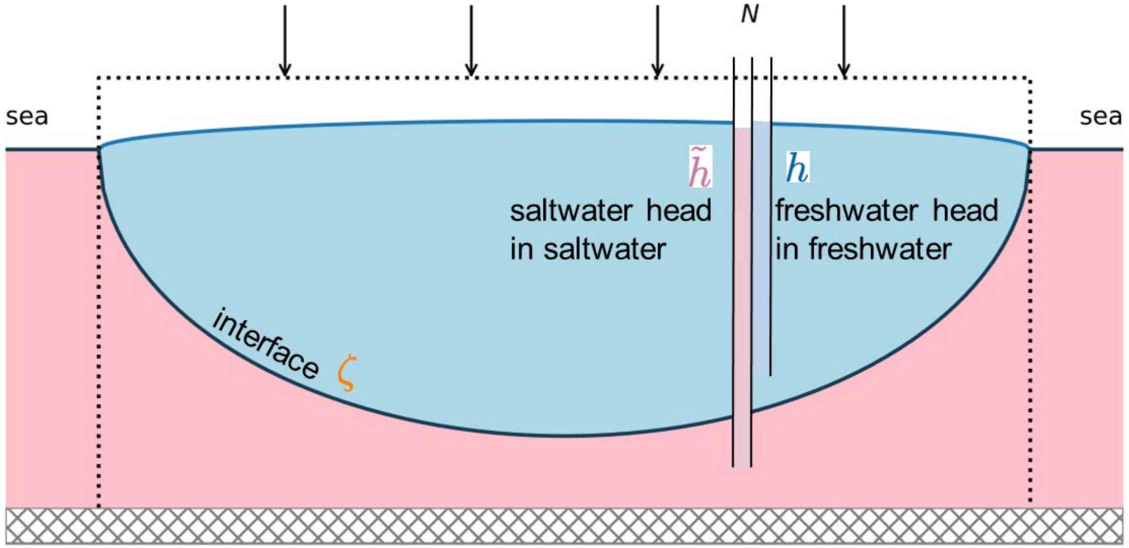
- Simulates variable-density groundwater flow and transport
- Use cases: brine migration, seawater intrusion, CF&T in coastal aquifers (integrated with MT3DMS)

SWI6

- Sharp-interface saltwater intrusion package for MODFLOW 6 based on Ghyben-Herzberg principle
- Simulates interface shifting in response to changes in recharge, pumping, sea level change, etc.
- Differs from SEAWAT by solving for interface elevation within single grid block/layer, rather than requiring high-resolution vertical discretization
- Sharp interface = much quicker computation time than SEAWAT at expense of interface gradient



(NAVFAC 2021)



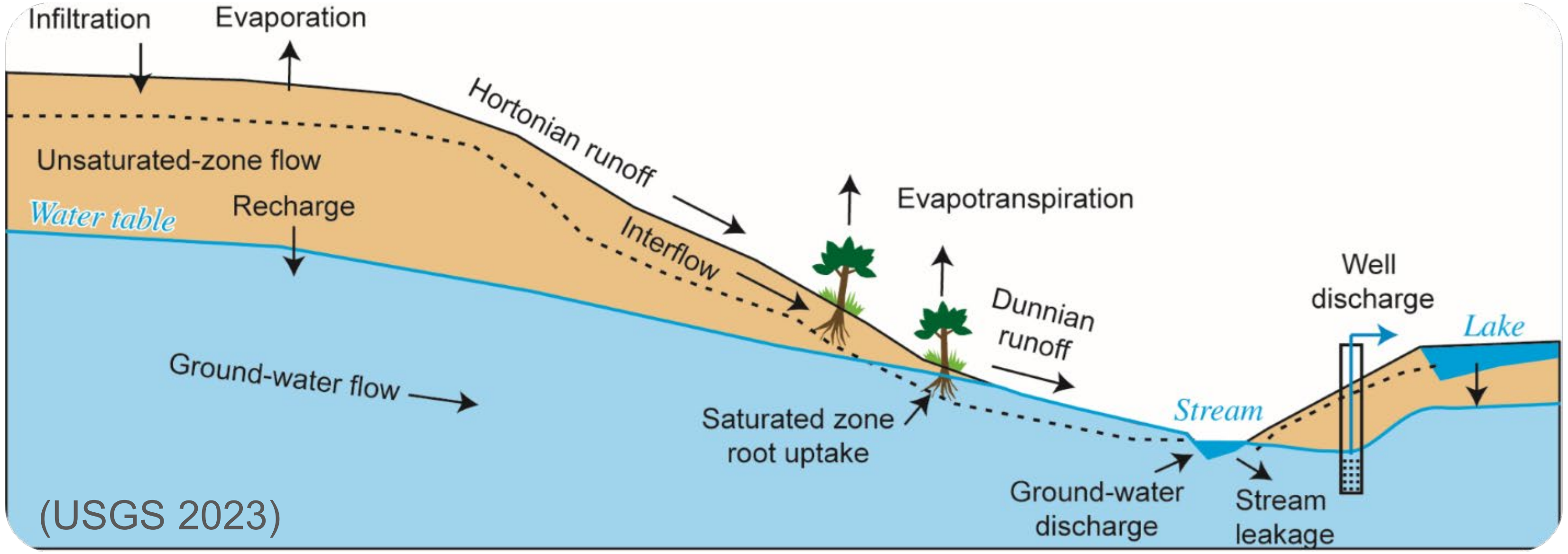
(Bakker et al. 2025)

CF&T: contaminant fate and transport

GSI Methods: Modeling

GSFLOW

- USGS model coupling MODFLOW with PRMS for integrated GW/SW simulation
- Integrated hydrologic model: flows are simulated, not specified
- Calibrate with streamflow data (PRMS) and GW heads (MODFLOW)



(USGS 2023)

PRMS: Precipitation Runoff Modeling System

GSI Methods: Modeling

How can models be useful?

1. Provide answers to specific objectives
2. Provide understanding of behavior of hydrogeologic system
3. Provide information on data gaps and parameters critical to prediction objectives
4. Provide evaluation of uncertainty in predictions due to known uncertainties in model parameterization
5. Provide mechanism for making informed decisions with data you have

A complex numerical model is useless without a robust CSM…

The reliability of model solutions is directly dependent on the quantity and quality of data inputs (recharge, water levels, lithology, etc.): good data in = good solution out

KEY POINT

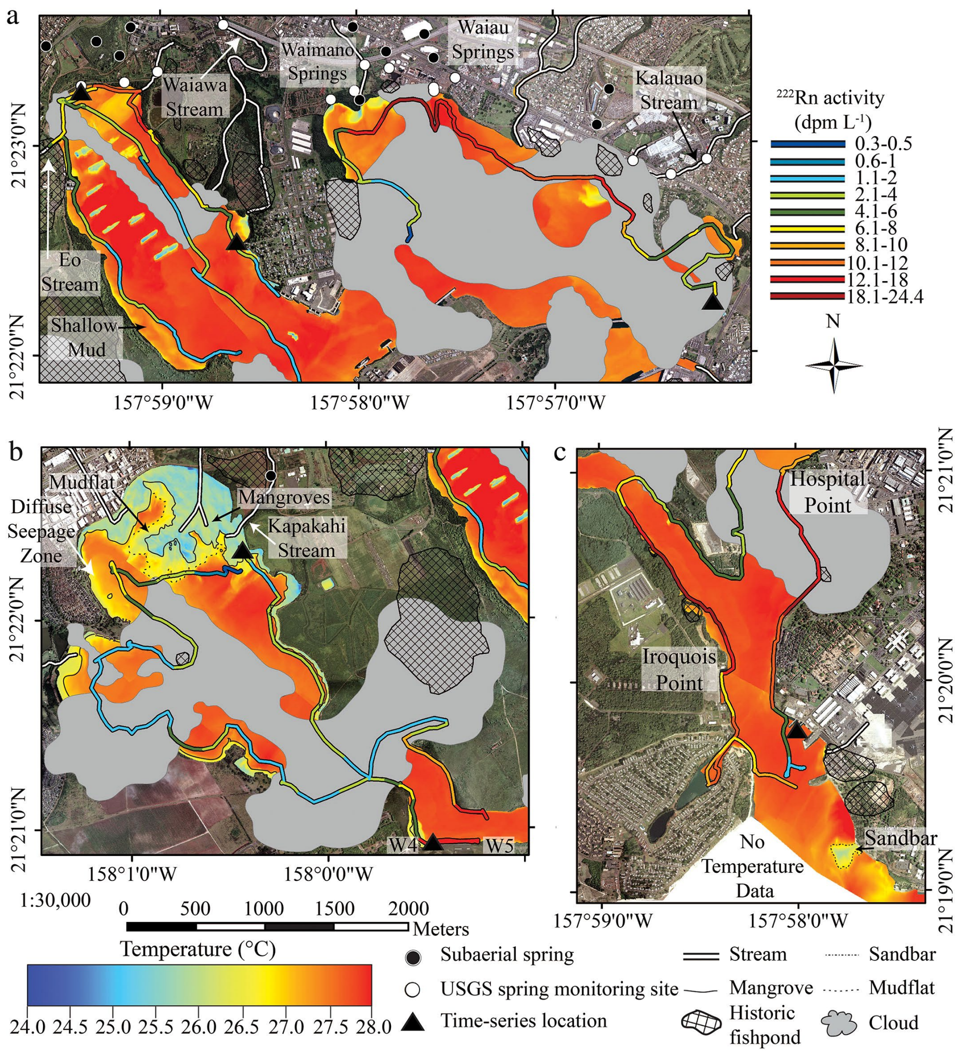
Managing expectations within project team, including Navy, contractors, regulators, and stakeholders, throughout modeling process is paramount to achieving successful outcomes.

GSI Methods: Paired Approach

Paired approach is valuable for multiple lines of evidence and comprehensive analysis of flux

Example: radon and thermal imaging

- Radon activity (dpm/L) point measurements
- Thermal imaging gives area of seep
- Discharge rate obtained by extrapolating radon point measurements across area of discharge as obtained by thermal imaging



(Kelly et al. 2018)

dpm/L: disintegrations per minute per liter

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How to Plan for and Scope GSI Investigations

Potential project-specific objectives of GSI investigation

- Determining whether GW migration pathways are complete
- Defining extent of contaminant migration
- Informing risk assessment
- Quantifying GW discharge and contaminant flux
- Informing remedial design strategies
- Monitoring remedy effectiveness

How to Plan for and Scope GSI Investigations

First, look for publicly-available data

- Water levels, stream flow/stage, and/or temperature (USGS)
- Soil and land use (USDA)
- Tides (NOAA)
- Other sources of available data: universities, state agencies, etc.
- Reports from nearby impacted sites, if any

NOAA: National Oceanic and Atmospheric Association
USDA: United States Department of Agriculture

Defining Extent of Contaminant Migration

Are GW migration pathways complete?

- Do plumes extend to downgradient SW bodies?
- Are baseline SW data available for prerelease conditions?
- Look for signs of GW inputs
  - Start with visual observations (bubbling, iron staining, etc.) and field measurements (temperature, DO, etc.); compare to publicly available data
- For more extensive evaluation, use TIR, tracer methods, hydrologic, or geophysical methods
- For advanced evaluation, use GW model

Informing Risk Assessment

(Mathioudakis 2020)

Should receptors in SW be considered?

- In small stream/river, even small discharge of impacted GW can have significant effects
- In large stream/river or offshore, discharge may have minimal impact due to buffering capacity of SW
- Point-source vs. diffuse discharges
  - Point-source: greater impact on water quality at discharge location
  - Diffuse: lesser impacts but more widespread

Quantifying GW Discharge and Contaminant Flux

How much contaminant mass is reaching SW?

To quantify mass flux, need to know volume and concentration of discharge

1) **Locate GW discharge**
   (visual evidence, field observations, TIR, etc.)
2) **Estimate GW discharge rate (volume/time)**
   (any number of methods discussed previously)
3) **Measure COC concentration (mass/volume)**
   of contaminant in GW discharge (sample)
4) **Calculate COC mass discharge (mass/time)**

(Mathioudakis 2021)

COC: contaminant of concern

Knowledge Check

Quantifying Contaminant Flux

GW is discharging to small stream at a rate of 5,000 L/day. PFOS concentrations in piezometers immediately adjacent to the stream are 800 ng/L. What is the PFOS mass flux to the stream in grams per year?

1) **Locate GW discharge**
2) **Estimate GW discharge rate (volume/time): q_{GW}**
3) **Measure COC concentration (mass/volume): C_{PFOS}**
4) **Calculate COC mass discharge (mass/time): J_{PFOS}**

$$J_{PFOS} = q_{GW} C_{PFOS}$$

$$J_{PFOS} = 5000\,\frac{L}{d} \times 800\,\frac{ng}{L} \times \frac{1\ g}{1{,}000{,}000{,}000\ ng} \times \frac{365\ days}{1\ year} = \mathbf{1.5\ g/year}$$

L/d: liters per day
ng/L: nanograms per liter
PFOS: perfluorooctanesulfonic acid

Informing Remedial Design Strategies

Reduced remediation costs resulting from improved CSMs for seep locations and fluxes

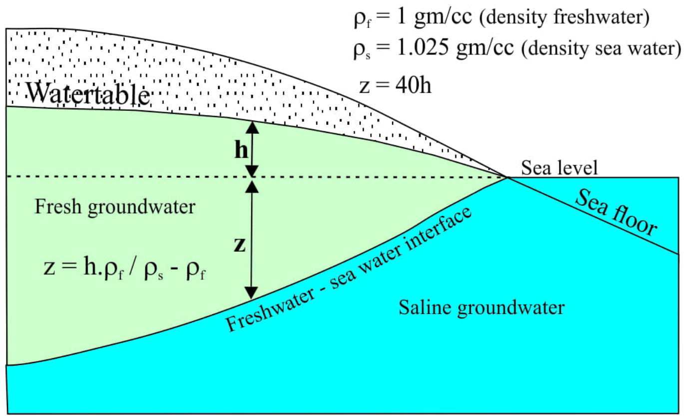
Will remediation impact natural flow regimes?

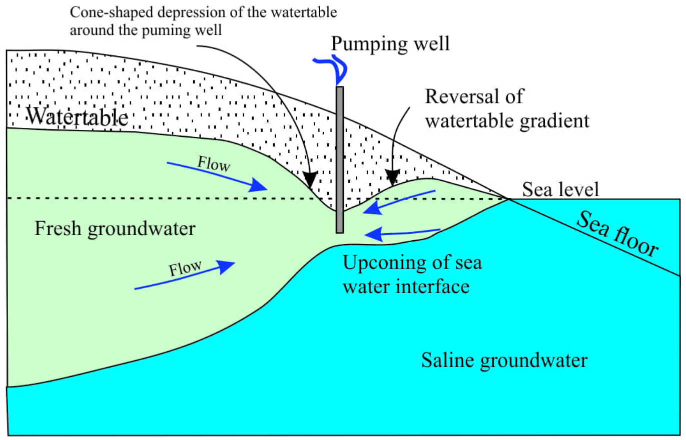
- e.g., pump and treat system could lower stream flows or induce saltwater intrusion into aquifer

If plume is reaching SW, engineering controls may be needed

- e.g., hydraulic controls, oleophilic biobarrier

The Ghyben-Herzberg Principle

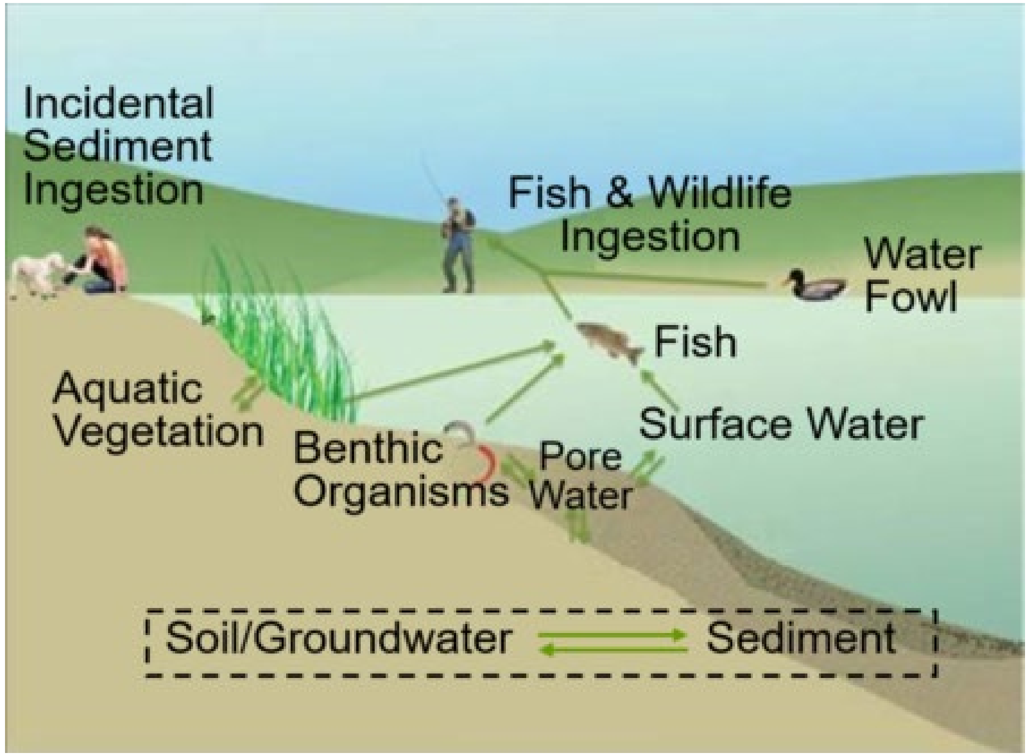




Pumping induced sea water intrusion

(Geological Digressions 2016)

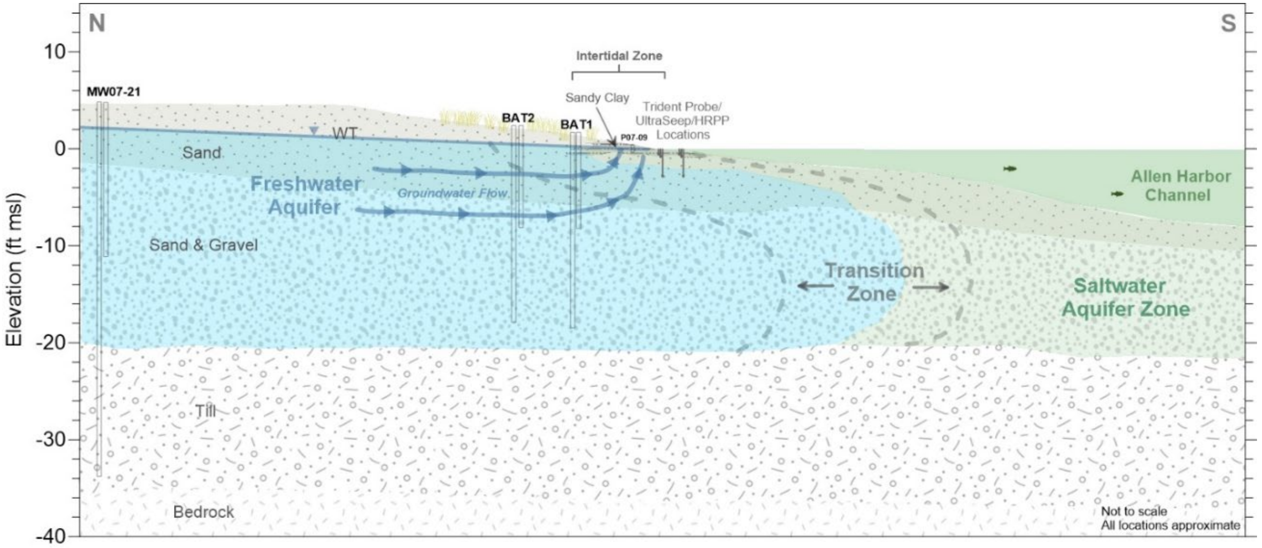
Monitoring Remedy Effectiveness



(Envirowiki 2026)

- Are COC concentrations decreasing in sediment/SW?
- Are geochemistry and riparian/riverine/coastal habitats returning to prerelease conditions?
- Are recovery systems functioning as intended without lowering stream flows?

Monitored Natural Attenuation (MNA)



(NAVFAC 2021)

CVOC: chlorinated volatile organic compound
DCE: dichloroethene
MNA: monitored natural attenuation
OoM: order of magnitude
POC: point of compliance
TCE: trichloroethene
VC: vinyl chloride

2021 NAVFAC Study (Davisville, Rhode Island):

- Reductive dechlorination (TCE → DCE → VC → Ethene) along flow path from shoreline wells to surface sediment
- Degradation + dilution → up to 3 OoM attenuation of CVOC concentrations between shoreline wells and potential points of exposure in surface sediment. SEAWAT model matched empirical (sampling) data.
- Use of shoreline wells as POCs fails to account for attenuation processes
- SW quality criteria can be adjusted for attenuation level to establish interim cleanup goals in GW at shoreline wells.

How to Plan for and Scope GSI Investigations

Cost	Method	Question(s) to Answer
$	Field observations/measurements	Discharge location
$$	Seepage meters, SBFMs	GW flux to SW (single location)
$$	Seepage run	GW flux to river/stream (segments)
$$	Tracer study (natural)	GW flux to SW, COC mass reaching SW
$$-$$$	Thermal infrared imaging	Location and area of GW discharge to SW
$$$	Tracer study (artificial)	GW flux to SW, COC mass reaching SW
$$$	Stream gauge/piezometer pairs	GW flux to SW over time
$$$	Time-series temperature (FO-DTS)	Location and variability of GW discharge to SW
$$$	Geophysics (ERT, waterborne EM)	GW discharge location, infer volume
$$$	Paired study	Discharge locations, Volume flux, COC mass flux
$$-$$$	GW model	All (volume flux, mass flux, discharge location, etc.)

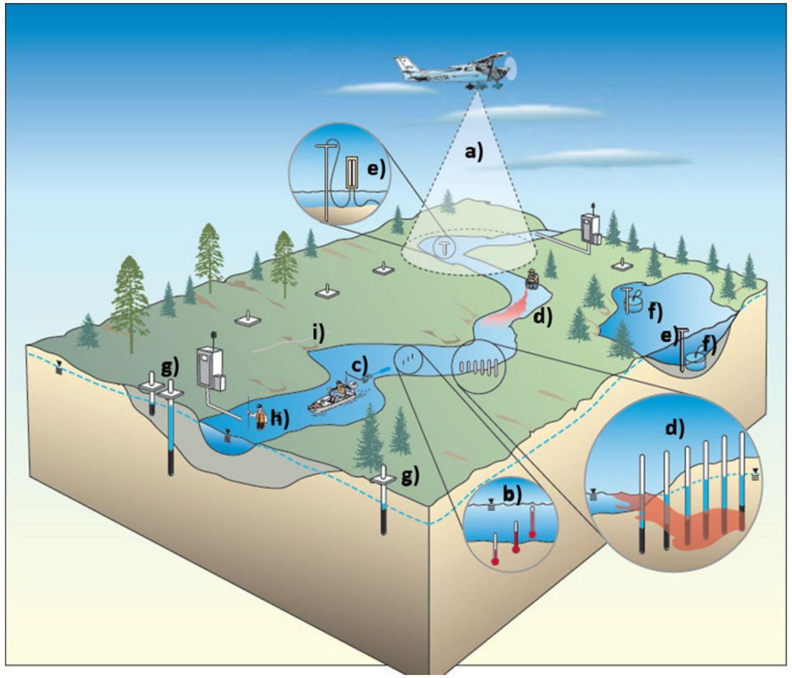
How to Plan for and Scope GSI Investigations

Publicly available tools

[USGS Hydrologic Toolbox]()

[USGS GW/SW Method Selection Tool]()

[SERDP Transition Assessment Tool]()



(The Groundwater Project 2020)

KEY POINT

Scoping a GSI investigation is extremely site-specific, so all site/project-specific considerations should be accounted for by RPM and/or consultant.

RPM: remedial project manager

SERDP: Strategic Environmental Research and Development Program

Naval Facilities Engineering Systems Command
EXWC Engineering and Expeditionary Warfare Center

Break

Knowledge Check

For each release scenario, which methods are most appropriate for investigating GSI at site?

1. Large hydrocarbon release to shallow anaerobic aquifer occurs approximately 0.5 miles from gaining stream reach. What methods could be employed to assess whether SW is potential receptor?
2. Historical AFFF releases occurred from a fire training area approximately 1 mile from tributary that feeds into coastal estuary. An innovative ex situ treatment system is being installed. Before pumping wells are installed, what methods could be used to investigate impact of pumping on nearby surface water?

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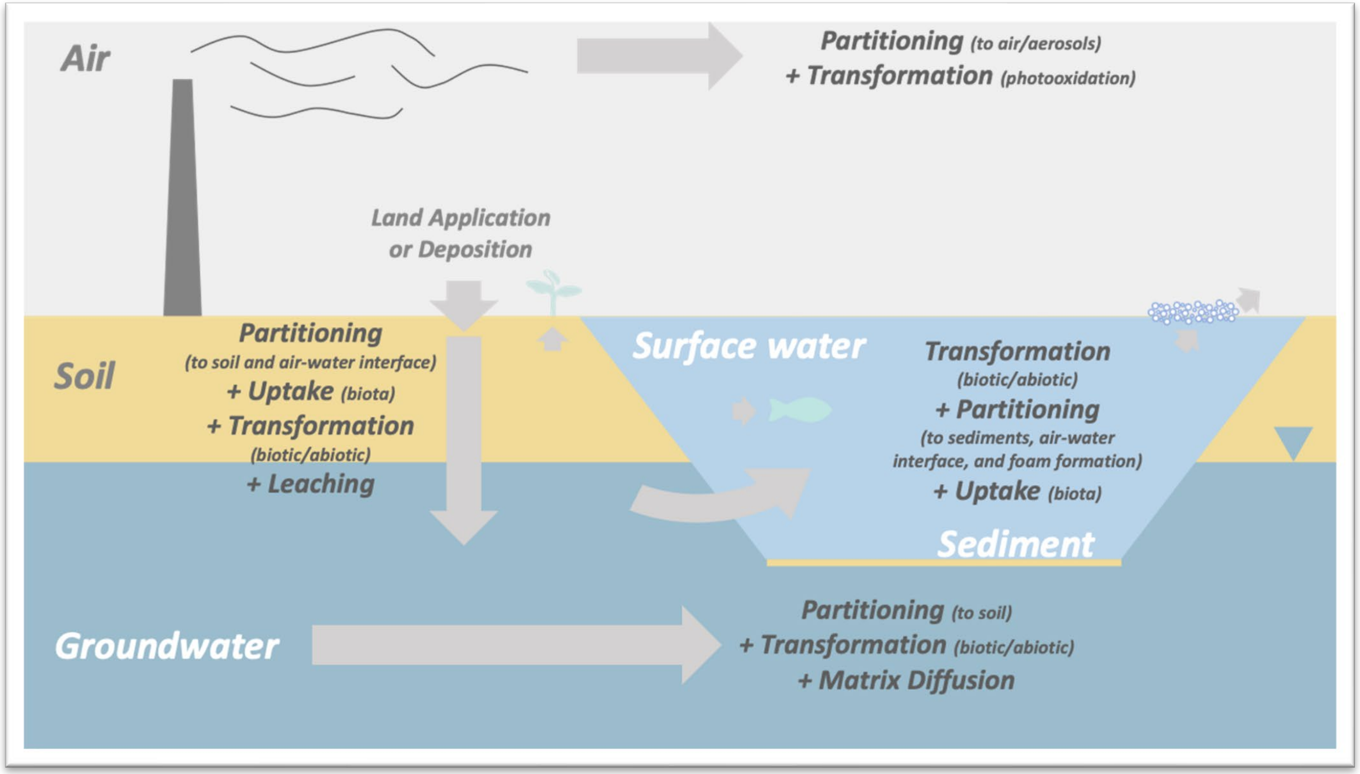
Unique Challenges of GSI Investigations for PFAS

PFAS basics

- PFAS move easily through soil into groundwater, resisting natural degradation due to strength of C-F bond
- Hydrophilic head (functional group) and hydrophobic tail (C-F chain)

Compound-specific properties to consider for GSI

- **Chain length:** short chain = more soluble
- **Functional group:** sulfonates (-S) have greater sorption affinity for soil; carboxylates (-A) more soluble in water

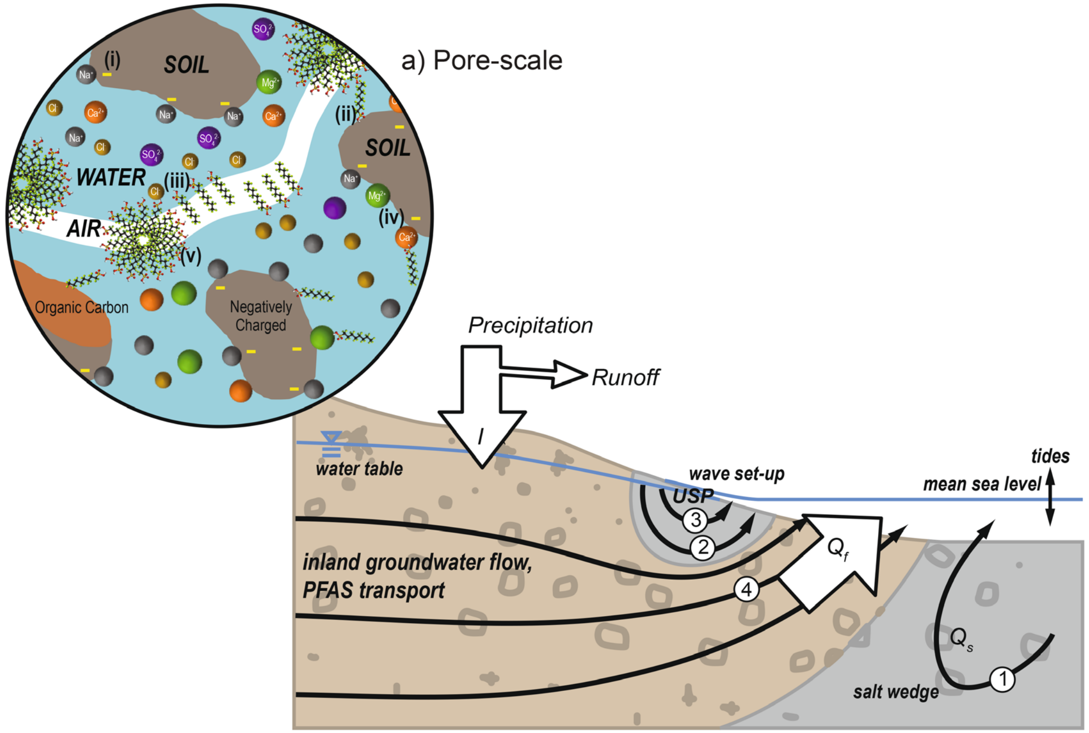


(ITRC 2026)

ITRC: Interstate Technology and Regulatory Council

PFAS: per- and polyfluoroalkyl substances

Unique Challenges of GSI Investigations for PFAS



(Hort et al. 2024)

- **PFAS water solubility** decreases as carbon chain length increases; short-chain carboxylates (e.g., PFHxA, PFBA, PFPeA) are the most mobile PFAS in GW, thus most likely to reach SW from GW release
- **Precursor transformation**: Hyporheic zone and subterranean estuary are extremely biogeochemically-active zones
- **PFAS salting out** onto aquifer solids in coastal GW discharge zones (SGD)
  - Reduces PFAS mass discharge, but PFAS could remobilize under future salinity changes
  - 1-to-25-fold estimated increase in sorption of PFAS depending on salinity increases (highest in West Coast bays and North Atlantic coastline; Hort et al. 2024)

PFBA: perfluorobutanoic acid
PFHxA: perfluorohexanoic acid
PFPeA: perfluoropentanoic acid

Unique Challenges of GSI Investigations for PFAS

Site-specific considerations

Geology/soil

- Fine-grained lenses can allow plume to persist for decades, sustaining mass flux to SW via matrix diffusion
- Fractured rock systems allow preferential flow to SW
- High organic carbon content = more sorption of long-chain PFAS

Vadose zone thickness and moisture retention

- Thick vadose zone = more sorption, transformation, and retention
- Moisture content affects air-water interfaces

Redox environment

- Oxic environments favor precursor transformation
- Fluctuating redox conditions (e.g., in hyporheic zone) can enhance transformation

Presence of co-contaminants

- Competitive sorption can affect PFAS partitioning
- Redox conditions can change due to biodegradation of co-contaminants

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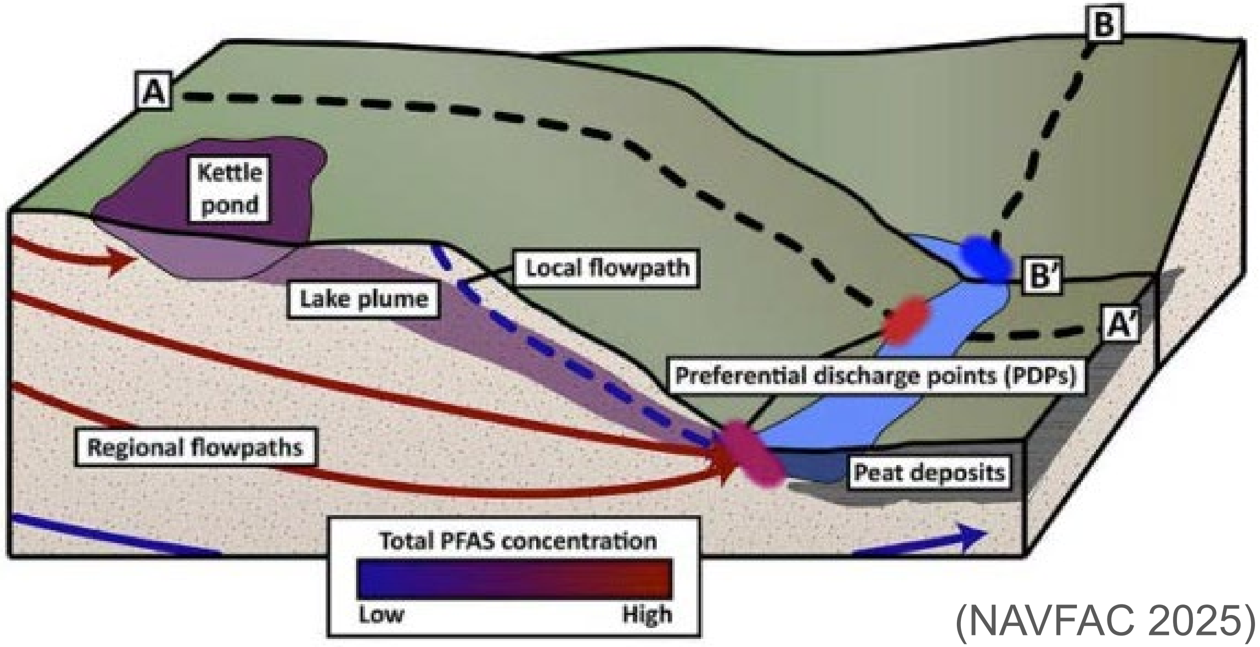
Case Study #1: Joint Base Cape Cod

Joint Base Cape Cod: PFAS

- ESTCP Project ER21-5237
- Joint Base Cape Cod FTA upgradient of Quashnet River and associated wetlands
- SW temp: 5–25°C; GW temp: 9.5–11.5°C
- Paired approach using FO-DTS, seepage meters, and sampling



(NAVFAC 2025)

KEY POINT

Main objective of case study was to locate discharge zones where PFAS-impacted GW emerges into river and to quantify spatial and temporal variability in PFAS mass loading at those discharge zones.

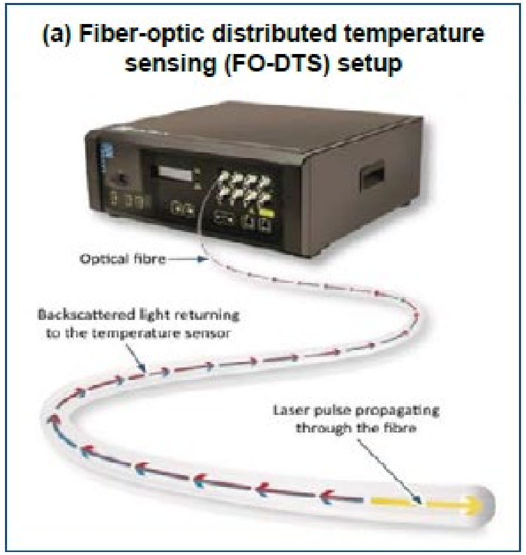
Case Study #1: Joint Base Cape Cod

FO-DTS

- Cable placed along GW-SW interface
- **Time-series measurements of temperature** along length of cable for detecting GW seeps (PDPs)
- Surveys conducted in June 2022 following UAS-TIR surveys in March 2022
- 57 PDPs detected

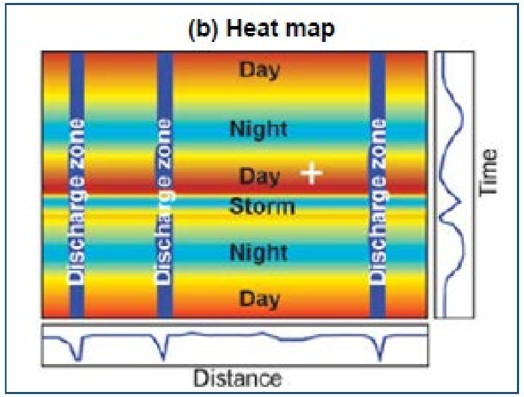
NAVFAC FO-DTS Fact Sheet

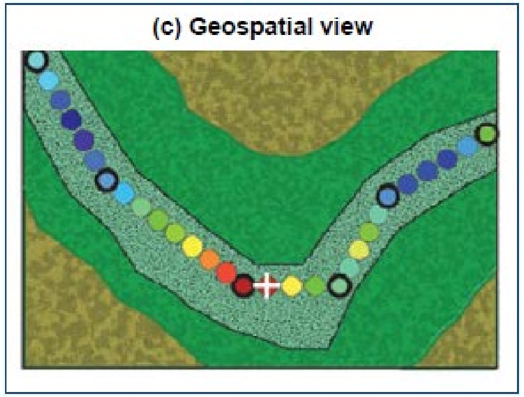
PDP: preferential discharge point


(a) Fiber-optic distributed temperature sensing (FO-DTS) setup

- (a) FO-DTS control unit with fiber-optic cable
- (b) FO-DTS data displayed in a heat map as temperature versus distance and time
- (c) Temperature along the cable, with locations interpolated linearly between points

NOTE: FO-DTS photo courtesy of Silixa LLC. Images adapted from Domanski et al. (2020)


(b) Heat map


(c) Geospatial view

(NAVFAC 2025)

Case Study #1: Joint Base Cape Cod

UAS-TIR

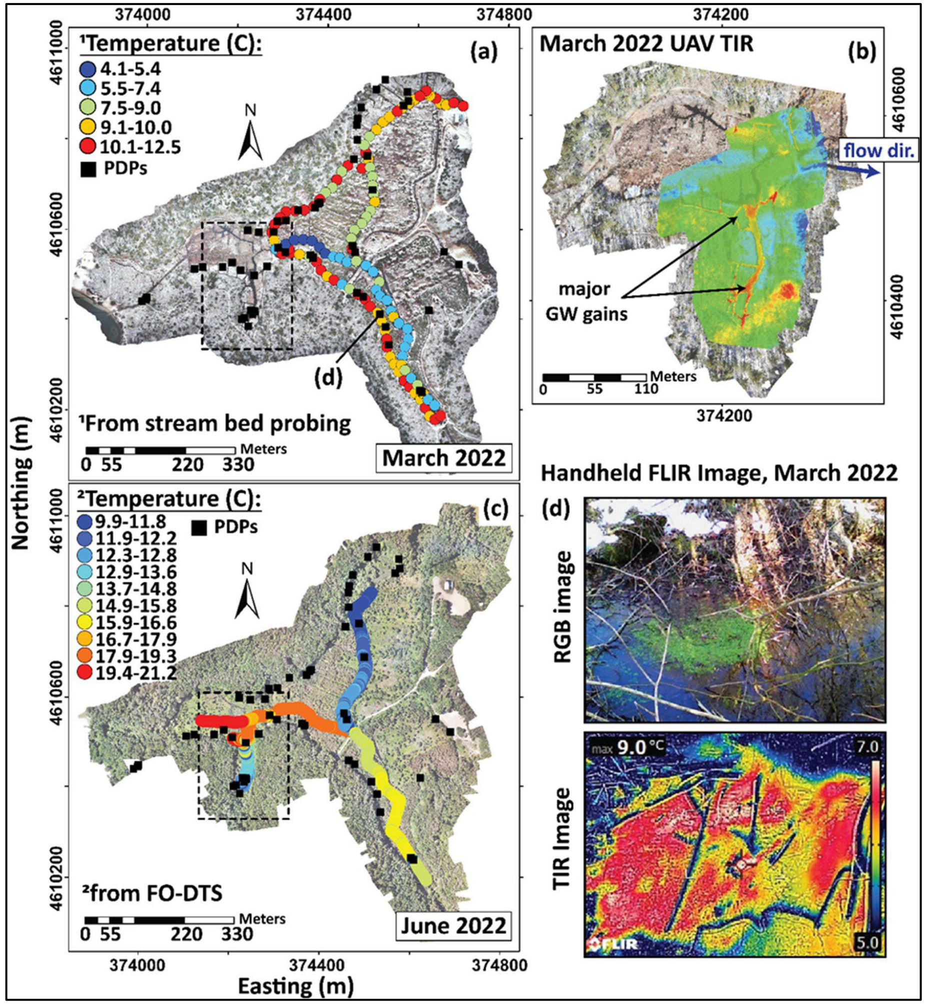
- Surface temperature
- **Pros**: **remote measurements;** can cover large area in short period of time with **limited setup**
- **Cons**: measurements for **single point in time**; can be limited by **overhead obstructions** or vegetation

FO-DTS

- GW-SW interface temperature (e.g., streambed)
- **Pros**: **time-series measurements**; not limited by vegetation or overhead obstructions
- **Cons**: **setup** (requires deployment of cable along full length of streambed)

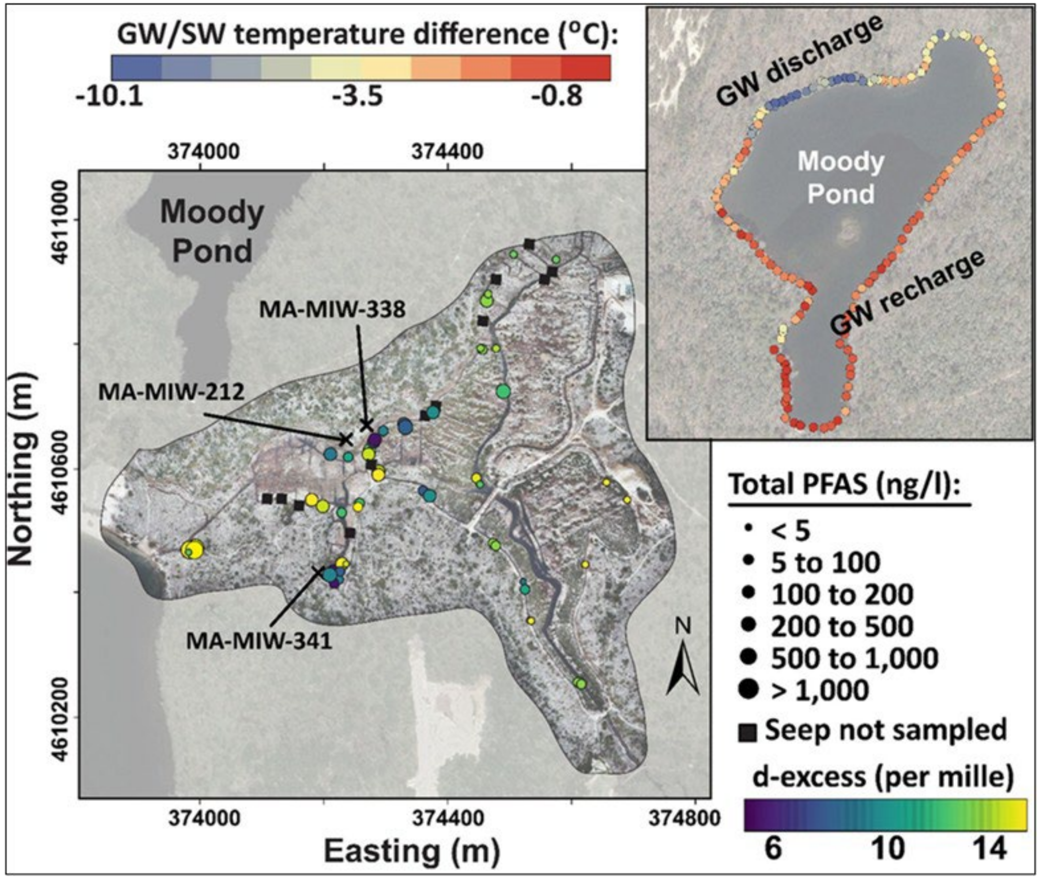
Both technologies can guide targeted sampling for COCs

Paired approach: UAS-TIR for initial survey; FO-DTS for time series at targeted locations



(Rey et al. 2025)

Case Study #1: Joint Base Cape Cod



(Rey et al. 2025)

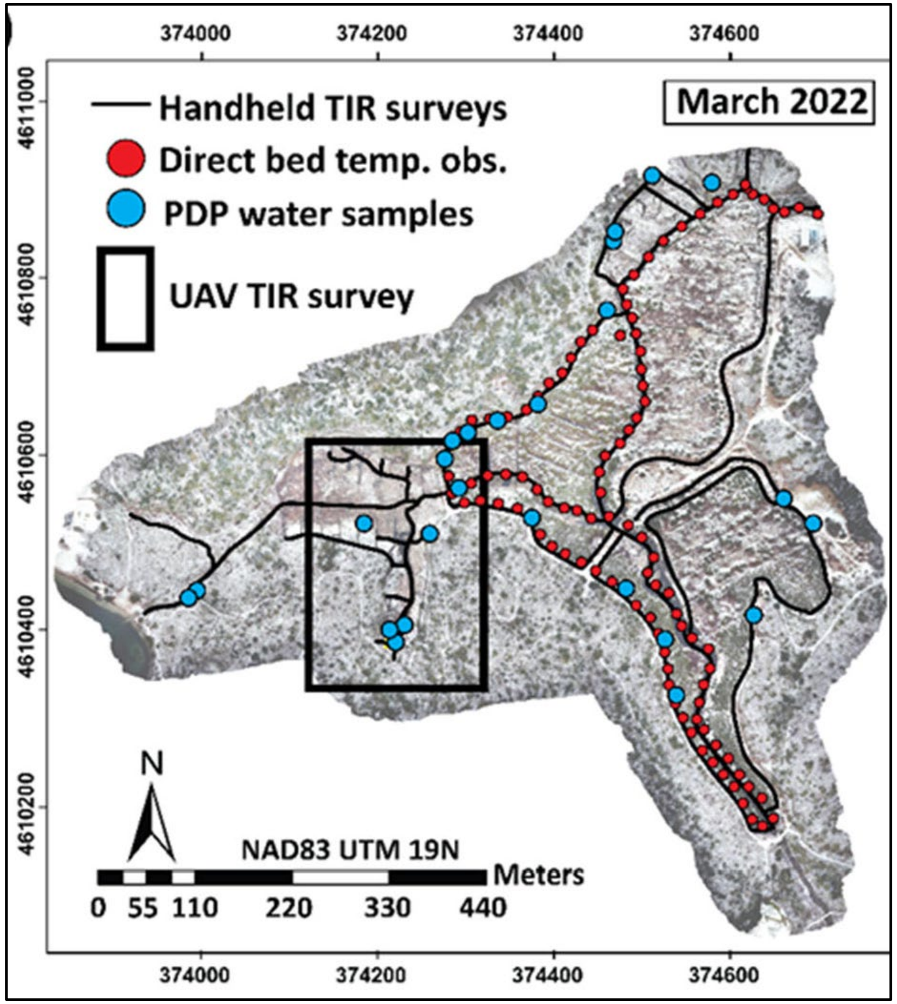
Seepage meters and sampling

- Seepage meters placed at nine PDPs to measure discharge
  - 0.2–3.2 m/day (1.1 m/day mean)
- High-flux PDPs sampled for PFAS, DO, and stable isotopes of water
  - PFAS: ND to ~5 µg/L
  - Isotopes showed differing sources (meteoric and lake/pond)
- Some seeps rich in PFOS and others rich in short-chains or precursors
- **Discharge measurements paired with sample concentrations allowed for calculation of PFAS mass loading (seeps ~200–800 µg/d)**

µg/L: micrograms per liter
m/day: meters per day

ND: nondetect

Case Study #1: Joint Base Cape Cod



(Rey et al. 2025)

Summary of GSI investigation process

1. **Locate** GW discharges (PDPs/seeps) based on temperature anomalies found with FO-DTS
2. **Quantify** GW discharges with seepage meters
3. **Calculate** PFAS mass loading from GW with targeted sampling
4. **Determine source** of seeps with water isotopes
5. **Inform** CSM and remedial design strategy

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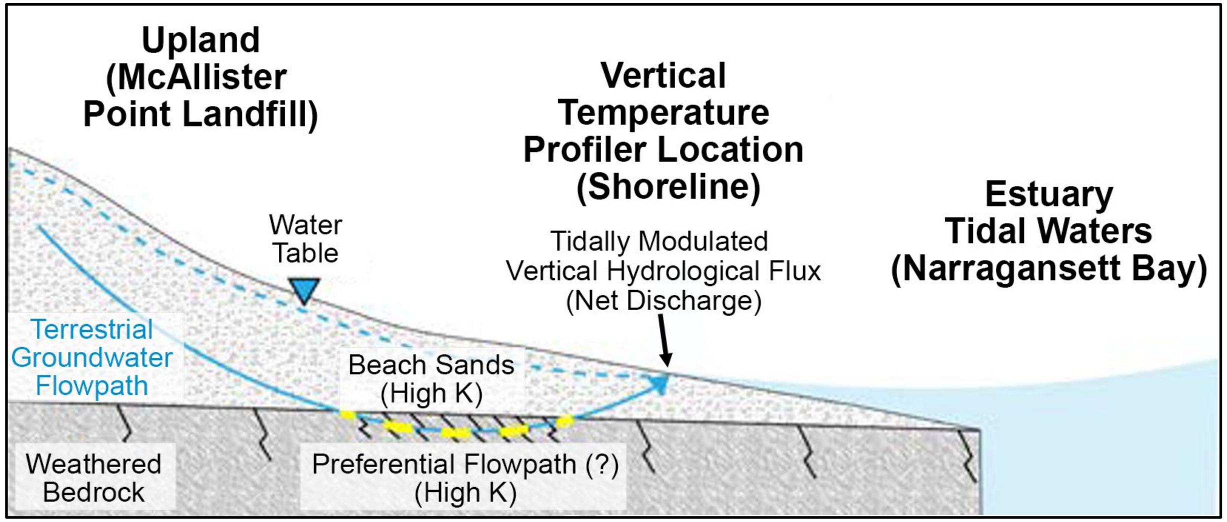
Case Study #2: Naval Station Newport

McAllister Point Landfill: Metals

- ESTCP Project ER21-5237
- 10.5-acre Installation Restoration Program site
- Capped landfill on Aquidneck Island
- GW ~10–15 feet below ground and influenced by semidiurnal tides
- Paired approach using FO-DTS, waterborne ERT, waterborne EM induction, conductivity measurements, UAS-TIR, handheld TIR, seepage meters, VTPs, and sampling



(NAVFAC 2025)

KEY POINT

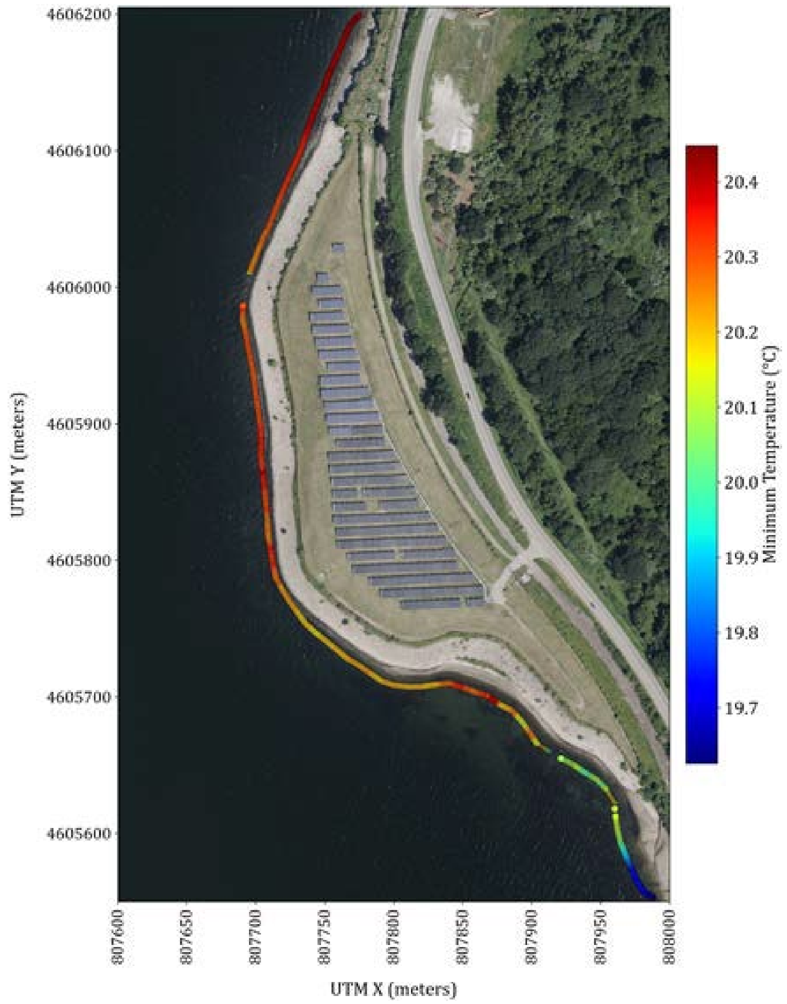
Main objective of case study was to validate site investigation approach that integrates multiscale thermal and EM tools to map GSI and quantify mass flux of metals to Narragansett Bay.

VTP: vertical temperature profiler

Case Study #2: Naval Station Newport

UAS-TIR and FO-DTS

- UAS-TIR revealed ~600-foot band of cool GW (~17–19°C) that contrasted with bay’s SW temperature (~23–25°C); confirmed by follow-up FO-DTS surveys
- Waterborne EM induction, ERT, and conductivity measurements independently confirmed GW seeps
- FO-DTS data revealed GW fluxes are tide-dependent and precipitation enhances flushing (increases mass flux)
- **Seeps samples combined with VTP modeled fluxes to determine metal contaminant mass fluxes into bay**
    - Copper: 0.5–56.5 µg/d
    - Nickel: 0.4–63.1 µg/d



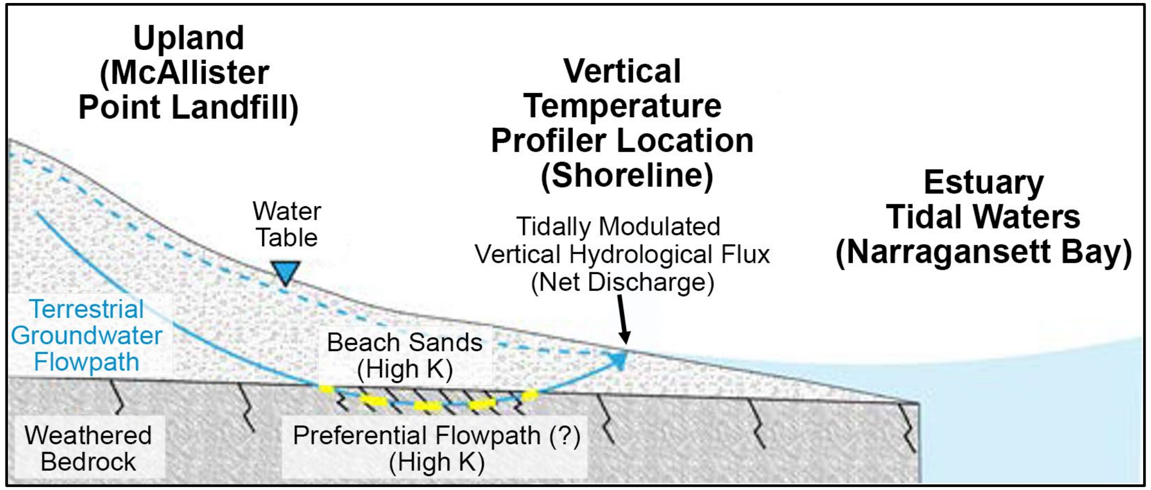
(NAVFAC 2025)

µg/d: micrograms per day

Case Study #2: Naval Station Newport

Conclusions

- Mass flux and variable geochemistry confirmed high-flux seeps drive metals transport into bay
- Future remedial optimization efforts should address the spatial heterogeneity in metals mass flux and target cleanup where highest metals mass loading is occurring



(NAVFAC 2025)

Summary of GSI investigation process

1. **Locate** GW discharges (seeps) based on temperature anomalies found with UAS-TIR and FO-DTS
    a) **Confirm** GW discharges with waterborne EM induction, ERT, and conductivity
2. **Quantify** GW discharges with VTP modeled fluxes and seepage meters
3. **Calculate** metals mass loading from GW with targeted sampling
4. **Inform** CSM and remedial optimization efforts

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Summary and Closing

There are numerous methods available for GSI investigations; no single best method—each serves different purpose at different cost

Thus, method selection should be done on site-specific basis based on regulatory drivers, cost considerations, CSM, etc.

Summary of typical GSI investigation process

1. **Locate** GW discharges based on tracer measurements
2. **Quantify** GW discharges with various methods
3. **Calculate** mass loading from GW with targeted sampling
4. **Determine source** of seeps with isotopes, modeling, etc.
5. **Inform** CSM and remedial design strategy

(Mathioudakis 2017)

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Questions